

DELINEATION OF GROUNDWATER PROTECTION
ZONES: TOWARDS A GROUNDWATER
MANAGEMENT PLAN IN THE SUTHERLAND AREA,
SOUTH AFRICA.

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DECLARATION

I, Daniél Mulder, hereby declare that the dissertation hereby submitted by me to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State, in fulfilment of the degree of Magister Scientiae, is my own independent work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

I furthermore cede copyright of the dissertation and its contents in favour of the University of the Free State.

Daniél Mulder

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ABBREVIATIONS

AFYM	Aquifer Firm Yield Model
ARE	Artificial Recharge Enhancement
BH	Borehole
CDT	Constant Discharge Test
CGS	Council for Geoscience
CMB	Chloride Mass Balance
DD	Decimal Degrees
DTH	Down-The-Hole
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water Affairs and Sanitation
EC	Electrical Conductivity
EM	Electromagnetics
ERT	Electrical Resistivity Tomography
FEC	Fluid Electrical Conductivity
FEM	Frequency-Domain Electromagnetic
GRAII	Groundwater Resource Assessment II
GRU	Groundwater Response Unit
GPS	Global Positioning System
HD	Horizontal Dipole
ID	Inner Diameter
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Managed Aquifer Recharge
MAR	(Hydrological)Mean Annual Recharge
NE	North-East
NGO	Non-Government Organisation

NGS	National Groundwater Strategy
NW	North-West
NWRS	National Water Resource Strategy
NWU	North-West University
RAF	Radial Acting Flow
RWL	Resting Water Level
SANS	South African National Standard
SE	South-East
SL	Sutherland
SOP	Standard operating procedure
SW	South-West
TDS	Total Dissolved Solids
TMG	Table Mountain Group
UFS	University of the Free State
UKEA	United Kingdom Environment Agency
UN	United Nations
uPVC	Unplasticised Polyvinyl Chloride
VD	Vertical Dipole
WGS	World Geodetic System
WWTW	Waste-Water Treatment Works

MEASUREMENT UNITS

$\mu\text{g/l}$	micrograms per litre
C	Celcius
km	Kilometers
L/s	litres per second
m	metres
m^2/d	square meters per day
m^3/d	metres per day
mamsl	meters above mean sea level
mbgl	meters below ground level
meq/L	milliequivalents per litre
mg/L	milligrams per litre
mm	millimeters
mm/a	millimeters per annum
mS/m	milliSiemens per meter
Ωm	ohm.meter

CHAPTER 1: INTRODUCTION

1.1 GENERAL INTRODUCTION

The water resources of the largely groundwater-dependent Central Karoo region have been put under much strain as a result of continuous drought over the past seven years (DWS, 2021a). Rainfall patterns have been erratic, with the lowest recorded rainfall in decades. Hence, there has been limited recharge to the respective aquifers, resulting in declining groundwater levels and a decrease in borehole yields.

The town of Sutherland relies solely on groundwater for its water supply. It was reported by the DWS (2021a) that in the long term, continuous water level monitoring of the production boreholes has indicated a general drop in water levels and a correlating decline in yields. In addition to dropping water levels, there has been a large increase in the number of privately owned boreholes drilled within the town area. Previously, these boreholes mostly targeted shallow water strikes within the fractured aquifer. However, with the declining water levels noted above, these boreholes have become increasingly low yielding and, in some cases, even dry. The response to this has been private drilling continuing past the shallow fractures to deeper water strikes in the aquifer, likely contributing towards a general drop in water levels within production boreholes close to town.

The existing water supply boreholes are located within a 1-km radius of the town where the significant increase in groundwater use is occurring. Furthermore, historically, other than wellhead protection, the supply boreholes have been unprotected against contamination and the impact of other groundwater users. Figure 1 depicts one of the existing production boreholes and wellhead protection with a residential area in the background. In 2021, the expansion of the existing town supply with newly developed boreholes and wellfields targeted relatively undeveloped and undisturbed areas. This presented the opportunity to delineate protection zones and to develop standard operating procedures for sustainable aquifer management that will prevent the deterioration of groundwater quality and the aquifer itself through contamination and over-abstraction.



Figure 1: Example of a protected production borehole with enclosure and proper monitoring infrastructure

1.2 PROBLEM STATEMENT

As part of the National Water Resource Strategy (NWRS) of South Africa (DWA, 2013) groundwater is considered a significant water resource and is often the only water resource in many parts of the country. The All-Town study completed as part of the NWRS in 2013 indicated that groundwater is a very important resource for town water supply, often undervalued or underutilised (DWA, 2013). Furthermore, in most rural and low-rainfall regions, groundwater is the primary source of clean and safe drinking water. The National Groundwater Strategy (NGS) estimated that groundwater contributed to around 15% of the water supply in South Africa and groundwater use is ever-increasing (DWS, 2016).

In many cases where groundwater is utilised for town water supply, groundwater management and protection are poor with over-abstraction, dropping groundwater levels, deteriorating groundwater quality, and groundwater contamination. This is not necessarily the shortage of skilled management or staff, but rather the absence of a good understanding of what is being managed and a standard operating procedure. This emphasises the importance of developing and implementing a groundwater management strategy that includes a groundwater protection protocol and standard operating procedures, taking into account site-specific requirements. Such a groundwater management strategy will ensure long-term sustainable groundwater management.

Water resource protection policies and programmes have been endorsed and adapted in South Africa (DWS, 2016). However, these have not been implemented in the study area. Therefore, a lot still needs to be done concerning the implementation of resource protection programmes and monitoring of the crucial water supply resource for the town of Sutherland. Moreover, it is very important to understand groundwater sources and vulnerable areas, susceptible to contamination and over-abstraction considering the aquifer characteristics.

1.3 AIMS AND OBJECTIVES

The research aim is to delineate groundwater protection zones within the Sutherland area. The dissertation considers an approach involving the characterisation of the geohydrological setting which entails borehole development and borehole testing to better understand aquifer parameters and safe yields. The objectives are listed as follows:

- To gain an understanding of the geological setting of the study area.
- To conceptualise geological factors controlling the occurrence of groundwater,
- To estimate the aquifer hydraulic parameters,
- To gain a conceptual understanding of the geohydrological setting,
- To develop a conceptual model of the Sutherland area,
- To assess the methodologies that could be applied to delineate groundwater protection zones,
- To delineate groundwater protection zones, and,
- To design a groundwater management plan and develop standard operating procedures implementing protection zones for the study area.

1.4 RESEARCH METHODOLOGY

The research methodology consists of a phased approach to address the aims and objectives outlined:

- All existing reports, databases and existing groundwater information within the study area will be collated and reviewed as part of a literature study.
- A desktop-based assessment and structural mapping will be done to delineate geological structures associated with a higher potential to be associated with fractured bedrock. This will be done by incorporating information on the locations of existing boreholes.

- On-site geological mapping and geophysical surveys (electromagnetic method and electric resistivity tomography method) will be done to confirm the presence of geological structures in areas of interest.
- The presence and positions of existing boreholes will be confirmed, and major and minor geological structures will be delineated.
- Exploration boreholes will be drilled at suitable locations. During drilling, on-site monitoring of drilling proceedings will take place, and geological and geohydrological logging of the boreholes will be done. Logging will include inspection of the drill cuttings (every meter), noting the depths and yields of water-bearing zones intersected, and groundwater quality assessment using a basic field chemistry set.
- Pumping tests will be performed on boreholes to estimate hydraulic conductivity, transmissivity, storativity, and aquifer characteristics.
- The results from the pumping test will be used to determine the safe yield of individual boreholes and the capture zone as a whole. The analysis will be done using the FC (flow characteristic) method as well as the Cooper-Jacob and Barker methods of analysis.
- Groundwater sampling for chemical analysis will be done during the pumping tests. Groundwater samples will be submitted to a recognised laboratory for analysis of major ion species and minor trace elements.
- All the collected data will be analysed to develop a conceptual hydrogeological model of the study area.
- Groundwater protection zones and areas will be delineated by applying appropriate methods based on the availability of data.

1.5 STRUCTURE OF DISSERTATION

The structure of this dissertation is as follows:

- **Chapter 1** gives a general introduction to the study, summarises the aims and objectives of the research, and outlines the research methodology followed to achieve the aims and objectives. Furthermore, it outlines the structure of the dissertation.
- **Chapter 2** includes a desktop study of aquifer types, groundwater access, groundwater quality, and the protected yield of an aquifer. It also considers aquifer characteristics in the Karoo setting. Furthermore, it includes a review of existing literature on methodologies used

to delineate groundwater sources and protection zone, data requirements in a fractured bedrock setting, and recharge estimation.

- **Chapter 3** consists of a detailed description of the Sutherland study area in terms of the general setting, climate, geology, hydrogeological characteristics, and borehole network used. This information is important for understanding the need for and development of source protection zones within the study area.
- **Chapter 4** entails a detailed description of the methods and materials adopted for achieving the aims and objectives described in Chapter 1. These methods include geological mapping, ground-based geophysics, data analysis of discharge tests, chemical analysis of groundwater, conceptual modelling, safe yield estimation, and delineation of protection zones.
- **Chapter 5** describes the results obtained during the exploration phase of the project, entailing geophysics, drilling, pump testing, and analysis of borehole water chemistry. The results are summarised and incorporated into methods used for delineating groundwater protection zones.
- **Chapter 6** outlines the proposed regulations for implementing the source protection zones and the proposed groundwater management and monitoring plan.
- **Chapter 7** summarises the research and provides conclusions and recommendations on the way forward, lists shortcomings, and identifies areas requiring improvement. Furthermore, guidelines for the implementation of source protection zones are proposed.

CHAPTER 2: LITERATURE REVIEW

In this chapter, a review of the literature relevant to the delineation of groundwater protection zones is given. First, the need for groundwater protection zones is discussed. Thereafter, different concepts relevant to the determination of protection zones around groundwater abstraction points are described. These include the hydrological cycle, aquifer types, how groundwater is typically accessed from the surface, groundwater-surface water interaction, aquifer vulnerability, and factors that may affect groundwater quality. It is then explained how groundwater protection zones are defined and which factors need to be considered when delineating these zones. These factors include groundwater recharge, knowledge of the presence of geological structures that may affect the groundwater environment, and aquifer hydraulic parameters. For this reason, descriptions of recharge estimation methods, ground geophysical techniques and hydraulic tests are given. Then the geohydrological conditions that can be expected in Karoo settings are described. Finally, two South African case studies of the determination of protection zones are provided as examples.

2.1 NEED FOR GROUNDWATER PROTECTION ZONES

The occurrence, role, and importance of groundwater are often misunderstood. Recognition of the contribution of groundwater to the water supply is ever-increasing, especially for town water supply in low rainfall regions. This recognition is driven by inconsistent rainfall patterns, climate change, and an increase in water demand. In 2016, groundwater constituted 15% of the water supply in South Africa and this dependence is ever-increasing (DWS, 2016).

Groundwater protection is a largely unknown topic in the South African context, as groundwater management often only occurs through monitoring of a single borehole or on a well-field scale and does not necessarily consider the geohydrological capture zone. This is considered a one-dimensional approach and groundwater management should rather focus on the protection of the groundwater resource, i.e., an aquifer, or even the whole catchment area (Nel *et al.*, 2014).

Groundwater protection aims to ensure that the resource under consideration is used sustainably, and this is achieved through planning and risk-based mitigation measures (Nel *et al.*, 2014). The protection of the groundwater resource in different settings is usually formulated in a hierarchical manner which can include portions of or whole capture zones, the aquifers within the geological setting, recharge areas, and wellhead (borehole) protection areas (Stauffer *et al.*, 2005).

2.2 THE HYDROLOGICAL CYCLE

To understand the occurrence of groundwater, it is important to conceptualise its role and position within the hydrological cycle on a wide range of scales. The hydrological cycle can be described as the process of how water is cycled through the earth's atmosphere, surface, and oceans (Winter *et al.*, 1998). All water on earth at some point in time occurs as precipitation. Most of this precipitation then flows down-gradient in small streams and rivers to eventually fill dams or reach the sea. Some end up back in the atmosphere through mechanisms such as evaporation, while importantly, some infiltrates into the soil and rocks below the surface. The water that infiltrates below the surface accumulates in the pore space within the subsurface, becoming groundwater (DWA, 2011). When groundwater is present in meaningful quantities in permeable rock units, these units are referred to as aquifers.

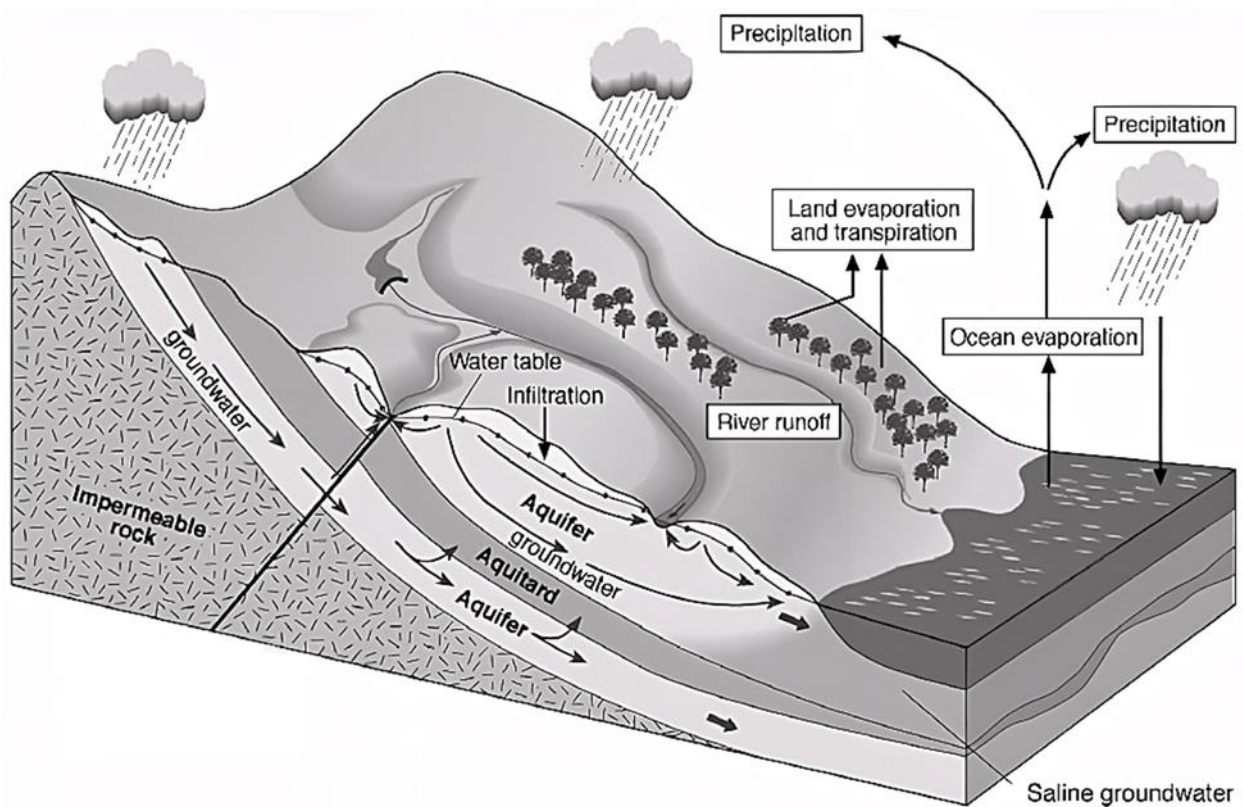


Figure 2: Diagram of the hydrological cycle and groundwater recharge (Chilton & Seiler, 2006)

2.3 AQUIFER TYPES

An aquifer represents a system from which groundwater abstraction can occur at economically viable volumes. There are three main types of aquifers, namely: primary aquifers, secondary aquifers, and karst aquifers.

2.3.1 Primary intergranular aquifer

In primary intergranular aquifers, groundwater flows in pore spaces between sedimentary material (i.e., in loose sands, gravel, etc.). The typical yield in a primary aquifer depends on particle size and sorting. Higher porosities are associated with well-sorted and coarse-grained deposits. Intergranular aquifers are not limited to shallow unconfined conditions – numerous known aquifers are associated with deep coarse-grained alluvial deposits overlain by confining clay-rich material (Van der Gun, 2002). Furthermore, gravel layers may form within residual bedrock as a result of the weathering of certain rock types (e.g., a gravel layer on top of granite intrusion below parent sedimentary bedrock).

2.3.2 Secondary fractured aquifer

Secondary fractured aquifers are located within a hard rock setting where groundwater flow occurs through cracks, fissures, fractures, joints, and faults within the bedrock (DWA, 2011). The aquifer type is associated with little to no decomposition and therefore has limited storage capability compared to other aquifer types (Nel, 2011). Single fractures or fractured zones may act as conduits for groundwater flow. However, such fractures often have a limited areal extent which is considered a major controlling factor for the typical yield of boreholes intersecting the fracture. Furthermore, the fractured density controls the connectivity within a fractured rock aquifer, and therefore also the yield and potential storage.

2.3.3 Karst fractured aquifer

Karstic aquifers are associated with a fractured rock setting and are characterised by groundwater movement through fractures and dissolution vugs or cavities (Freeze and Cherry, 1979). The formation of large open fractures and dissolution cavities is as result of the chemically soluble host rock, predominantly carbonate rock, i.e., limestone and dolomite. These systems are complex and heterogenous, and are often associated with high permeabilities of the aquifer matrix and conduits (Nel, 2011). The management of karst aquifers is challenging under both natural and anthropogenic conditions. Due to the chemical characteristics of dolomitic rocks, dissolution cavities may form when these rocks are exposed to acidic conditions, which can greatly affect the physical properties of the rocks. Sources of acidic water may include dissolved organic matter and contaminants resulting from fertilizer application, septic tanks, or acid-mine drainage (Freeze and Cherry, 1979).

2.3.4 Confined and unconfined aquifers

Aquifers can be classified as confined, unconfined and some cases semi-confined based on its groundwater flow and storage characteristics. Unconfined aquifers are typically found near the ground surface, where the water table is exposed to the atmosphere through the openings and void spaces (most common in intergranular aquifers), with the pressure in the aquifer in equilibrium with that of the atmosphere (DWA, 2011). A confined aquifer is where groundwater is isolated from the atmosphere, located between two confining (impermeable) geological units. The pressure in a confined aquifer is greater than that of the atmosphere and the water table will rise within the aquifer even where groundwater physically occurs in fractured zones in bedrock or in porous zones underlying a confining clay layer (Freeze and Cherry, 1979). In some confined aquifers, depending on the pressure within the aquifer, the water level will rise above the land surface resulting in an artesian flow. Figure 3 depicts an illustration of a confined and unconfined aquifer and its associated piezometric surface and water table, respectively.

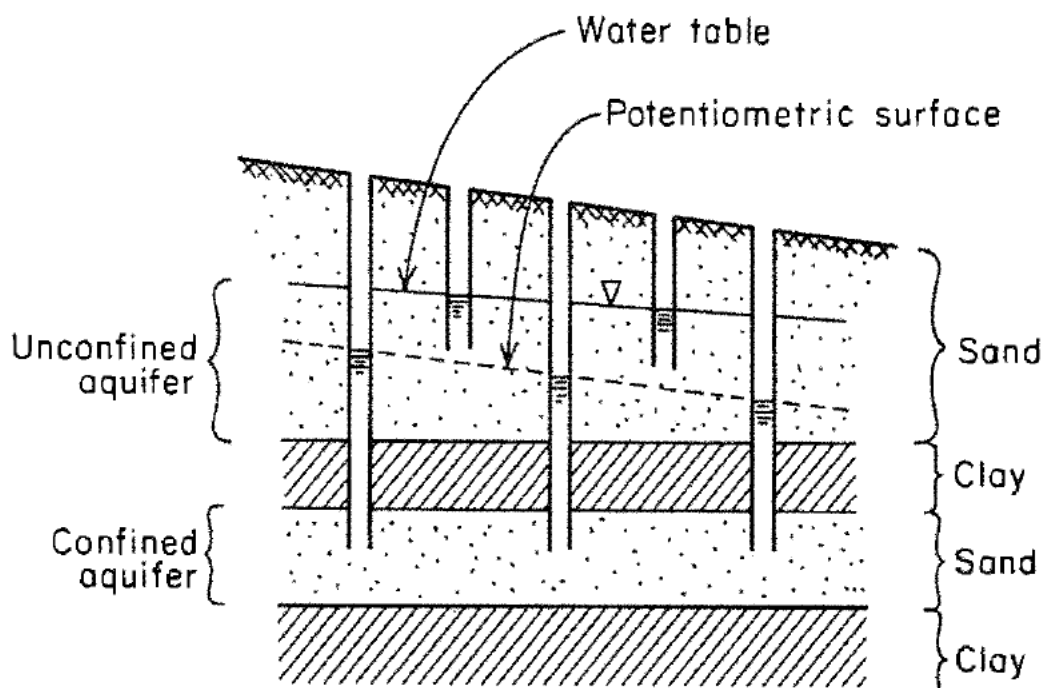


Figure 3: Illustration of a confined aquifer with its potentiometric surface and an unconfined aquifer with its water table (Freeze and Cherry, 1979)

2.4 GROUNDWATER ACCESS

Groundwater can be accessed in numerous ways, either under natural conditions (e.g., surface water, springs, and seeps), or through anthropogenic methods (e.g., boreholes or dug wells). The occurrence of springs is closely related to the physical characteristics of the geological setting, i.e., at the contact

zone between a porous medium and an impermeable formation (Freeze and Cherry, 1979). The hydraulic head within an aquifer often emulates the topographic elevation, from which it can be assumed that groundwater flows from high to low topographic elevations following the local topographic gradient. Springs appear where the hydraulic head in an aquifer exceeds the local topographic elevation, causing flow onto the surface. Historically, before the development of technology that could access groundwater through boreholes, springs were the first access points. For example, the City of Bloemfontein was founded because of a perennial spring which was essential for water supply during the 1840s (Woodford and Chevalier, 2002).

Modern-day access points to groundwater include basic wells to technologically advanced boreholes. Wells may be dug by hand or machine, with the installation of permeable casing material, which is often installed using high-end drilling techniques, followed by the installation of casing material that allows abstraction from the aquifer. The aquifer type and characteristics determine how a borehole should be constructed to allow efficient abstraction of groundwater from the aquifer.

2.5 GROUNDWATER-SURFACE WATER INTERACTION

Groundwater and surface water form part of the hydrological cycle and can be seen as a single resource (Winter *et al.*, 1998). Groundwater-surface water exchange flow is dependent on the aquifer characteristics and hydraulic head within the system. The groundwater-surface water interface occurs where the water table intersects the land surface. Environments, where this occurs, include streams, rivers, lakes, wetlands and coastal environments.

The groundwater surface water flux can be in both directions, and surface water features are classified as gaining, losing or disconnected depending on whether they receive or discharge water (Winter *et al.*, 1998). A river can be both gaining on certain reaches and losing on other reaches, depending on the river stage. The groundwater contribution to stream flow is recognised as a contribution to the baseflow of the stream. Hence, low flows of a stream during non-rainfall periods are often attributed to groundwater discharge.

2.6 AQUIFER VULNERABILITY

Aquifer vulnerability depends on its physical characteristics and to some degree the geomorphology. For example, a shallow unconfined aquifer would be more susceptible to point source contamination and drought conditions than a deeper confined aquifer, where direct flow towards the aquifer is retarded or prohibited by a confining layer (Chave *et al.*, 2006). Poorly designed boreholes can result in the mixing of the water from different intersected aquifers, depending on the hydraulic gradient

between the aquifers and the difference between the unconfined and confined systems. In such cases, contaminated water introduced into the confined system through a point source may end up in the unconfined aquifer. Similarly, saline water associated with the confined aquifer may reach the unconfined aquifer along the borehole pathway.

2.7 GROUNDWATER QUALITY AND CONTAMINATION

Under natural conditions, groundwater quality is dependent on the geology and the chemical characteristics of the natural recharge. As natural recharge is generally of good quality the groundwater quality is mostly dependant on which salts or metals can be leached from the host rock. Therefore, in settings where the host rock is competent and not easily dissolved, groundwater is often of good quality and the preferred water resource due to this characteristic (Chave *et al.*, 2006).

Over time, if the rock is leachable, the groundwater composition will slowly increase in the concentrations of leached components. This can naturally change the characteristics of the groundwater or lead to a deterioration in groundwater quality. However, the groundwater quality can also be rapidly changed through anthropogenic means. In some unique cases, this change can be an improvement, such as when enhancing recharge into the aquifer using water of higher quality (discussed further in Section 6.4). Anthropogenic changes to groundwater can also deteriorate the quality, mostly through contaminants leaking into the groundwater or over-abstraction from the aquifer causing increased salinity.

Once a contaminant is released into the natural environment and moves into the aquifer, the transport thereof could be at a similar rate to the local groundwater flow. This is called advective transport (Phillips and Castro, 2014). However, as a result of the contaminant characteristics, this is not necessarily always true. Some of the important characteristics of contaminants that influence their subsurface movement include their aqueous solubility, inorganic constituents, organic constituents, and particulate matter (Nel, 2011; Nel *et al.*, 2014; Dustay, 2020). Moreover, the transport or retardation mechanism within the aquifer also plays a role, whether through, advection, dispersion, matrix diffusion, sorption, or decay (Van Wyk, 2010).

Groundwater contamination can be triggered by naturally occurring or anthropogenic factors. Lapworth *et al.* (2022) referred to the United Nations World Development Report (UN, 2022) which asserted that global groundwater contaminants are well documented. The major challenges related to macro-chemical contamination are the build-up of soil and groundwater salinity. This may occur in ways, including through the introduction of inorganic agrochemicals from large-scale agricultural irrigation activities, seawater intrusion in fresh coastal groundwater resources as a result of

abstraction, and extensive irrigation in arid areas with small depths to the phreatic surface. Furthermore, increases in the microbial contaminant loads due to urbanisation also generally lead to additional detrimental impacts on groundwater quality.

Climate change could also potentially affect groundwater quality in several ways. Intense rainfall events due to climate change may lead to increased leaching of contaminants into the groundwater during and after these events. Climate change may also lead to rises in the sea level, which could lead to seawater intrusion into coastal aquifers due to onshore hydraulic gradients (Lapworth *et al.*, 2022).

Concerns have also been raised with regard to a list of emerging contaminants: pharmaceuticals and personal care products, veterinary products, biocides, per-, and polyfluoroalkyl (PFAS) substances, and microplastics (Lapworth *et al.*, 2022). Only a few studies of microplastics in the groundwater environment have been completed. These studies have mainly focussed on vulnerable hydrogeological settings with common contaminant sources (landfill leachates, waste water effluents, surface runoffs and anthropogenic activities) (Huang *et al.*, 2021; Lapworth *et al.*, 2022).

2.8 ESTIMATION OF AQUIFER HYDRAULIC PARAMETERS

This section describes the process through which aquifer parameters are calculated to improve the understanding of groundwater movement within the hydrostratigraphic units within the geological setting. Parameters include hydraulic conductivity, transmissivity, aquifer storativity, and specific yield. These are determined through completing pumping tests and analysing the recorded data.

2.8.1 Pumping tests

Pumping tests are in-field experiments on boreholes used to improve the understanding of groundwater flow characteristics within an aquifer. The two main objectives of pumping tests are to estimate aquifer parameters and the sustainable yields of boreholes (Van Tonder *et al.* 2001). Pumping tests are generally conducted on a single borehole, where groundwater is pumped from a borehole at a constant rate for an extended period of time with the monitoring of the discharge (pumping) rate and groundwater levels at predefined intervals. This also often involves the measurement of water levels in monitoring boreholes or piezometers at known distances from the pumped boreholes. These boreholes are then referred to as *observation* boreholes.

2.8.1.1 Pumping test data collection

A pumping test methodology is subject to the purpose of the test; however, it must comply with minimum requirements. In South Africa, this means that pumping tests must follow the methodology

specified by the South African National Standard (SANS 10299-4:2003, Part 4 – Test pumping of water boreholes). The pumping test manual developed by Van Tonder *et al* (2001) outlines a guideline on the steps for conducting an in-field pumping test. If available, borehole log information is used to plan for the testing. Such information includes the airlift yield and the positions of fractured zones that were considered water-bearing. A standard pumping test comprises different field tests, including a step test, a constant discharge test (CDT) and a recovery test (Van Tonder *et al.*, 2001).

2.8.1.1.1 Step drawdown test

A step drawdown test is conducted with the purpose of stressing the aquifer in the immediate area around the borehole. The step test is typically completed over four consecutive steps, each step having a higher abstraction rate. The minimum requirement for a step duration is one hour of continuous pumping (Van Tonder *et al.*, 2001). Should the data obtained not be sufficient from the perspective of the hydrogeologists, more steps can be completed at higher pumping rates. There are different recommendations on how to choose the step increments, but these are usually based on the maximum expected flow rate of the borehole. The WRS (2020) recommends that the flow rates for the steps should be as follows:

- Step 1: 50% of the maximum rate,
- Step 2: 75% of the maximum rate,
- Step 3: The maximum flow rate, and,
- Step 4: 125% of the maximum rate.

By comparison, the SANS 10299-4:2003, Part 4 – Test pumping of water boreholes recommends:

- Step 1: a third of the maximum rate,
- Step 2: two thirds of the maximum rate,
- Step 3: the maximum flow rate, and,
- Step 4: 150% of the maximum rate

From the step test data, the succeeding constant discharge test can be planned.

2.8.1.1.2 Constant discharge test (CDT)

The interpretation of pumping tests heavily relies on the CDT data from which aquifer parameters, the sustainable yield and operating water levels can be calculated and predicted. The duration of the CDT depends on the purpose of the test and is decided on by the hydrogeologists. Guidelines on the

durations for pumping tests CDTs have been outlined in the National Standard (SANS 10299-4:2003, Part 4 – Test pumping of water boreholes). Different guidelines are specified, depending on the intended use of the water (Table 1). Once the CDT has been completed the pump is switched off and water level recovery is monitored.

Table 1: Recommended test type and duration of test as outlined by the South African National Standard (SANS 10299-4:2003, Part 4 – Test pumping of water boreholes

Identification of use	Type of test	Duration of test
Livestock or domestic	Extended step	Total of 6 h
Hand pump	Extended step	Total of 6 h
Irrigation (low cost consequence if failure occurs)	Step CDT	4 × 1 h 24 h
Irrigation (high cost consequence if failure occurs)	Step CDT	4 × 1 h 48 h or more
Engine-driven pump for rural village water supply	Step CDT	4 × 1 h 48 h
Town water supply (low yield borehole)	Step CDT	4 × 1 h 48 h
Town water supply (high yield borehole or main borehole)	Step CDT	4 × 1 h 72 h or more
Factory (water supply not critical to production)	Step CDT	4 × 1 h 48 h
Factory (water supply critical to production)	Step CDT	4 × 1 h 100 h or more
Power station and similar water use	Step CDT	4 × 1 h 48 h to 30 d

2.8.1.1.3 Recovery test

A recovery test is the monitoring of water levels in the borehole once a drawdown test has been stopped. Recovery is the release of groundwater from storage (bedrock matrix) towards a fractured zone or borehole from which abstraction took place with a corresponding decline in the hydraulic head. Recovery is monitored until the water level has returned to 95% of the total drawdown observed during the CDT (Van Tonder *et al.*, 2001). The accuracy of the data is generally higher than for a CDT due to less anthropogenic interference (e.g., during a CDT the discharge rate is not truly constant) (Kruseman and De Ridder, 2002).

2.8.1.2 Pumping test data analysis

Several methods can be used for the analysis of pumping test data in fracture rock settings. In South African, reference is often made to the Manual on Pumping Test Analysis in Fractured-Rock Aquifers (Van Tonder *et al.*, 2001) which describes the requirements for estimating aquifer parameters and

calculating the sustainable yield. Furthermore, the flow characterisation (FC) program developed by Van Tonder *et al* (2001) is often used for estimating aquifer parameters and sustainable yields.

2.8.1.2.1 *Estimating sustainable yield from a pumping test*

The Pumping Test Manual (Van Tonder *et al.*, 2001) describes how the sustainable yield can be calculated through long-term extrapolation of the CDT data using the Cooper-Jacob (1946) approximation of Theis and the Barker (1988) method in the FC method (Murray, 2020). The sustainable yield of a borehole can be described as the pumping rate and duration that will not result in a drop in the groundwater level below a prescribed limit. The depth of the water level limit is referred to as the available drawdown and is usually taken as the depth to the main water strike from the initial (rest) water level.

Van Tonder *et al* (2001) recommended an extrapolation period of 1 to 5 years, depending on the climate of the study area, especially in areas experiencing typical semi-arid to arid conditions as in South Africa. It is important that a representative portion of the CDT data is used for the extrapolation for the chosen time period. The representative portion is defined as the data that corresponds to infinite radial acting flow (IRAF). This extrapolation can be done through curve fitting methods based on the Theis or Cooper-Jacob method, the Barker method, and the FC method. The three methods and their applications to predict long-term theoretical drawdown are described below:

- The Cooper Jacob (Theis) method can be applied in fractured aquifers where IRAF is evident. Furthermore, this method allows the estimation of transmissivities and an effective transmissivity of the fractured zone (Meier *et al.*, 1998).
- The Barker Generalised Radial Flow (GRF) model can be applied by adjusting hydraulic parameters, including the hydraulic conductivity, fracture storativity and the flow domain. The theoretical drawdown curve can be fitted to the measured drawdown data to make predictions about long-term drawdowns.
- The FC method is included in the FC spreadsheet and comprises the Basic FC, the FC Inflection Point and the FC Non-Linear approaches. Data obtained during the step test is fitted to the curve of the FC Non-Linear method. However, due to the short duration of a step test, it is usually not included if there is a big difference between the results obtained with this method and the other methods of analysis. The Basic FC and Inflection Point methods incorporate the derivatives of measured drawdown data.

Van Tonder *et al.* (1999) described the ratio between the pumping rate and drawdown in the borehole as constant. The ratio can be expressed as:

$$Q_{Sustainable} = Q_{Pump\ Test} \frac{s_{Available} (t = t_{long})}{s_{Pump\ Test} (t = t_{long})} \quad (1)$$

Thus, the extrapolation of the measured drawdown observed during the CDT of the pumping test can be used to determine the sustainable yield ($Q_{Sustainable}$) if the maximum operation time (t_{long}) where drawdown is observed during pumping does not exceed the maximum drawdown ($s_{Available}$). This extrapolation depends on the transmissivity (T) and storativity (S) calculated during the pumping test in the Cooper-Jacob method. For the FC method, this extrapolation is calculated based on the first and second derivatives measured during the CDT. This can be expressed as:

$$s_{extrapolated} = s_{test} + \left[\log \left(\frac{t_{extrapolated}}{t_{test}} \right) \right] \times s' \cdot 0.5 \times \left[\log \left(\frac{t_{extrapolated}}{t_{test}} \right) \right]^2 \times s'' \quad (2)$$

where:

$s_{extrapolated}$ is the predicted theoretical long-term drawdown,

s_{test} is the measured drawdown during the CDT,

$t_{extrapolated}$ is the extrapolation time,

t_{test} is the duration of the test,

s' is the average maximum first derivative of the drawdown data, and,

s'' is the average maximum second derivative.

This method is focussed on ensuring that water levels do not reach the predefined critical water levels within individual production boreholes. To sustainably manage groundwater abstraction from multiple production boreholes within an area, the calculated aquifer parameters are used to assess cumulative impacts from multiple abstractions.

2.8.1.2.2 Estimating aquifer parameters from pumping test data

The response of an aquifer to groundwater abstraction during a pumping test depends on the aquifer parameters' transmissivity (T) and the storage coefficient, also referred to as storativity (S). Once groundwater is abstracted from a borehole, the water level declines in the borehole itself and groundwater start to flow from the aquifer storage into the borehole. This resultant movement of groundwater forms a cone of depression in the aquifer. In a confined aquifer, the cone of depression is expressed as the potentiometric surface in the aquifer, corresponding to a relative pressure head

(WRS, 2020). Figure 4 depicts a representation of non-pumping conditions (t_0) and conditions during pumping where drawdown occurs (t_1) with high and low T - and S -values, respectively.

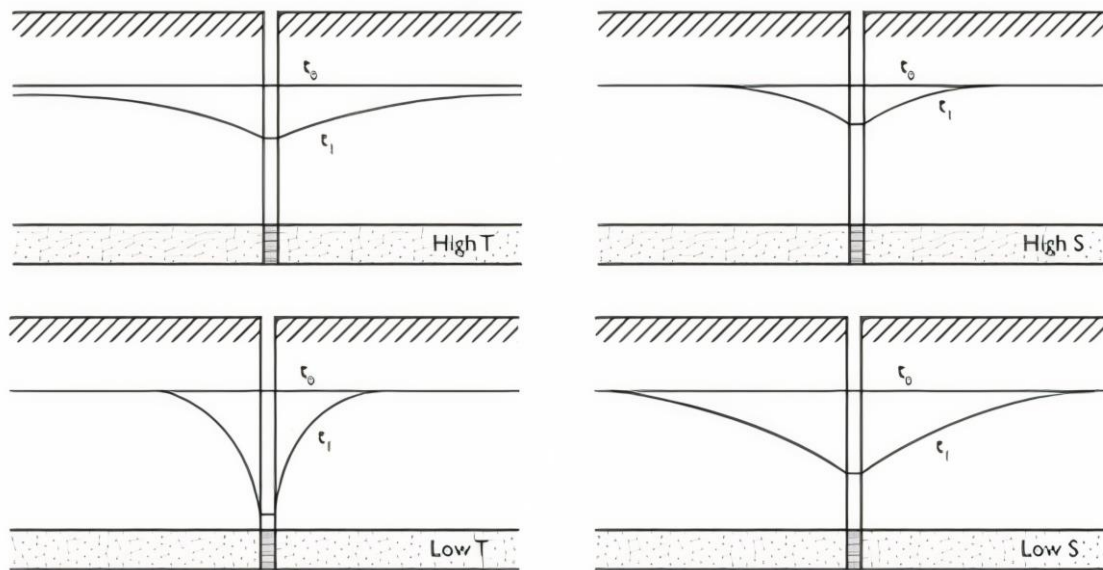


Figure 4: A comparison of cones of depression with different T - and S -values (WRS, 2020; adapted from Freeze and Cherry, 1979)

The comparison, adapted from Freeze and Cherry (1979) shows the following responses of an aquifer to drawdown under different conditions (WRS, 2020):

- High T -values are associated with a shallow cone of depression with a larger radius of influence as the aquifer quickly responds to the change in hydraulic head.
- High S -values result in a small cone of depression which does not spread over a large area as the water is readily released from storage.
- Low T -values are associated with a greater drawdown response and a smaller radius of influence. Therefore, the transmission of the change in the head is not rapid outwards from the borehole and requires a greater cone of depression to access water from the aquifer storage.
- Low S -values release less water from storage and this results in a much larger area being dewatered to compensate for the abstraction. A larger cone of depression and radius of influence therefore occurs.

The Cooper-Jacob (1946) method is an approximation of the Theis (1935) solution for confined aquifers, designed for porous media aquifers, where infinite radial acting flow (IRAF) is observed in the drawdown data during the pumping of a borehole. The Theis (1935) solution is shown in Equations (3) and (4):

$$s = \frac{Q}{4\pi T} w(u) \quad (3)$$

$$u = \frac{r^2 S}{4Tt} \quad (4)$$

where:

Q is the abstraction rate (L^3/T),

r is the distance of the observation borehole to the pumping borehole [L],

s is drawdown [L],

S is storativity [dimensionless],

t is the elapsed time since the start of abstraction [T], and,

T is transmissivity [L^2/T].

The function $w(u)$ represents the Theis borehole function for non-leaky confined aquifers [dimensionless]. Equation (5) shows the calculation of Theis function $w(u)$:

$$w(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} + \frac{u^4}{4 \cdot 4!} + \dots \quad (5)$$

The Cooper and Jacob (1946) approximation assume a suitably high value of u (discussed below), which allows the following approximation:

$$w(u) \cong -0.5772 - \ln(u) \quad (6)$$

The value of u is used to evaluate the validity of the Cooper-Jacob method. Different threshold values for u have been proposed throughout literature. Kruseman and De Ridder (2000) make use of $u \leq 0.01$, whereas Freeze and Cherry (1979) use $u \leq 0.02$, and Driscoll (1986) make use of $u \leq 0.05$. Equations (3), (4) and (6) can be combined to form a straight-line equation:

$$s = \frac{Q}{4\pi T} \left[-0.5772 - \ln \left(\frac{Sr^2}{4\pi t} \right) \right] \quad (7)$$

The conventional Cooper-Jacob equation is found by converting \ln to \log :

$$s = \frac{2.303Q}{4\pi T} \log \left(\frac{2.25Tt}{Sr^2} \right) \quad (8)$$

Drawdown (s) can then be plotted as a function of logarithmic time on a semi-log plot where a straight line drawn through the data plot represents infinite acting radial flow. The transmissivity is calculated from:

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (9)$$

where Δs is the gradient of the fitted line for the change in drawdown over one full log cycle (i.e., 10–100 minutes or 100–1000 minutes).

The recovery data can also be used to calculate aquifer parameters by applying the Theis equation. The transmissivity can be calculated by plotting the recovery drawdown data against the logarithm of the elapsed time since pumping ceased (t'), and finding the “best fit” straight line through the data. The Theis equation used in the recovery method is:

$$s' = \frac{2.303Q}{4\pi T} \left[\log\left(\frac{t}{t'}\right) - \log\left(\frac{S}{S'}\right) \right] \quad (10)$$

where:

s' is the remaining drawdown during recovery [L],

t' is elapsed time since abstraction ceased [T], and,

S' is storativity during recovery [dimensionless].

The transmissivity is then approximated with Equation (11), using the same approach to get from Theis to a Cooper-Jacob approximation:

$$T = \frac{2.3Q}{4\pi\Delta s'} \quad (11)$$

2.8.1.3 Aquifer characteristics derived from pumping tests

Groundwater flow regimes are considered a specific form of the transient drawdown response in an aquifer due to pumping. Numerous methods have been developed in hydrogeology for a more realistic analysis of heterogeneous aquifers which do not perfectly conform to Theissian flow systems (Ferroud *et al.*, 2019). In Theissian flow systems, the groundwater flow and storage properties of an area can be described by transmissivity, storativity, and recharge. Pumping tests can be used to analyse transmissivity (the ease of groundwater flow) and storativity (dimensionless ratio). However, these are often heterogenous and different equations can describe different flow regimes at set times

or distances from a pumping borehole. Analysing the first derivative is commonly used to determine aquifer characteristics or geometry in an area. A summary of the derivate plots on a log-log scale is shown in Figure 5 which illustrates some of these common flow characteristics.

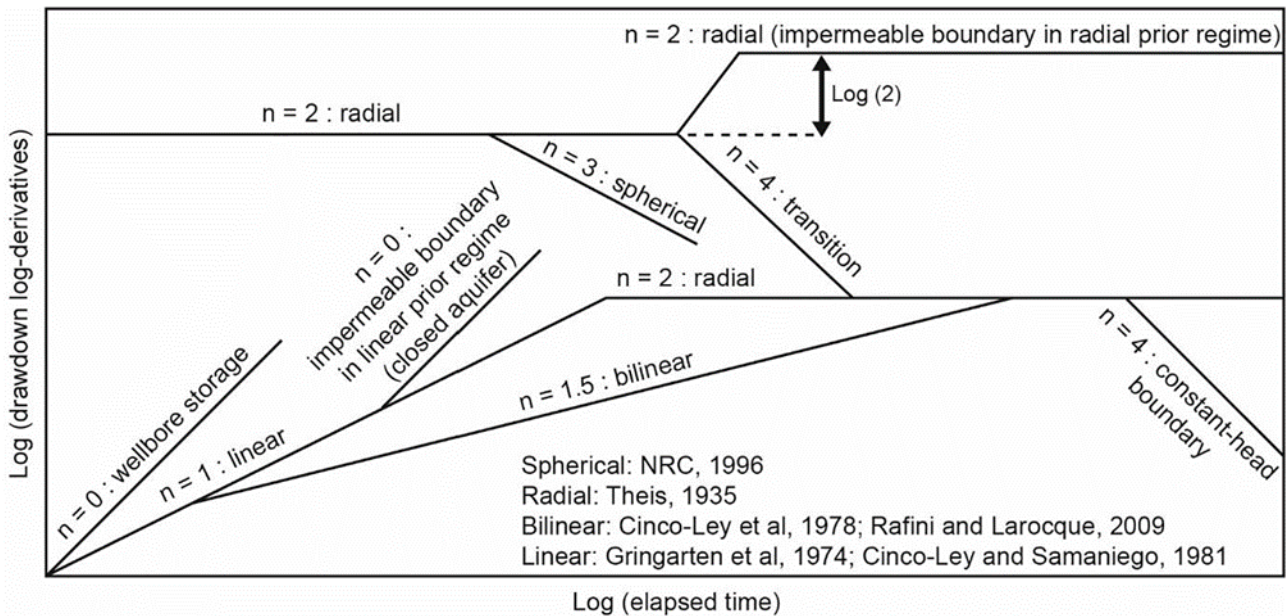


Figure 5: Summary of published theoretical flow regimes and their associated flow dimensions, modified from Ehlig-Economides *et al.* (1994) (Ferroud *et al.*, 2019)

2.8.1.3.1 Linear flow ($n=1$)

Linear flow implies that groundwater flow remains constant in a fractured zone with changing pressure. Pressure gradients develop in the aquifer matrix in the proximity of the fracture which generates one-directional flow to the fracture (Ferroud *et al.*, 2019). The typical occurrence of linear flow is observed in vertical or subvertical features like faults or matrix-related flow within a fracture (Figure 6).

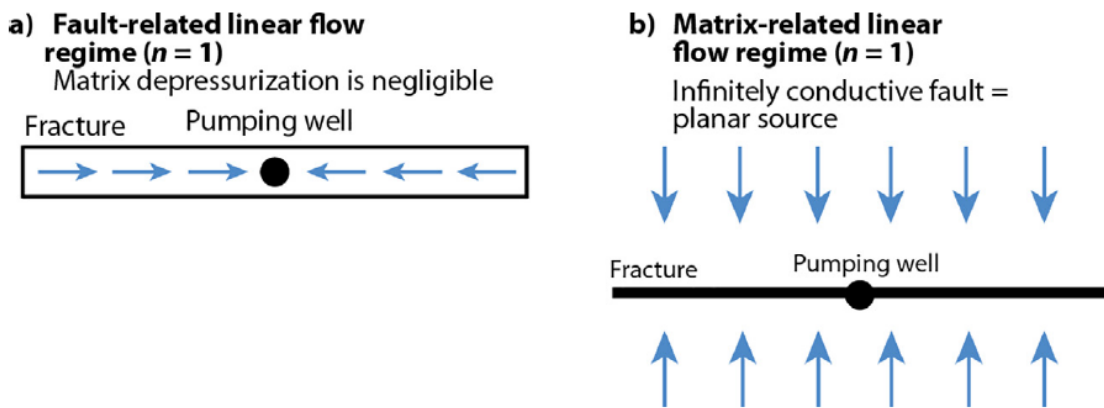


Figure 6: Conceptual ($n=1$) models of linear flow in; a) a finite-conductivity fracture or fault and b) an infinite conductivity fracture

2.8.1.3.2 Radial flow ($n=2$)

Radial flow, often referred to as infinite radial acting flow (IRAF) or pseudo-radial flow, occurs where the cone of depression resulting from abstraction from a borehole is approximately circular. It often occurs in formations that are homogeneous or in fractured aquifers that can be considered as a continuum. Radial flow is typically observed during a very late time of pumping when the cone of depression is so large that fractures and faults in the bedrock aquifer are small in comparison the volume of the depressurised aquifer (Van Tonder *et al.*, 2002; Murray *et al.*, 2012; Ferroud, *et al.* 2019).

The applicability of the Cooper-Jacob solution (which assumes IRAF) in a heterogenous aquifer has been validated through numerical modelling by Meier *et al.* (1998) and Sánchez-Vila *et al.* (1999). These models showed that a radial flow regime can be produced with diffuse transmissivity fields and concentric storage conditions (Ferroud *et al.*, 2019). Reference is made by Ferroud *et al.* (2019) to a flow dimension database (Ferroud *et al.*, 2018) where late-time radial flow regimes were evident in carbonate rocks, indicating that the bedrock matrix was well-connected through bedding plane fractures and contributed towards flow in the aquifer.

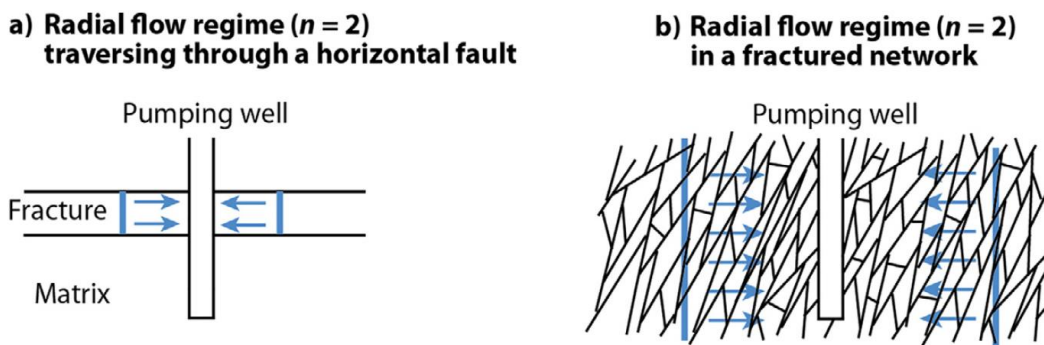


Figure 7: Conceptual flow model in a fractured rock setting with a radial flow regime ($n=2$) (Ferroud *et al.*, 2019)

2.8.1.3.3 Bi-linear flow regime ($n=1.5$)

Ferroud *et al.* (2019) defined the bi-linear flow regime as a condition where flow occurs in an area of the matrix with high enough permeability which results in two simultaneous one-dimensional sets of flow. This happens when linear flow occurs in the fracture, while simultaneous flow in the aquifer matrix is perpendicular to that of the fracture. A simplified conceptual model of bi-linear flow to a pumping well is shown in Figure 8.

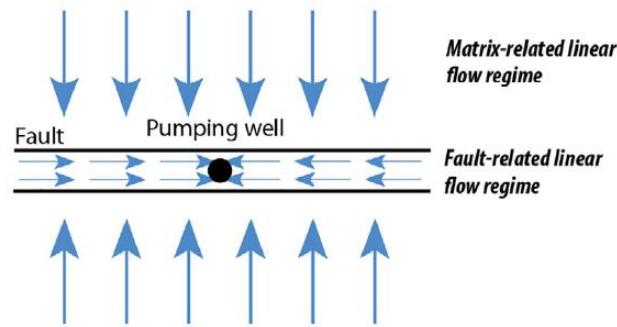


Figure 8: Bi linear flow regime (modified from Ferroud *et al.*, 2019)

2.8.1.3.4 Spherical flow regime

Conceptually, spherical flow regimes are observed mainly in cases where the abstraction is a point source in an isotropic medium and the cone of depression consists of spheres that grow outwards (Ferroud *et al.*, 2019). However, spherical flow is localised in small dimensions and over short periods of time. In most cases the spherical cone of depression will reach the bottom of the aquifer and become radial outwards, conforming to a radial flow regime.

2.8.2 Slug test (falling or rising head test)

During a slug test (rising or falling head test), hydraulic parameters are estimated locally around a test site or borehole through injecting or withdrawing a known volume of water into a borehole (Kruseman and De Ridder, 2002). The change in the volume of water causes a sudden displacement in the hydraulic head within the borehole, after which the head in the borehole will gradually return to the initial head measured. The subsequent falling or rising water level is then measured over time in either the control or observation borehole.

The limitation of this methodology is that the results are not representative of the larger aquifer, only local conditions. These conditions could include aquifer heterogeneity, drilling-related damaged zone, well efficiency, or something similar. Depending on the aquifer characteristics, different methods can be applied to estimate the hydraulic parameters, each with its own set of assumptions. The Bouwer and Rice (1976) method is applied for unconfined aquifers, steady-state conditions, and with an apparently infinite areal extent. The method can be applied to both partially or fully penetrating boreholes. The method of Cooper *et al.* (1967) uses curve fitting to estimate the hydraulic parameters for boreholes that fully penetrate confined aquifers of infinite areal extent. The Barker and Black (1983) method is a mathematical solution that can be applied in a confined aquifer, where the well is fully penetrating. This method is useful for double-porosity fractured aquifers.

2.9 DELINEATION OF GROUNDWATER PROTECTION ZONES

Groundwater protection zones are areas where the groundwater supply could potentially be negatively impacted by anthropogenic factors, resulting in deteriorating groundwater quality and the general status of the aquifer (Nel, 2011). The delineation of protection zones is a preventative measure to protect critical groundwater resources. Delineation of protection zones is typically not limited to a single borehole but considers all components of the hydrological cycle that contribute to aquifer recharge. Estimating the recharge areas of abstraction points will not be sufficient to protect the aquifer of interest.

The development of protection zones must be appropriate to the sensitivity of the site. Where the development or activity is serious or irreversible, one should adopt a precautionary principle to manage and protect groundwater, while in areas less susceptible to aquifer deterioration, a risk-based approach can be adopted (UKEA, 2017). Several steps should be considered during the development of groundwater protection zones (Chave *et al.*, 2006; Nel *et al.*, 2014; UKEA, 2019):

- involving stakeholders,
- confirming whether there is a need for a protection zone using a precautionary or risk-based approach for potential hazards,
- defining aquifer characteristics,
- delineating protection zones,
- collating groundwater data and establishing a groundwater database,
- developing a conceptual model, and,
- monitoring the status of groundwater protection zones.

Groundwater protection zones have been developed by applying a variety of concepts and principles, but with the main aim of controlling polluting activities around abstraction points to reduce the potential for contamination of the abstracted groundwater (Chave *et al.*, 2006). Many of these approaches take into consideration the travel time of potential contaminants from their sources to the abstraction points. Different hierarchies for groundwater protection zones have been proposed and implemented (Robinson, 2002; Nel, 2011; Nel *et al.*, 2014; UKEA, 2019) (Figure 9):

- The *wellhead operational zone* is the proximal area to the point of access to the underlying aquifer, either a spring, boreholes, or a wellfield. No land use other than that relating to the

production borehole is permitted. Throughout literature it is indicated that the wellhead protection zone must consider a travel-time of one day or a minimum fixed radius of 10 m.

- An *inner protection zone* is designed to protect the source against nitrate and microbial contaminants (Robinson, 2002). Land restrictions include pit latrines, road infrastructure, inorganic farming activities, etc. Robinson (2002) gave a summary of techniques for the delineation of protection zones and indicated that the minimum requirement may be based on a fixed radius from the abstraction borehole, predefined travel-times, residence times, radii based on fracture characteristics, as well as predicted drawdown responses due to abstraction.
- An *outer protection zone*, is defined based on the minimum time required for dilution and effective attenuation of slowly degrading substances to an acceptable level. A minimum radius of 250 m–500 m has been proposed by the UKEA (2019), depending on the magnitude of the abstraction. Various restrictions can be imposed on land use within this zone.
- The *source catchment protection zone* or the *total capture zone*, is the area around an abstraction point within which all groundwater is presumed to end up at the abstraction point (UKEA, 2019). This zone is designed to mitigate the long-term deterioration of the aquifer.

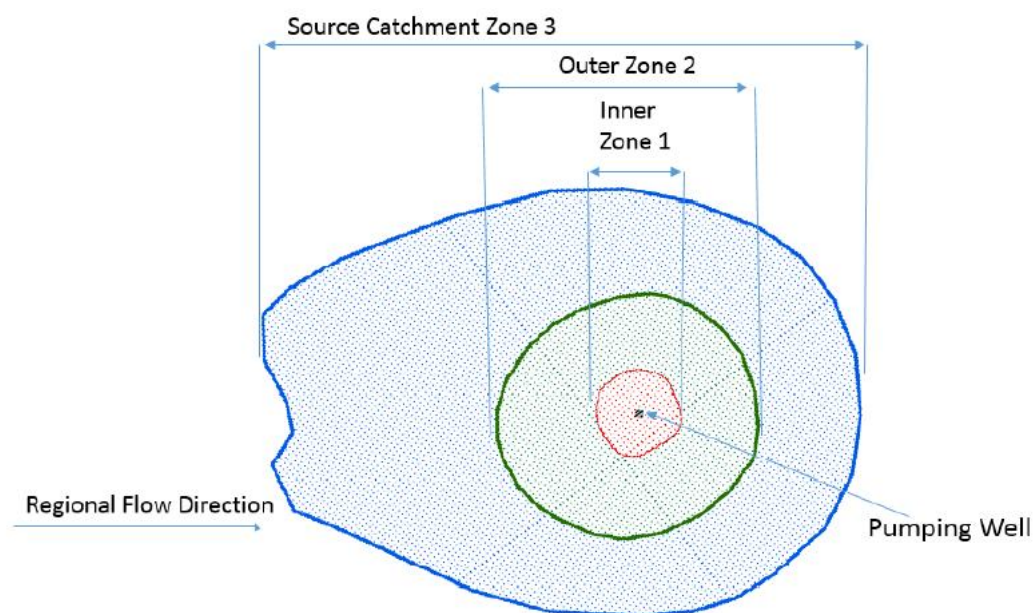


Figure 9: Schematic representation of the wellhead (pumping well), inner zone, outer zone, and the source catchment zone considering the regional groundwater flow direction (UKEA, 2019)

Approaches for the delineation of protection zones vary from simple to very complex methods, depending on the sensitivity of the aquifer and ultimately data availability. This includes basic methods based on fixed radii to high-end modelling approaches, based on criteria as listed by Chave *et al.* (2006), namely: distance between potential point source pollution and abstraction point; the

drawdown of the water table and associated cone of depression within an unconfined aquifer; travel time before the juncture where a contaminant reaches the aquifer; assimilative capacity and boundary conditions; whether recharge boundaries, no-flow boundaries or other groundwater controlling features occur in the vicinity of the abstraction point.

There are numerous methods for assessing and delineating groundwater protection zones. Most can, however, be reduced to the following (Robinson, 2002; Nel, 2011; Nel *et al.*, 2014; UKEA, 2019):

- **Hydrogeological mapping:** entails a conceptual understanding of the study area involving the identification of recharge zones and the source extent through conceptualising the topography, geology, geohydrology, and geochemical characteristics of the aquifer.
- **Arbitrary fixed radius:** comprises a circle or a fixed radius drawn around the abstraction point. However, low cost and minimal expertise are required for this method, and it has a low degree of certainty and is not considered to be a scientific approach. These protection zones have been shown to be unrealistic, radial and uniform and not suited to a heterogenous aquifer.
- **Calculated fixed radius:** draws a circle of specified travel time using a simple equation based on the volume of water drawn towards the well in a specified time. The method requires data but can be completed quickly.
- **Vulnerability mapping:** takes into account numerous site-specific factors to identify areas particularly vulnerable to groundwater contamination. This method is often used in combination with other methods and as input to other methods to delineate wellhead protection plans (Robinson, 2002).
- **Simplified variable shapes:** protection zones are delineated by shapes which depend on the groundwater flow patterns in the vicinity of the abstraction borehole.
- **Analytical models:** consider the travel time calculations and drawdown calculations to delineate distances for protection zones. These methods incorporate aquifer flow fundamentals such as Darcy's law, the principle of mass conservation and aquifer geometry, boundary conditions, recharge, pumping rates, abstraction location, as well as historical conditions. Many analytical models are available that describe solutions to the groundwater flow equations derived for specific hydrogeological settings and associated aquifer conditions. Analytical models convert complex aquifer settings into more ideal geometric shapes. This method is satisfactory for less complex settings.
- **Numerical modelling; flow and transport models:** involve devising, calibrating, and applying numerical models that simulate groundwater flow and contaminant transport

processes in the subsurface. These methods can be broadly grouped into simple and complex models.

For any study to determine groundwater protection zones, the method used will depend on the complexity of the aquifer and the availability of data, the accuracy of results required, and the capabilities of the management team. The US EPA (1991) documented various criteria which may be used in the process of delineating protection zones in a fractured aquifer setting (Robinson, 2002). These include:

- Distance from the abstraction point,
- Drawdown due to groundwater abstraction,
- Travel-time to the abstraction point,
- Flow system boundaries, and,
- The storage capacity of the aquifer.

Table 2 provides a summary of the methods outlined above and lists the advantages, disadvantages, and data requirements for each method.

Table 2: Summary of protection zone methodologies, advantages, disadvantages, and data requirements

Method	Advantages	Disadvantages	Data requirement	References
Hydrogeological mapping	Low cost	Quantitative	Base map (google earth)	UKEA (2019)
	Easy to implement	Less suitable for deep confined aquifers	Criteria for generalisation	Nel (2011)
	Minimal technical experience required	Requires experience input in terms of geological mapping and hydrogeological interpretation	Geology maps	Nel <i>et al.</i> (2014)
	Well suited for unconfined and homegenous aquifers. Also, in fractured aquifers and karst aquifers	Moderate to high manpower and data-collection costs	Aquifer characteristics (thickness etc)	
	Required for defining aquifer boundary conditions		Soil characteristics	
Arbitrary fixed radius	Low cost, easy and quick to implement	Low vulnerability aquifers over-protected and high vulnerability aquifers under-protected	Geology and aquifer type	Chave <i>et al.</i> (2006)
	Highlights lack of data	Too simple; potentially low hydrogeological precision	Soil type	Nel (2011)
	Requires minimal technical skills	Large degree of uncertainty. Hence compensation with larger threshold radius	Land use	
Vulnerability Mapping	Does not require aquifer parameters or assumptions	No direct protection zone defined	Depth to groundwater	UKEA (2019)
	Do not require numerous data sources	Results subjective to a degree	Recharge estimation	Nel <i>et al.</i> (2014)
	Can be used in combination with other methods (i.e. variable shapes)	Do not consider hydrogeological conditions of the aquifer	Aquifer media	Robinson (2002)
		Low confidence in the degree of protection	Soil type, topography	
		Impact of the vadose zone		

Table 2 (continued): Summary of protection zone methodologies, advantages, disadvantages, and data requirements

Method	Advantages	Disadvantages	Data requirement	References
Calculated fixed radius	Simplistic	Too simplistic, does not represent detailed local hydrogeological conditions	Peak daily discharge	UKEA (2019)
	Low cost		24 hour pumping data	Nel <i>et al.</i> (2014)
	Based on simple hydrogeological principles	Results in a larger wellhead area	Aquifer characteristics & parameters	Nel (2011)
	Greater accuracy than the arbitrary method	Tends to overprotect downgradient and underprotect upgradient because does not account for ZOC	Land use	
	Less susceptible to legal challenge		Specific borehole information	
	Protects area directly around well/borehole	Does not account for natural groundwater flow conditions, hence unconfined systems		
	Good application for confined systems	Protection zone may include areas outside of area supplying water to an abstraction point Reduced confidence in degree of protection		
Simplified variable shapes	Easy and quick to implement	Local conditions may differ significantly from those used in the initial delineation		UKEA (2019)
	Can represent a very simple system			Nel <i>et al.</i> (2014)
	Semi-quantitative	Data requirement not available		

Table 2 (continued): Summary of protection zone methodologies, advantages, disadvantages, and data requirements

Method	Advantages	Disadvantages	Data requirement	References
Analytical models	Rapid and accurate for flow equations in simple settings	Modest data requirements	Aquifer thickness	Nel (2011)
	Capture zones based on idealized representation of local aquifer conditions	Assumes infinite aquifer	Hydraulic conductivity	Robinson (2002)
	Can represent a simple system	Does not allow complex boundary and recharge effects to be considered	Porosity	
	Simple and uniform boundaries and recharge allowed for	Limited to two-dimensional problems	Borehole abstraction rate	
	Capable of calculating effect of multiple boreholes			
	Can test different scenarios			
	Ability to estimate groundwater flow paths and time of travel more accurately than previous methods			
	Input parameters can be used for a site specific assessment			
Numerical modelling; flow and transport models	Quantitative	Data requirements can be large	Water levels	UKEA (2019)
	Capture zones based on idealized representation of local aquifer conditions	Darcian flow assumed	Conceptual model	Nel <i>et al.</i> (2014)
	Allows for complex boundaries and recharge effects	Assumes infinite aquifer	Borehole construction	Robinson (2002)
	Can test different scenarios	Requires expensive software	Pumping rates	Nel (2011)
	Potentially high level accuracy	Expensive	River conductance	
		Requires high degree of hydrogeological modelling expertise	Recharge	
		Less suitable than analytical methods for assessing drawdowns close to pumping wells	Evapotranspiration	
		Extensive specific aquifer data required	Chemistry data	
		Land use		
		Potential contaminant sources		
		Topography data		

2.10 THE PROTECTED YIELD OF AN AQUIFER

As outlined in the groundwater dictionary (DWA, 2011), the safe yield of an aquifer is considered the rate of withdrawal at which aquifer deterioration will not occur. This concept focuses on adopting a safe abstraction regime that will not result in a decline in the hydraulic head within the aquifer. Such a decline could result in detrimental or irreversible impacts, including physical damage to the aquifer system and groundwater quality deterioration. In literature, discrepancies between calculated safe yields and the associated time frames have been a topic of debate. However, the safe yield is still a valid concept if a good conceptual understanding exists of the aquifer in question (DWA, 2011; Murray *et al.*, 2012).

In countries like the United Kingdom, the safe yield is often referred to as the protected yield. The UKEA has adopted an approach in which the protected yield is used in the early stages of delineating protection zones (UKEA, 2019). It is stipulated that the protected yield is equal to the volume specified by the water use license; however, this volume can be reduced if the aquifer cannot sustainably meet the demand (UKEA, 2019). In such cases, pumping test results (or other sources of reliable information) are used to assess the true value of the protected yield. This assessment of the protected yield is not limited to calculations based on the efficiency of a single borehole or wellfield but is rather based on the hydraulic capacity of the aquifer.

2.10.1 Estimating a safe yield for the total capture zone

A single cell box model approach was developed by Murray *et al.* (2012) that allows for the estimation of obtainable groundwater volumes within a source capture zone, whether abstracted from a single or multiple boreholes. The often-utilised aquifer firm yield model (AFYM) in a South African context is based on the evaluation of groundwater and surface water on a broader basis, the threshold of groundwater recharge, and the potential resultant change in the natural environment that might occur through abstraction (Murray *et al.*, 2012). The model considers critical management water levels, below which aquifer storage levels cannot be drawn down, to provide estimates of aquifer firm, and assured yields. The model further takes into account the influence of groundwater abstraction, evapotranspiration, recharge, and baseflow within the modelled area. The single cell box approach is presented schematically in Figure 10.

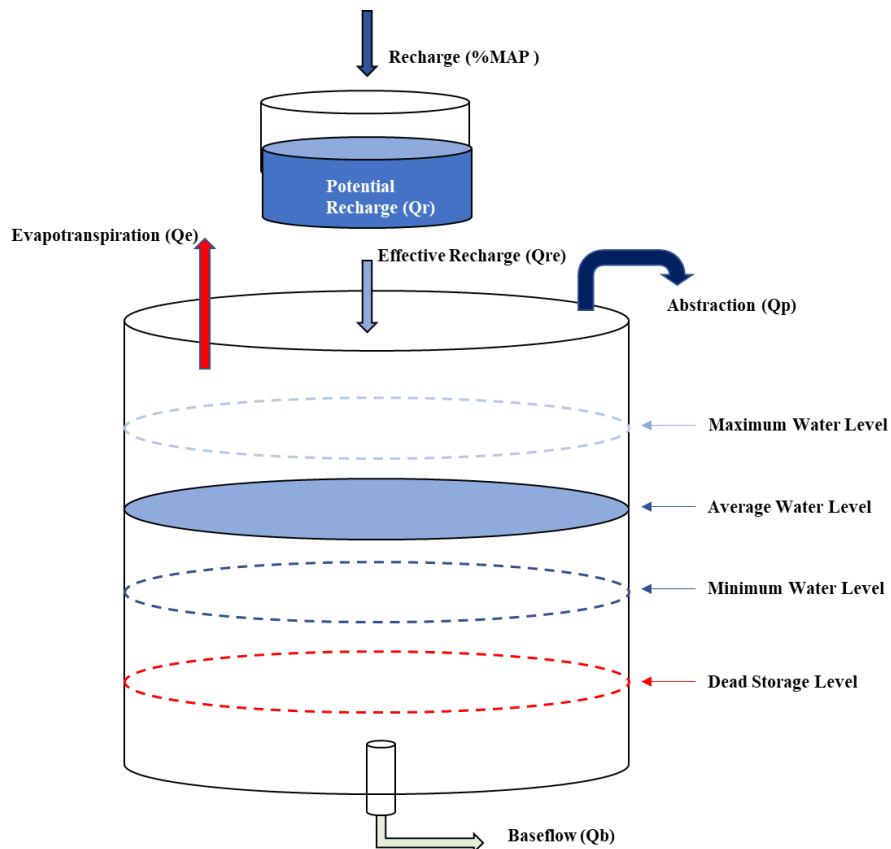


Figure 10: Aquifer firm yield lumped box model (modified from Murray *et al.*, 2012)

The model comes with a set of default parameters valid for the different quaternary catchments within the Karoo. These default parameters include data from the following sources (Murray *et al.*, 2012):

- Rainfall data from Middleton and Bailey (2008) and Schulze (2009),
- Specific yield data from the GRAII (DWAF, 2005),
- Baseflow data from the GRAII (DWAF, 2005), and,
- Data generated by Murray *et al.* (2012), including the recharge threshold and riparian zone data (% of the catchment area).

The critical water levels (Figure 10) obtained from the GRAII (DWAF, 2005) or that can be user defined, include the:

- Average water level, representing the hydraulic head within the aquifer,
- The maximum water level, which is the highest potential water level (shallowest depth to the water level) within the aquifer,
- The minimum water level, or the critical operational water level, is the lowest level at which the aquifer will still be operational and be able to yield water without failure, and,

- The dead storage level, where the aquifers storage has been depleted and no further abstraction can take place.

2.11 RECHARGE ESTIMATION

Groundwater recharge is the addition of water to the groundwater system and occurs through mechanisms such as the downward flow of water through the vadose zone to reach the water table. Another component of groundwater recharge to an aquifer is *interflow*, which is the lateral migration of water between aquifers, while the interchange between surface water sources is referred to as *groundwater-surface water interaction*.

Recharge is very important in the field of geohydrology and recharge estimation entails a lot more than estimating the average percentage of precipitation entering the aquifer (Holland, 2011). There is no linear correlation between rainfall and recharge, and the latter may be episodic and occur along preferred pathways (Holland, 2011). There is usually a high degree of uncertainty in the estimation of recharge, especially in heterogenous, complex fractured aquifers (Chilton and Foster, 1995). Several conventional methods applicable to the semi-arid South African conditions can be used to estimate recharge, including the chloride mass balance (CMB), cumulative rainfall departure (CRD), lumped parameter (EARTH), groundwater modelling (GM), saturated volume fluctuation (SVF) and water level fluctuation (WTF) methods (Xu and Beekman 2003). Three of the most widely applied methods mentioned by Xu and Beekman (2003) are briefly described below.

2.11.1 The chloride mass balance (CMB) method

Holland (2011) asserts that the chloride mass balance (CMB) method is considered one of the most reliable methods for estimating recharge (Cook, 2003). However, Banks *et al.* (2009) stated that the estimate should be considered as a minimum rate due to the addition of chloride to an aquifer through other sources, e.g., bedrock weathering. Therefore, for more accurate recharge estimations, the method should be used in conjunction with other methods and should include water level and rainfall monitoring.

The CMB method considers a comparison between the fluctuation in moisture and recharge, which provides insight into the recharge (Cook, 2003):

$$R_d = \frac{P \times Cl_p + D}{Cl_{gw}} \quad (12)$$

where:

R_d is the direct recharge,

P is the precipitation (mm/a),

Cl_p is the chloride concentration in the precipitation (mg/L)

D is the dry chloride deposition (mg/m²/a), and,

$Cl_w = Cl$ in groundwater (based on unimpacted boreholes)

2.11.2 The cumulative rainfall departure (CRD) method

The CRD method considers the water balance, where the water level response in an aquifer can be caused by rainfall (Van Tonder et al., 2001). Bredenkamp et al. (1995) argues that average annual precipitation and the associated groundwater level response can reach equilibrium even if there is a variation in the annual precipitation. With the CRD method, recharge is calculated as (Xu and Van Tonder, 2001):

$$CRD_i = \sum_{i=1}^N R_i - \left(2 - \frac{1}{R_{av}i} \sum_{i=1}^N R_i \right) iR_t \quad (13)$$

where:

R_i is the rainfall for the month i , and,

R_t is a threshold value representing aquifer boundary conditions.

R_t ranges from zero to R_{av} , with zero representative of a closed aquifer, and R_{av} representative of an open aquifer. The cumulative rainfall average would conform to an open aquifer (R_{av}) if there is no clear rainfall trend, that is when:

$$R_t = kR_{av} \quad (14)$$

where k is a constant of proportionality.

From Equation (13) it can be deduced that any change in the monthly water level is proportional to the CRD assuming that other stress factors are constant.

2.11.3 Groundwater modelling (GM)

Groundwater modelling is largely applied to simulate groundwater flow under different stress situations. The general governing groundwater flow equation assuming uniform fluid density and viscosity is (Bear, 1972):

$$\frac{\partial}{\partial x_i} \left(K_{ij} \frac{\partial h}{\partial x_{ij}} \right) + q_s = S_s \frac{\partial h}{\partial t} \quad (15)$$

where:

i, j are the principal coordinates directions,

h is the hydraulic head [L],

K is the hydraulic conductivity [L/T],

S_s is the specific storage,

x is the space coordinate [L],

t is time [T], and,

q_s represents fluid sources such as recharge and often sinks such as abstraction [L/T].

Thus, if the water balance is well understood (e.g., baseflow, interflow, surface water flow, groundwater abstraction, evapotranspiration), the hydraulic head is known, The K and S_s parameters are known, and these values can be used in a numerical model to calculate a recharge value for the model domain (Xu and Beekman 2003). The numerical modelling approach is time-consuming and sensitive to boundary conditions and requires a comprehensive dataset. Confidence in recharge calculations through the modelling approach can be improved by incorporating transport flow models (Xu and Beekman 2003).

2.12 GEOPHYSICS

The investigation and confirmation of geological structures for groundwater exploration can be done by means of invasive and non-invasive techniques. Where invasive techniques, such as drilling and excavation, are expensive, non-invasive techniques such as geophysical surveys provide rapid and cost-effective solutions for identifying and delineating geological structures, either visible or hidden by surficial cover (Knödel *et al.* 2008). Ground-based techniques such as the electromagnetic (EM) and electric resistivity tomography (ERT) methods are popular geophysical techniques for

groundwater exploration. These techniques are sensitive to conductivity or resistivity contrasts in the subsurface.

2.12.1 Electromagnetic (EM) method

The electromagnetic method is applied in numerous fields to investigate the electrical conductivity distribution of the subsurface. Originally the method was used in the mining industry for mineral exploration, targeting ore bodies associated with high electrical conductivity (Telford *et al.*, 1990).

The principle of the EM method is based on the fact that an electrical current is induced into the subsurface media through a transmitter by means of EM waves moving through the material (Fourie, 2021). The behaviour of the currents depends on the conductivities of the subsurface material in which they flow. The currents are referred to as eddy currents which generate their own magnetic fields that can be measured to obtain information pertaining to the subsurface conductivities. These magnetic fields are then measured by the receiver of the instrument.

EM survey systems operate in either the time- or frequency-domain. In the time-domain, the primary magnetic field in the transmitter is terminated rapidly, whereafter the secondary magnetic field is measured in the absence of the primary. The decay rate of the secondary magnetic field contains information on the subsurface conductivity. In contrast, frequency-domain EM methods measure the secondary magnetic field in the presence of the primary magnetic field created at the transmitter. The phase shift between the secondary and primary magnetic fields is then used to calculate the apparent subsurface conductivity.

A direct correlation exists between the porosity of the subsurface media and the salinity of groundwater. Formations with higher porosity or salinity are generally associated with higher subsurface conductivities (Telford *et al.*, 1990). The basic principles of the EM survey method are discussed in Van Zijl (1986).

2.12.2 Electrical resistivity tomography (ERT) method

The electrical resistivity method is a non-invasive geophysical tool that can provide cost-effective solutions to subsurface questions. The bulk resistivity of different materials and geological units varies mostly because of changes in water saturation or porosity and/or salinity of the pore fluid (Telford *et al.*, 1990). The geoelectrical method is used to locate lateral and vertical changes in the electrical properties of the subsurface investigated, related to the physical characteristics of the underlying formations.

The most basic electrode setup used in resistivity surveys typically employs four electrodes: two current electrodes (A and B) and two electrodes used to measure the electric potential difference (the potential electrodes, M and N). From the ratio of the measured potential difference to the injected current, and by taking the distances between the different electrodes into account, an apparent resistivity is calculated for the subsurface. Larger separations between the current electrodes (larger AB spacings) lead to deeper penetration of the electrical current into the subsurface. The depth of investigation may thus be adjusted by changing the AB spacing (Telford *et al.*, 1990).

In the past, electrical resistivity surveys were usually done in a one-dimensional mode, by investigating either the lateral or vertical changes in the subsurface resistivity. During *profiling*, the electrode geometry remains fixed, but the entire array is moved laterally between successive measurements to investigate the lateral changes in the subsurface resistivity. *Sounding*, on the other hand, investigates the vertical changes in the subsurface resistivity. The centre of the electrode array is kept in the same position (the sounding centre), while the distances between the current electrodes are increased to allow deeper measurements. The recorded apparent resistivity data are then inverted through a mathematical procedure to obtain a model of the subsurface in terms of the thicknesses and resistivities of the different geological layers (Telford *et al.*, 1990).

Electrical resistivity tomography (ERT) may be seen as a combination of profiling and sounding since both the lateral and vertical changes in the subsurface resistivity are investigated during a survey (Mukhwathi and Fourie, 2020). By using survey setups with multiple electrodes inserted along a line, ERT allows the selection of which electrodes should act as current electrodes and which as potential electrodes. This allows the subsurface to be investigated in two-dimensional (2D) sections, as explained in Figure 11.

In addition to obtaining improved spatial information, ERT surveys are also rapid and cost-effective in comparison to traditional access-hole sampling and analysis (Sentenac *et al.*, 2018). The ERT method requires soil media that has a high concentration of charged particles to facilitate electrolytic conduction. ERT performs particularly well in soil media consisting of clay or silty soils due to excellent contact between electrodes and the soil media (Zumr *et al.*, 2018). However, due to clay being a good conductor, current input may be dispersed within the clay lenses providing poor skin depth and incorrect interpretation of data.

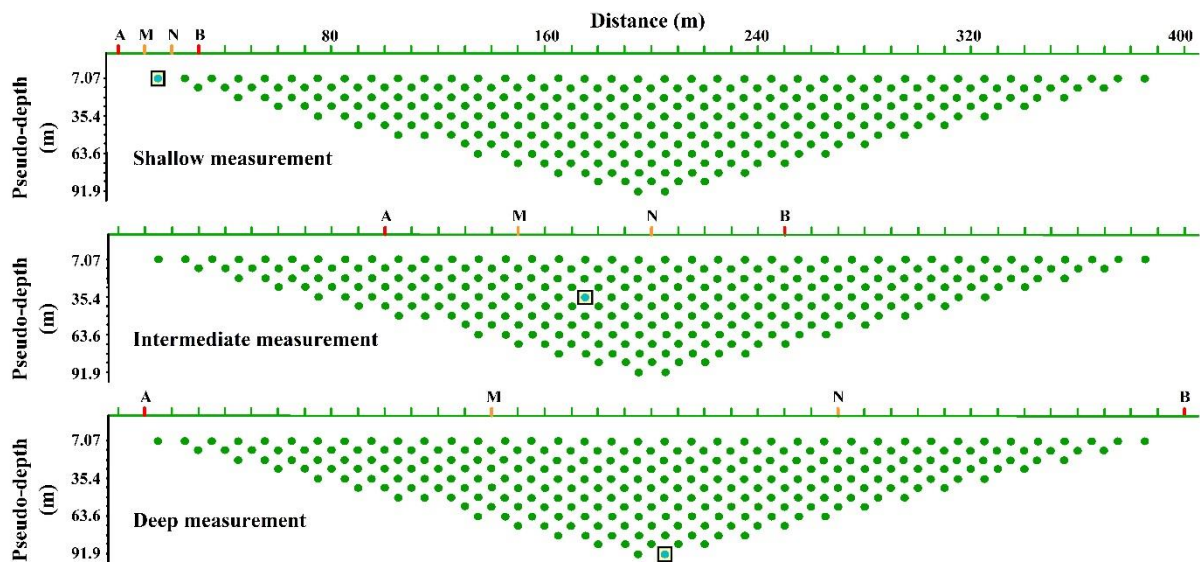


Figure 11: Measurements taken during 2D ERT surveys (Mukwathi and Fourie, 2020)

There are numerous arrays that can be employed during the electrical resistivity survey. The arrays that are most commonly used are: the Wenner array, the Schlumberger array, the dipole-dipole array and the pole-dipole array. According to Loke (2004) several factors need to be considered before choosing an array:

- The arrays sensitivity to horizontal and vertical changes in subsurface resistivity,
- The signal strength,
- The horizontal data coverage requirement,
- The geological structure type being investigated, and,
- The desired depth of investigation.

The Wenner array is the most commonly used in electrical resistivity surveys as it has the largest potential difference in comparison to the other three arrays, therefore the highest signal strength. Furthermore, the array is not that sensitive to changes in horizontal resistivity, but very sensitive to vertical changes (Herman, 2001). Therefore, it is well-suited for investigating horizontal geological structures. The configuration is simple and comprises four collinear and equidistant-spaced electrodes. The outer electrodes act as the current (AB) electrodes while the inner electrodes act as potential (MN) electrodes. In the Wenner configuration, the current and potential electrodes have a common mid-point and the distances between the adjacent electrodes are equal (Telford *et al.*, 1990).

2.13 GEOHYDROLOGY AND AQUIFERS IN THE KAROO

The DWA (1986) indicated that the Karoo area covers approximately 66% of the surface area of South Africa (Woodford and Chevalier, 2002). The occurrence of groundwater relies on the geology of the Karoo area, represented mostly by fractured hydrostratigraphic units of the Karoo Supergroup. The sedimentary bedrock generally comprises sandstone, siltstone, and mudstone.

2.13.1 Structural geology

Aquifer characteristics largely depend on the geology and structural control within the regional setting. Conduits for groundwater flow rely on geological structures and features associated with the geological setting. Woodford and Chevalier (2002) recognised fracture formation in the Karoo setting as being associated with different stress mechanisms. The major stress-controlling mechanisms include (Woodford and Chevalier, 2002):

- Mechanical and chemical weathering of bedrock. Mechanical weathering is the most dominant process towards the western portions of the Karoo and chemical weathering is more evident towards the humid East Coast of the country;
- Tectonic features that are non-intrusive, associated with faulting, regional lineaments, folding, vertical joints and fractures, bedding plane fracturing, furthermore, neotectonics and seismotectonic features;
- Intrusion events and magma events; and,
- Diagenesis, paleo-fluid movement, and thermos-metamorphism.

The stress-controlling processes for fracture formation are associated with a certain degree of fracturing and areal extent, largely dependent on the scale and significance of the event as well as the physical and chemical characteristics of the geological environment. The Karoo setting, especially towards the west is characterised by vertical jointing in the sandstone of the Beaufort Group associated with faults and fracturing, as well as the occurrence of bedding plan fractures (Woodford and Chevalier, 2002).

2.13.2 Flow in fractured media

The central Karoo region is characterised by fractured aquifers, while primary aquifers are essentially absent in the region due to minimal weathered and residual bedrock that can form an aquifer, as well as low rainfall. The secondary porosity of the large rock mass within the Karoo region constitutes the

storage of the aquifer, while the storage within fractured zones is limited by the apertures of the fractures and the areal extents of fractured zones (Woodford and Chevalier, 2002). It is often assumed that the fractures form an interconnected network of voids within the fractured medium. Groundwater flow in such a fractured medium can strongly resemble flow in a porous medium, especially when flow over large bulk volumes of the fractured medium is considered. Groundwater flow in such fractured media may therefore be described as Darcy's Law.

Where groundwater abstraction takes place in the dense geology of the Karoo sediments, the largest volume of groundwater will be from the transmissive fractured zone. This pumping will result in a drop in the piezometric pressure within the fracture, resulting in a flux of water through the interface between the rock matrix and the fractured zone:

$$V = \frac{Q}{A} \quad (16)$$

where V represents Darcy's velocity (Darcy's flux), Q is the rate of discharge and A is the cross-sectional area perpendicular to the groundwater flow direction. Also expressed as:

$$Q = K \frac{\Delta h}{\Delta l} \cdot A \quad (17)$$

The rate of movement (Q) of a fluid through a given material is proportional to the hydraulic gradient ($\Delta h/\Delta l$), based on the assumption that groundwater flows from a high to a low head across a cross-sectional area (A) of a material with K , the hydraulic conductivity of the material.

2.14 CASE STUDIES IN AN AFRICAN CONTEXT

Although several research projects have been completed to delineate protection zones in a South African context, very few projects have been launched to implement the findings of such studies. Groundwater use and management are instead usually regulated through governance according to the National Water Act of 1998 (Act 36 of 1998).

Research projects into the delineation of protection zones include a project by the Water Research Commission entitled "Towards a Guideline for the Delineation of Groundwater Protection Zones in Complex Aquifer Settings" (Net *et al.*, 2014) and work done by Nel (2014) as part of his doctoral research focussing on the implementation and benefit of groundwater source protection in fractured rock aquifers in South Africa. Nel (2014) described a case study for the town water supply of Leipoldtville on the West Coast of South Africa.

2.14.1 South African case study: simulated protection zones for the Gevonden Research Site in Rawsonville, Western Cape

Investigations were conducted at the Gevonden Research Site south of Rawsonville as part of a research project to develop guidelines for delineating protection zones within a fractured rock setting in a South African context. The main land use within the study area includes agricultural activities such as viniculture and small-scale breed cattle and chicken farming. The N1 national road between Worcester and Cape Town (N1) also runs through the study area. The research site is underlain by a primary intergranular aquifer and a secondary fractured aquifer. Groundwater in the unconsolidated aquifer is associated with alluvium of the Gevonden and Molenaars Rivers with baseflow evident during dry seasons. The fractured aquifer is associated with the bedrock of the Table Mountain Group (TMG) and is considered heterogenous with groundwater flow controlled by fractures, faults, and confining layers.

The fractured characteristic of the area is associated with regional faults, with several faults, including the Waterkloof Fault, cross-cutting the study area. Aquifer characteristics of both the unconsolidated unconfined aquifer and confined fractured aquifer were deduced from numerous data collection methods including geophysical surveys, borehole video logging, isotope analysis, and pumping tests.

Numerical modelling was done to simulate the travel time of groundwater to an abstraction borehole to delineate protection zones around that borehole. Two scenarios were simulated, namely 1) where the Waterkloof Fault acts as a conduit zone and 2) where the fault acts as a no-flow boundary. Three levels of protection were delineated based on the simulated travel time. Zone 1 was associated with a 1-year capture zone, Zone 2 with a 10-year capture zone, and Zone 3 with a 100-year capture zone. Furthermore, as part of the conservative approach to model protection zones, a 20% hydraulic property deviation was incorporated in the model simulation. The simulated protection zones are shown in Figure 12 where the capture zone for Zone 1 has a radial shape around the pumping well and extends along the fault structure. Similar trends are evident in Zone 2 and Zone 3. However, over 10 years of abstraction it is expected that the baseflow component would start contributing towards the volumes abstracted from the boreholes. Furthermore, the 100-year simulation shows a capture zone towards the higher-lying recharge areas, where the Molenaars River will start contributing water to the fractured aquifer.

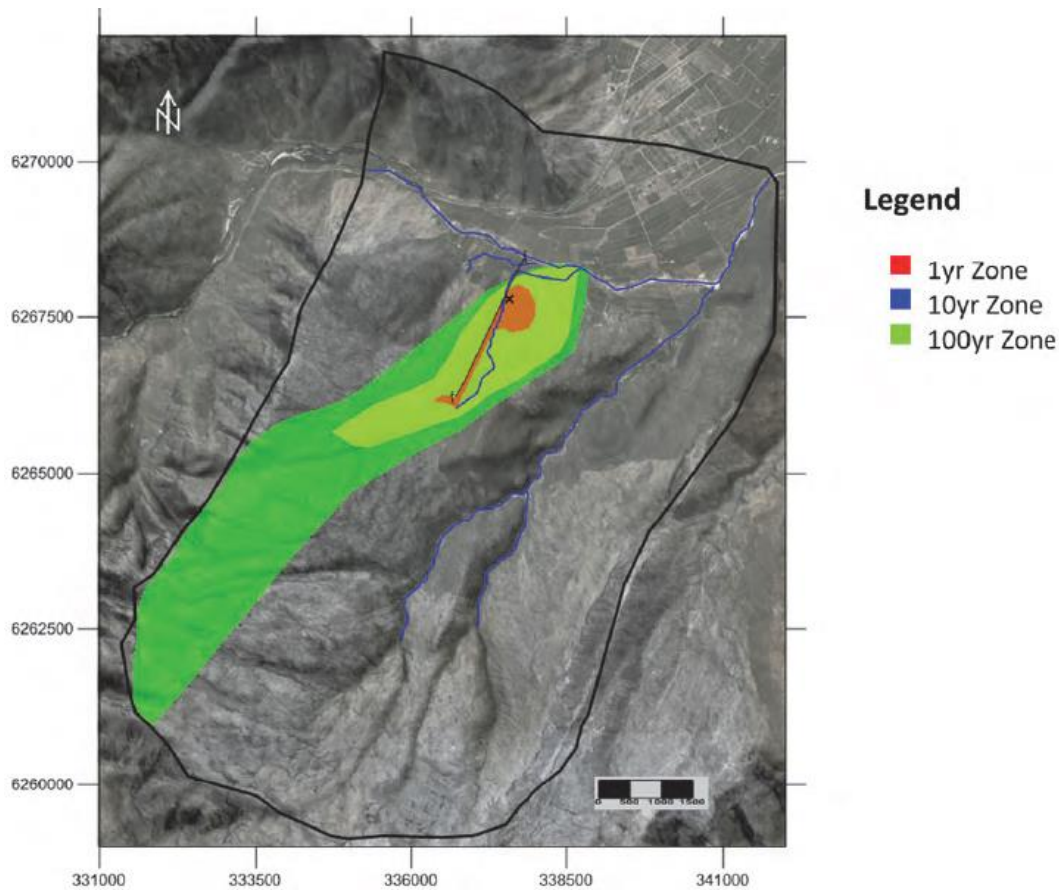


Figure 12: Delineated protection zones for 1-year (red), 10 years (lighter shade green), and 100-year (darker shade green) flow fields at the Gevonden research site (Nel *et al.*, 2014)

Data gaps were identified during the calibration and validation of the numerical model. These gaps included: limited information on historical borehole use, only localised borehole data, absence of information on borehole construction, absence of monitoring boreholes associated with the fault, and limited hydraulic parameters for the deeper fractured aquifer. Contaminant sources were identified within the different capture zones and mitigation measures were recommended. The potential contaminant sources are shown in Figure 13.

Based on the results of the model simulation and predictions, data gaps, and contaminant sources it was identified that more information was needed on the complex TMG aquifer and fracture characteristics. It was deemed that the ongoing monitoring needed to be expanded to update the conceptual model. The proposed expansion of the monitoring programme included the collection of more detailed water level, water quality, and water balance data. Several new monitoring points were suggested for both groundwater and surface water, and monitoring frequencies were proposed (monthly, bi-annually, yearly, etc.). It was concluded that monitoring of the groundwater levels was the most important aspect of the monitoring programme because localised groundwater abstraction had the potential to change the natural groundwater gradient.

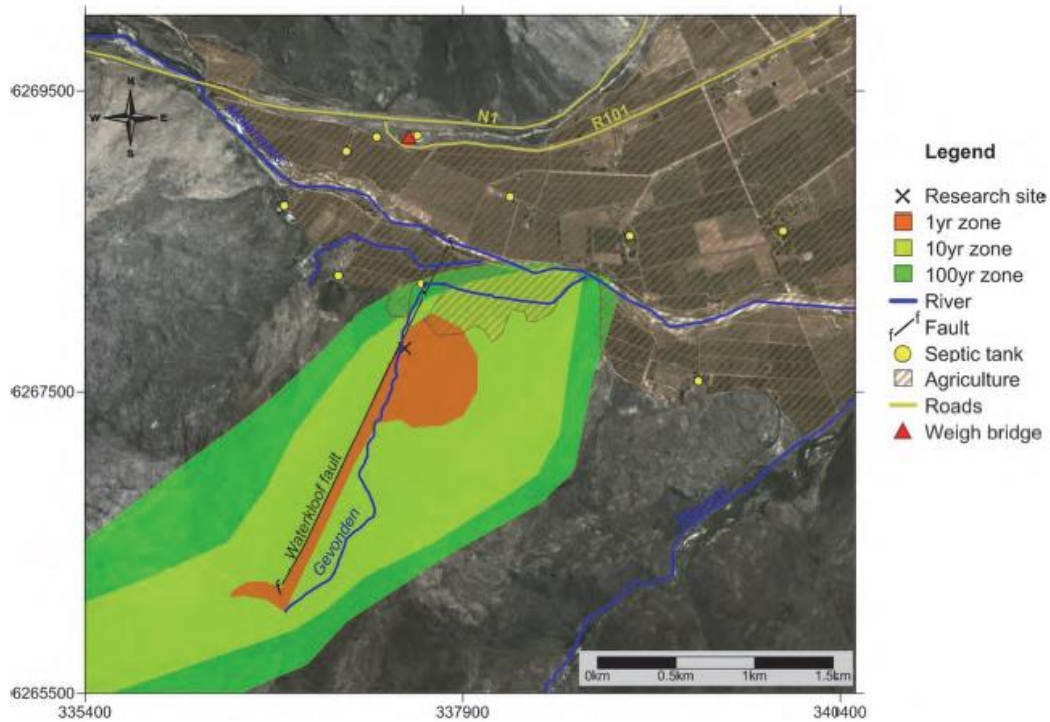


Figure 13: Potential contaminant sources within the delineated protection zones

2.14.2 Atlantic West Coast of South Africa: protection zones for Leipoldville supply

The Atlantic West Coast of South Africa is largely dependent on groundwater for its water supply, which includes the agricultural and municipal supply. Some important ecosystems in the area are also dependent on groundwater (DWAF, 2003a cited by Nel, 2011). Concerns have been expressed about the risk of some ecosystems (such as wetlands) drying out resulting in the disappearance of certain plant species. A well-known case is the drying out of the Verlorenvlei and the overall deterioration of the wetland due to ever-increasing agricultural activities, resulting in water levels dropping, depletion of the source, and potential contamination through fertilizer application.

Protection zones were delineated as part of the study completed by Nel (2011) incorporating a numerical modelling approach. The model took account of the complexity of the geological and geohydrological setting with the occurrence of both primary and secondary aquifers. The hydraulic properties of the aquifers were estimated through slug tests conducted in single boreholes, as well as fluid electrical conductivity logging (FEC). In addition, a conceptual model was developed to describe groundwater flow in the aquifer surrounding the Leipoldville municipal water supply. The results of the numerical model are portrayed through a zone of contribution to the wellfield, distinguishing between areas with near-natural groundwater levels and areas in which the groundwater level was lowered (Figure 14).

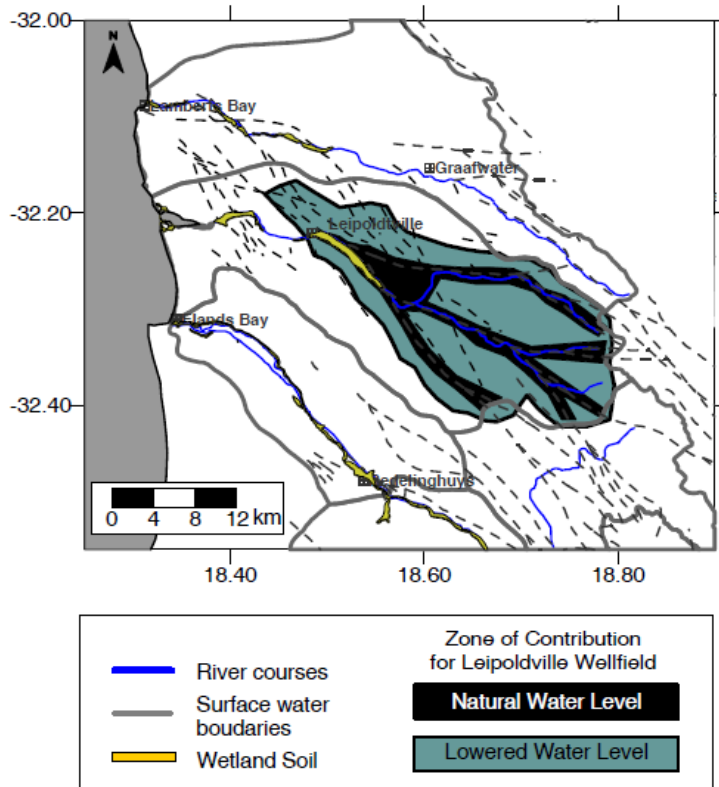


Figure 14: Protection zones for the Leipoldtville municipal resource under natural conditions relative to lowered water levels, West Coast, South Africa (Nel, 2011)

It was concluded that due to the complex nature of the geological setting, the water levels played a significant role in the management of the resource. Therefore, information on the groundwater water levels would allow groundwater users to estimate the impact of abstraction on the groundwater system by considering the capture zone around the municipal water supply, thereby protecting the resource and important ecosystems. It was recommended that a groundwater level database be compiled to estimate the protection zone. It was further recommended that a monitoring network and management plan be developed. The database could then be considered with the process of new groundwater use license applications to determine whether the addition of abstraction might occur without negatively impacting the aquifer in which the wellfield is located. Nel (2011) asserted that it could be difficult to enforce such regulations, but that it would be beneficial for groundwater-dependent practices and entities requiring uncontaminated low-salinity groundwater.

CHAPTER 3: SITE DESCRIPTION

3.1 REGIONAL SETTING

The study area is located in the Northern Cape part of the central Karoo region, approximately 267 km north-east of Cape Town, 160 km southeast of Calvinia, and 120 km south-west of Fraserburg, around latitude 20.66° and longitude -32.39° (Figure 8). The study site and surrounding areas are located within the D51A Quaternary catchment area.

3.2 GEOMORPHOLOGY AND SURFACE DRAINAGE

The study area is located in a topographical low within the regional setting, with elevations ranging from 1664 meters above mean sea level (mamsl) at the highest point south of town to 1447 mamsl at the lowest north of town. The drainage across the area is generally from the higher-lying western, south-western, and eastern mountains towards the north along non-perennial streams, draining channels, and the non-perennial Dorpsrivier.

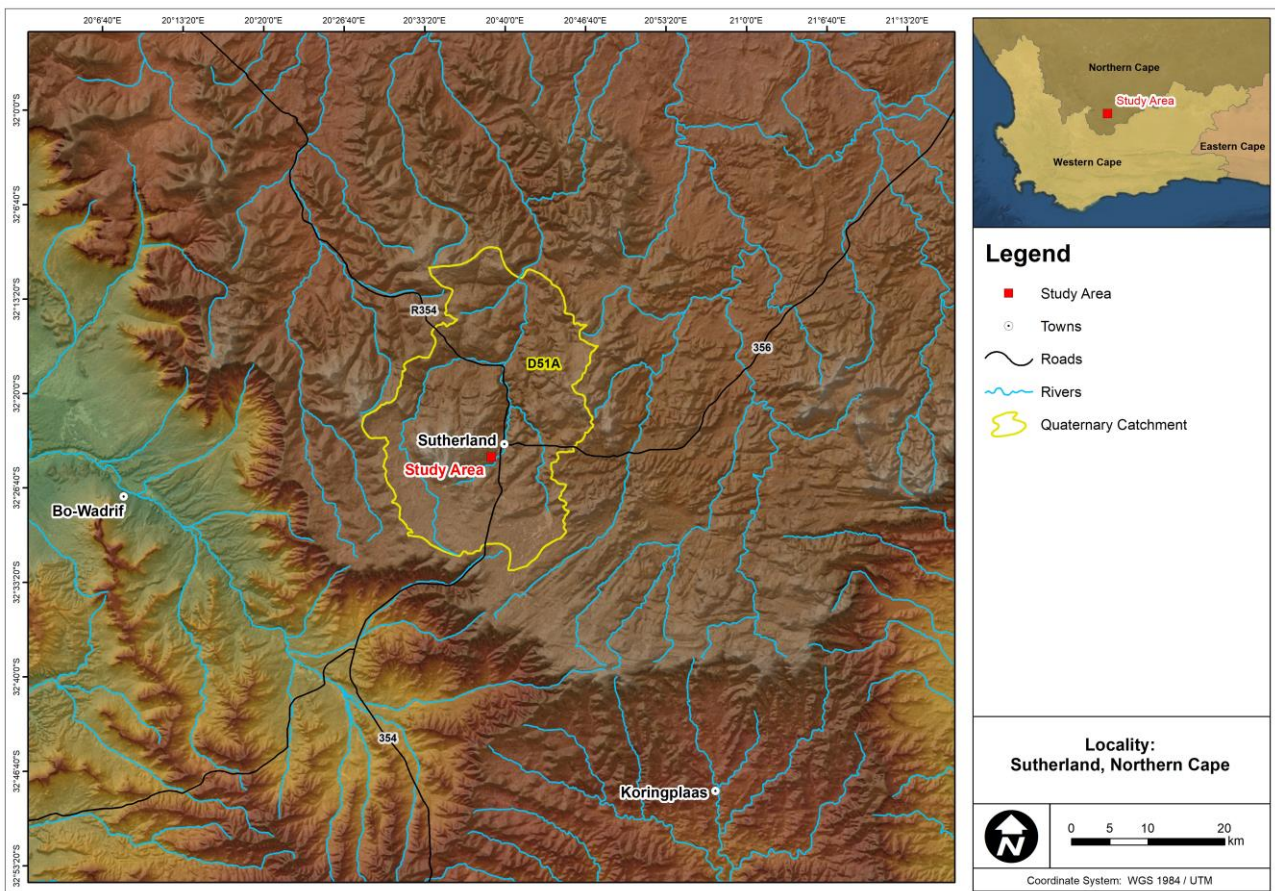


Figure 15: Regional setting of the study area, indicating the town of Sutherland in Quaternary catchment D51A.

3.3 CLIMATE

Sutherland is characterised by variable rainfall patterns, historically peaking in May to August from 1950 – 2000 as shown in Figure 16 with a mean of 311 mm/a. The precipitation in the region is characterised by snowfall during winter months and strong low-pressure systems moving across the southern portions of South Africa. The upper escarpments of the Sutherland regions experience cold temperatures and snowfall due to its high altitude (~1500 mamsl), thinner atmospheric conditions, lower air pressure, and increased moisture.

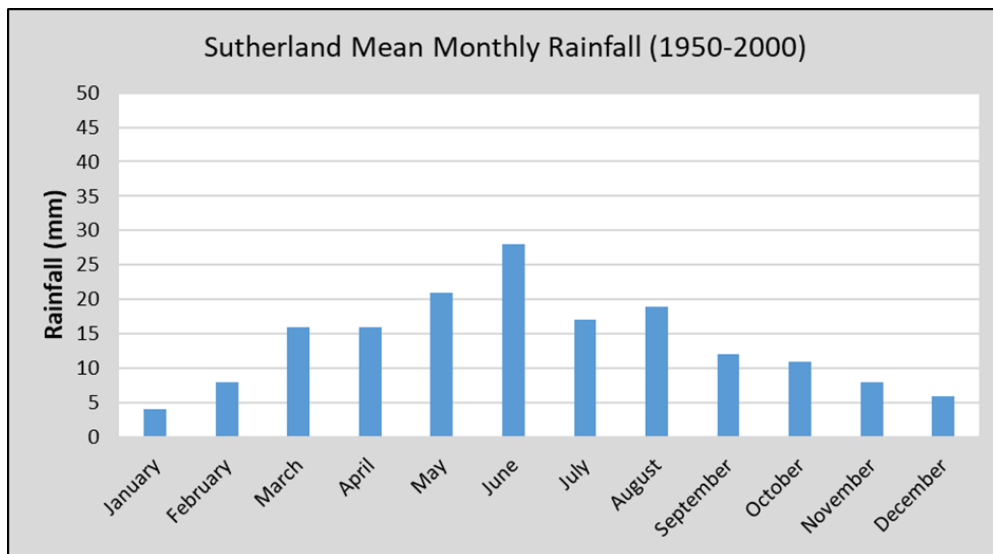


Figure 16: Monthly average rainfall distribution for the Sutherland area (Schulze, 2009)






Figure 17: Weather station in Sutherland located at -32.399678°S and 20.663027°E

3.4 GEOLOGICAL SETTING

3.4.1 Introduction

The geological setting is well represented by the younger intrusive bedrock of the Sutherland Suite, Jurassic age intrusive events, deformation as a result of these intrusive events, and sedimentary bedrock of the Beaufort Group. Table 3, summarised by Theron (1983), depicts the geological formations, geological structures, and hydrostratigraphic groups. The stratigraphy and structures are described in chronological order from youngest to oldest.

Table 3: Stratigraphy of the Sutherland area

Age range (Ma)	Code	Formation	Group	Description
66	Ksa	Sutherland Suite		Agglomerate, tuff, breccia
	Ksm			Melilite basalt
	Kst			Trachyte
182	Jd	N/A		Dolerite
		N/A		Monocline
		N/A		Anticline
		N/A		Syncline structure
266 – 260	Pa	Abrahamskraal	Beaufort	Mudstone, siltstone, thin chert beds

The geology is mapped as consisting of different formations of the Karoo Supergroup, Jurassic age intrusive rock, and Cretaceous age bedrock of the Sutherland Suite (Figure 18). The geology of the study area comprises predominantly a layered succession of the Abrahamskraal Formation, consisting of alternating layers of mudstone, siltstone, thin chert beds, and sandstone. The mudstone is massively layered, blue and green, red-purple in some places. The interlayered blue to greenish-grey sandstone layers ranges from 0.1 m–10 m in thickness within the regional setting and can be as thick as 30 m in the Sutherland area (Theron, 1983). The sandstone is characterised by fine to medium-grained, silty in some places, and red-brown weathering.

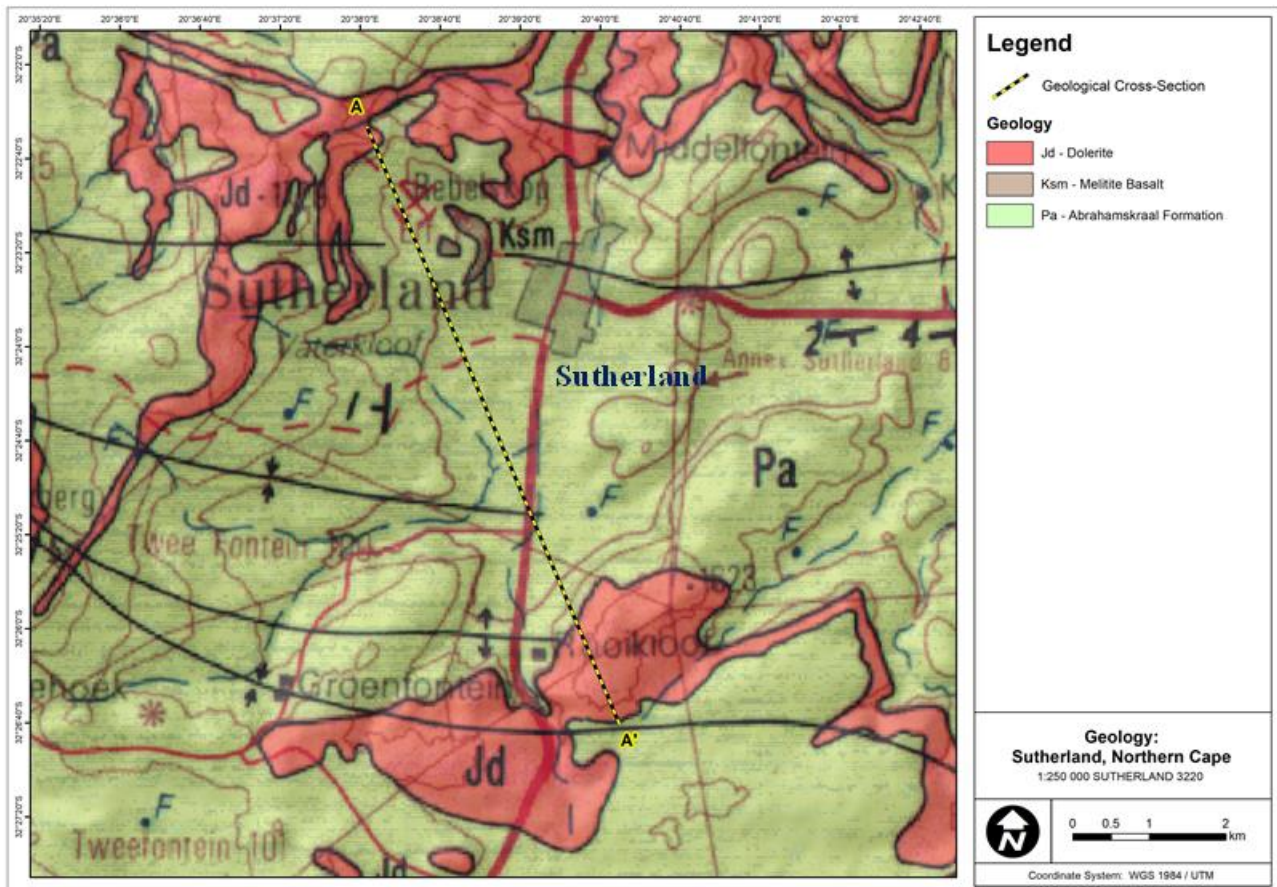


Figure 18: Regional geological setting

3.4.2 Intrusive bedrock

The Karoo Supergroup has been altered by two different age intrusive events, i.e., the intrusion of widespread dolerite sills and dykes during the Jurassic era and the intrusions of the Cretaceous age. The sedimentary rocks have been altered in places by these intrusive events, with a low degree of metamorphism and extensive fracturing patterns. This has been noted as numerous intrusion phases, or a continuous intrusion phase over a long period considering the vast amount of dolerite intrusions within the regional setting. The dolerite intrusions within the Sutherland area are predominantly younger than the structural folding and follow the regional structural pattern (Theron, 1983), thus relatively conformably overlying the sedimentary units of the Abrahamskraal Formation, forming the cap of the higher-lying areas surrounding the Sutherland basin. A sill is evident in the study area, preserved in the form of a hill towards the south with a thickness in the range of 20 meters (Mahed, 2016)

The Salpeterkop intrusion comprises of older trachyte intrusions and agglomerate, tuff, and breccia forming the larger structure (Theron, 1983). The bedrock has further been altered as a result of a melilite basalt intrusion located just west of town, forming an elevated area and smaller associated radial fracturing. The fracturing pattern evident in the larger Sutherland area is likely associated with

the intrusion of the volcanic pipe, Salpeterkop. The bedrock within the regional setting shows a general trend with major north-east/south-west fracturing (linear features) which extends across several kilometers, and several minor northwest-southeast, north-south, and east-west trending fracture zones, some radial to the Salpeterkop intrusion (Newton, 1987).

3.4.3 Structural geology

The area is characterised by flat and gently dipping bedrock with east-west trending anticline, syncline, and monocline structures. The central portion of the town is underlain by an anticline dipping around 2 – 4 degrees to the north and the south, folding into a syncline towards the south of town (CGS, 1978). Furthermore, the sedimentary succession has been intruded by a volcanic pipe, better known as Salpeterkop approximately 18 km towards the southeast of the town resulting in the regional fracturing pattern (Newton, 1987).

Major lineaments associated with fractured zones in the proximity of the town have similar trends to that of the regional setting, with several north-east/south-west trending features visible on aerial photographs. This correlates with fractured bedrock and abrupt depressions in the general topography. The fractured zones are approximately 3 m–5 m wide and are anticipated to be vertical and sub-vertical, extending more than 10 km towards the south of town (Figure 19).

In addition to the major structures, several northwest-southeast and east-west structures are evident in the setting, some radial to the melilite basalt intrusion mapped towards the west of town (Newton, 1987). This basalt outcrop is limited and appears to be capped in places by sandstone and mudstone of the Abrahamskraal Formation, and is highly weathered at the surface. Several small radial fractured zones are visible in the field and on aerial photographs within the proximity of the intrusion with a low degree of metamorphism evident in the proximity of the intrusions. Individual linear dyke-like features have been identified in the field, which has been targeted with exploration drilling associated with confining conditions, resulting in perched water tables discussed further in this report. A geohydrological study of the Sutherland area completed by Mahed (2016) asserts the abovementioned with the major north-east to south-west fractured zones (Figure 20).

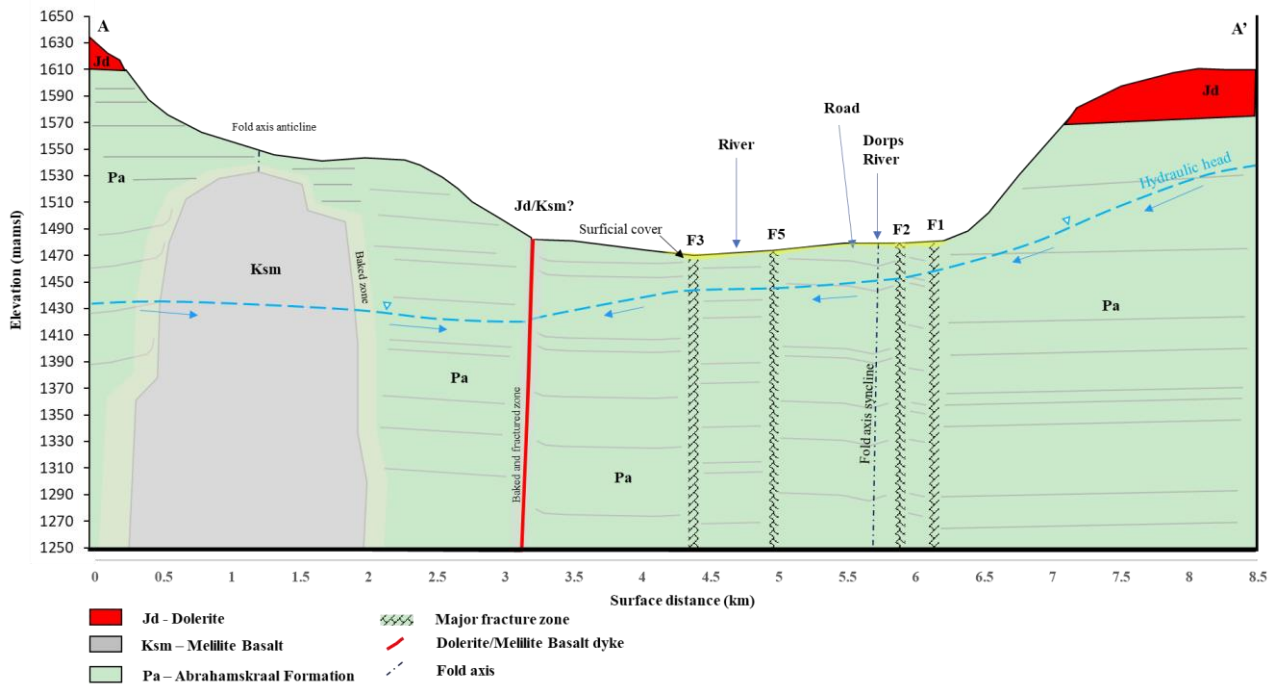


Figure 19: Geological cross-section through the study area along line AA' (see Figure 18)

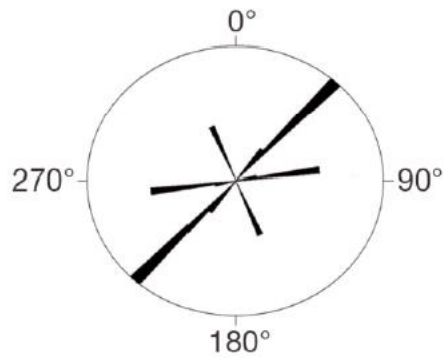


Figure 20: Rose diagram of the dominant fractured zone orientation within the Sutherland area (Mahed, 2016)

CHAPTER 4: METHODS AND MATERIALS

4.1 INTRODUCTION

The main aim of the current study is to delineate groundwater protection zones within the Sutherland area. To address this aim, the study involved a detailed literature review and fieldwork applying best scientific practices. The fieldwork included a hydrocensus, geological mapping, surface-based geophysical survey, detailed logging of drilling results, borehole camera logging, and groundwater sampling from the tested boreholes for chemical analysis. The results of these investigations were used to develop a conceptual hydrogeological model of the study area and to delineate protection zones around the production boreholes.

4.2 DESKTOP ASSESSMENT

The initial phases of the project entailed a desktop study which included an assessment of any existing information that could aid in confirming and delineating geological structures within the study area which could be associated with higher transmissivities and greater exploitation potential of the fractured aquifer. The following information and sources were consulted:

- 1:250 000 scale geological map series and associated structures from the Council for Geosciences (CGS),
- 1:250 000 explanation booklet of the Sutherland area,
- Monitoring data obtained and collated by the DWS, and,
- Previous reports including, geological, hydrogeological, and status assessment reports.

From this desktop study, areas were identified with potentially favourable geological targets for groundwater development.

4.3 HYDROCENSUS

A hydrocensus was completed with an 8-km radius around the town to identify boreholes and groundwater users. This entailed capturing coordinates, the status of the borehole (in use or not), measurement of borehole depths (when open, otherwise reported depth from drilling), groundwater levels, and groundwater quality using a basic field chemistry set, and an indication of the yield based on verbal discussions with the landowners.

4.4 SITE VISIT AND STRUCTURAL MAPPING

A site visit was conducted to allow familiarisation with the field conditions and to assess the general site geology. Target structures previously identified from geological maps, old reports, and aerial photographs were also visited. Outcrops of the geological targets were marked as control points with a handheld GPS device.

4.5 GEOPHYSICS

The geophysical survey was planned and completed in the area earmarked for the wellfield development. Geophysical traverses were selected to cross the geological targets identified from the desktop study and verified during the site visit. Where possible, the geophysical traverses were oriented perpendicular to the strikes of the target features to record well-defined anomalies. Where no evidence of the targets was visible at the surface (e.g., due to the presence of alluvial material in the lower-lying areas), the GPS control points recorded during the site visit were used to estimate the positions of the targeted structures.

Some of the limiting factors during the survey included harsh terrain, existing electrical infrastructure, fences, overhead power lines, and roads crosscutting the area being investigated. Considering the geology and anthropogenic factors, the electromagnetic (EM) method and the electrical resistivity tomography (ERT) methods were chosen for the geophysical survey. Although the magnetic method is often the preferred geophysical method in Karoo settings, a test survey conducted on the first day of the geophysical survey did not yield valuable data. The magnetic method was therefore excluded from all further geophysical surveys.

4.5.1 EM survey

Data were acquired during the EM survey using the GF Instruments CMD DUO frequency-domain electromagnetic conductivity meter. The data were obtained using a 40-m coil separation with coplanar horizontal dipole (HD) and vertical dipole (VD) coil geometries. Such coil geometries allow typical investigation depths of 30 m and 60 m for the HD and VD orientations, respectively. The station spacing employed during the EM survey was approximately 5 m.

4.5.2 ERT survey

The ERT survey was conducted with the GF Instruments ARES resistivity and IP imaging system for assessing subsurface structures with measurements made at the surface. The ARES system is an automated resistivity data acquisition tool that provides 2D cross-sections of the subsurface of the

area investigated along the profile. The Wenner array was selected for the survey due to its fast acquisition time, low susceptible to noise, and suitability for surveys in high-resistivity conditions.

The apparent resistivity data acquired in the field were inverted using the Res2DInv software (Loke and Barker, 1996) to provide a true-depth resistivity section. The only pre-processing done was to erase erratic data points (minimal). The resulting modelled resistivity sections were interpreted in terms of the depth to bedrock and the presence of the targeted geological structures.

4.6 BOREHOLE DRILLING

Eleven boreholes were drilled within the study area and each borehole was designed according to the anticipated drilling conditions, based on the geological target. The depth to bedrock was found to be less than 2 m below ground level (mbgl) across the study area from the data obtained during the hydrocensus and geophysical survey. This interpretation was supported by the presence of outcrops of the bedrock near most of the drilling sites. All of the boreholes were drilled through normal down-the-hole (DTH) air percussion drilling through the overburden into competent bedrock, after which an inner steel casing was installed, seated into the competent bedrock, followed by drilling into the competent bedrock using a smaller diameter drill bit to the final depth of the borehole.

4.7 DOWN-HOLE CAMERA INSPECTION AND FRACTURE CHARACTERISATION

The down-hole camera investigation was conducted using the Laval Underground Surveys – R-CAM 1300 XLT: Water Well Video Inspection System furnished with two cameras in a single housing. Each camera is equipped with a wide-angle lens for viewing and recording downhole and side view images in water wells or boreholes. The camera was positioned in the centre of the borehole/well with centralizers and lowered slowly, initially using the down-hole view along with depth indicator to investigate the down-hole status of the borehole/well and identify any irregularities, casing connections, slots in the casing, cavities, collapses, obstructions and borehole infrastructure along with its correlating depth. If any of the abovementioned were identified in the borehole, the camera setting could be switched to the side view to investigate in more detail. The camera views were alternated between the down-hole and side views to get the most suitable display for the area within the borehole inspected. The depth of investigation depended on the borehole depth, borehole diameter, obstructions, borehole infrastructure, monitoring infrastructure, and skewness of the borehole. Notes were taken of the abovementioned observations to better understand the fractured characteristics of the aquifer and compared to the geological logs compiled during drilling.

4.8 PUMPING TESTS

Under the guidance of a hydrogeologist, and following the methodology specified by the South African National Standard (SANS 10299-4:2003, Part 4 – Test pumping of water boreholes), pumping tests were performed on selected boreholes by ATS, a consulting company specialising in pumping tests. The purpose of the pumping tests was to determine aquifer parameters, cones of depression and radial influences of the boreholes being pumped, sustainable yields, and pumping schedules for safe groundwater abstraction from the aquifer.

The pumping test included a step test and a constant discharge test with monitoring of groundwater level responses and recovery of each borehole to pumping. The step test preceded the CDT, consisting of several, usually four, sixty-minute pumping intervals.

In addition to the test pumping data acquisition, a modified falling head test was completed at one of the ARE holes, located in close proximity to a production borehole. To collect preliminary data on the aquifer matrix acceptance capacity. The falling head test involved repeated injection of a known volume of water into the borehole. The injection of water causes a sudden rise in the water level head (positive displacement). The subsequent falling water level response is then measured with time to estimate the hydraulic properties (Cooper *et al.*, 1967; Barker and Black, 1983).

4.9 ANALYSIS OF PUMPING TEST DATA

The data from the pumping tests were analysed in the FC program developed by the IGS (Institute for Groundwater Studies) at the University of the Free State (UFS) (Van Tonder *et al.*, 2001). Water level drawdown responses to the CDT and water level recoveries were analysed to determine aquifer parameters (transmissivity (T), and storativity (S) if observation boreholes were available). Furthermore, aquifer flow characteristics were determined from the pumping test data. The parameters and flow characteristics were determined through the application of the Theis method (1935), Cooper-Jacob method (1946), and Barker Generalised Radial Flow method (Barker, 1988), as well as analysis of the first derivatives of the drawdown curves.

4.10 GROUNDWATER LEVEL MEASUREMENTS

Groundwater levels were measured at a total of 16 boreholes from the borehole network. Measurements were taken during the hydrocensus conducted in and around the town of Sutherland. During the measurement, it was also noted whether the water levels corresponded to static water levels (SWLs) or whether the water levels may have been influenced by groundwater abstraction from the boreholes themselves or from other boreholes in the vicinity.

4.11 GROUNDWATER SAMPLING AND ANALYSES

Groundwater samples were collected either through a pump installed in the borehole or a selective-depth bailer where the boreholes were unequipped. Most of the boreholes were sampled at the end of the pumping tests and others were sampled using a selective-depth bailer at depths ranging between 5 m and 10 m below the rest water level, depending on the borehole depth. Boreholes with existing pump infrastructure were purged until the chemical parameters (pH, EC and TDS) stabilised, after which a representative sample was taken. Samples were collected from those boreholes on which pumping tests were completed within the last hour of the CDT.

Samples from all of the existing boreholes, identified during the hydrocensus were analysed for electrical conductivity (EC, mS/m), pH and total dissolved solids (TDS, mg/L) using a basic field chemistry kit. The samples submitted to a laboratory were analysed according to parameters outlined by SANS241-1:2015. All concentrations were measured in milligrams per litre (mg/L). The acceptable ionic balance calculation threshold for all samples analysed in a laboratory was $\pm 10\%$.

4.12 HYDROGEOCHEMICAL CHARACTERISATION

In this study, the hydrogeochemical data obtained from laboratory analyses of the groundwater samples were used to aid with the conceptual understanding of the aquifer, to build a database with baseline hydrogeochemistry representative of the aquifer, and to improve the understanding of recharge characteristics of the aquifer.

The results of the laboratory analyses were first used to classify the groundwater quality in terms of its suitability for human consumption. The measured concentrations were assessed against the water quality guidelines for domestic use, as specified by DWAF (1998). The groundwater was then characterised in terms of its chemical composition by making use of graphical representations of its ion content. Two standard graphical representations were used to display the ion content of the groundwater, namely the Piper and Stiff diagrams.

4.13 DEVELOPMENT OF A CONCEPTUAL HYDROGEOLOGICAL MODEL

The development of a conceptual hydrogeological model is an important step towards successfully managing an aquifer. A conceptual model provides the hydrogeologist with an improved understanding of the occurrence of groundwater, chemical characteristics and groundwater behaviour. The methodology for building a conceptual model entailed the collation of all geological, hydrogeological and information pertaining to the study area. This required the construction of a

database being mindful of the objectives of this study. The database included all geomorphological, geology, hydrogeology, geohydrochemistry and geophysics data. The potential impacts on the natural hydrogeological system were also considered, whether natural or anthropogenic. Climate data were also included due to the important role that climate plays in groundwater recharge. Furthermore, land use within the study area was taken into account.

The development of a conceptual model is an iterative process, in which the model is constantly updated as new data become available. Through this iterative process, the understanding of the system is improved. Figure 21 depicts the baseline items considered in the process of developing a conceptual hydrogeological model for the study area.

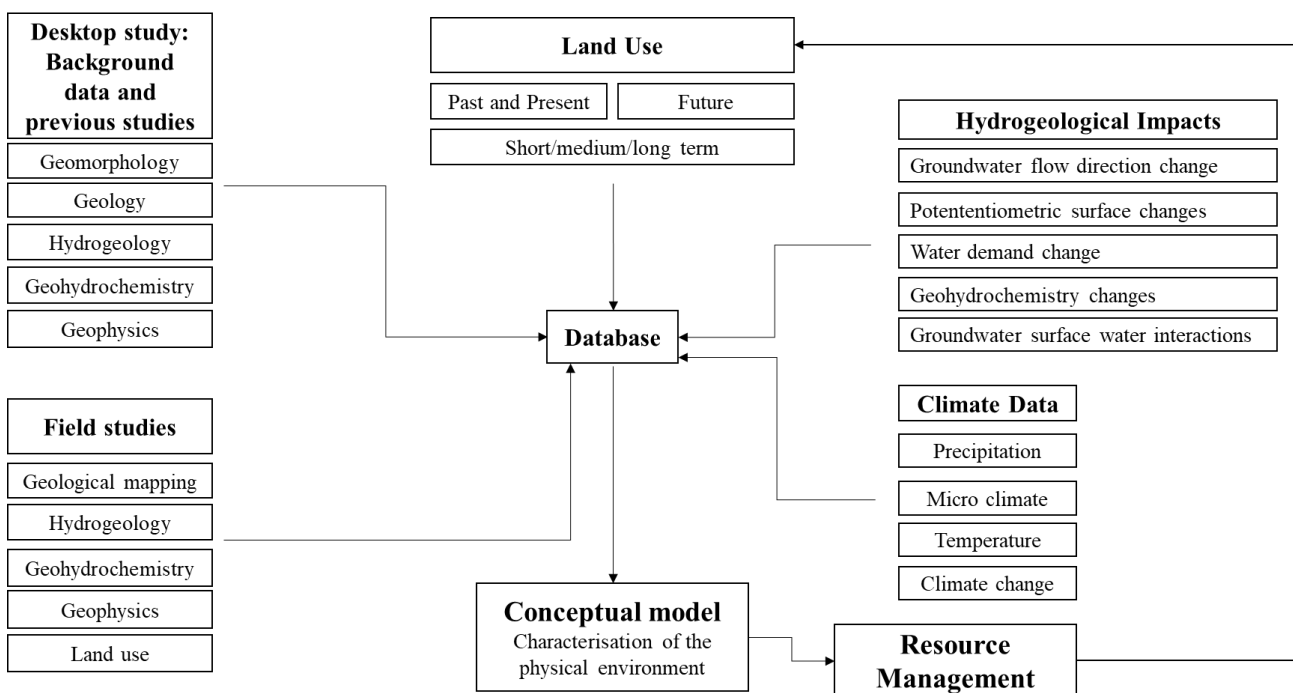


Figure 21: Flow chart for creating a conceptual model

4.14 ESTIMATING A SAFE YIELD FOR THE TOTAL CAPTURE ZONE

The safe yield for the total capture zone is an important indication of the total amount of groundwater that can safely be abstracted from the aquifer system. The safe yield for the total capture zone was determined using the AFYM developed by Murray *et al.* (2012) (refer to Section 2.10.1). For this investigation, the default parameter values for rainfall, recharge, and specific yield were replaced with more site-specific data valid for the study area by considering the local geological conditions and features. Recharge was calculated from literature chloride values using the CMB method.

4.15 DELINEATION OF PROTECTION ZONES

The delineation of protection zones around the wellfield within the study area was done by 1) assigning a safe radius around the production boreholes to form the wellhead protection zone, 2) considering the local topography to define the source catchment protection zone, and 3) by modelling the hydraulic head in the aquifer over time for groundwater abstraction from the boreholes in the wellfield, and by defining a maximum safe drawdown level. The Cooper-Jacob wellfield model (CJWFM) described by Murray et al. (2012) was used to delineate the latter two protection zones. The CJWFM is a simple analytical model, originally developed as a borehole spacing tool to design wellfields based on exploration borehole results. The specific way in which the CJWFM was applied in the current study, is described in Section 5.12.2.

4.16 RISK ASSESSMENT FOR CONTAMINATION

Risks pertaining to the deterioration of the source were considered with all variables throughout the study area. Each risk included has been assessed qualitatively based on factual data for the activity. The risks were categorised as follows:

- The probability of a negative impact on the source rated as a percentage according to the likelihood of that impact occurring,
- The intensity and the degree to which it may physically impact or affect the source,
- The duration and its associated impact,
- The extent evaluated within the respective zones of protection, and if probable on a regional scale, and,
- Confidence in the evaluation of the risk.

The abovementioned risk assessment criteria further consider the confidence with which site-specific activities can be evaluated. The evaluation of potential risks for contamination is done through consideration of potential sources, pathways, receptors, and protected yield. The risk rating matrix used during this study is shown in Table 4.

Table 4: Risk assessment matrix for potential impact on the aquifer through an activity

Rating	Categories				Confidence		
	Probability	Intensity	Duration	Extent			
0	Less than 20 % sure of a particular fact or of the likelihood of that impact occurring	Insignificant. Impact in such a manner that no natural functions are impacted.	Less than 1 day	Well head	1	2	3
1	20 - 40 % sure of a particular fact or of the likelihood of that impact occurring	Minor. Impact in such a manner that minimal natural functions are impacted.	1 week to 1 month	Inner zone	Low	Moderate	High
2	40 - 60 % sure of a particular fact or of the likelihood of that impact occurring	Moderate. Impact in such a manner that no natural functions modified, however, still functional.	1 month to 1 year	Outer zone	Impact managed through mitigation measures (0 - 6)		
3	60 - 80 % sure of a particular fact or of the likelihood of that impact occurring	Major. Impact in such a manner that no natural functions are greatly impacted with intense management implementation.	1 year to 10 years	Source catchment zone	Impact manageable through reducing risk mitigation measures (6 -12)		
4	80 - 100 % sure of a particular fact or of the likelihood of that impact occurring	Severe. Impact in such a manner that the natural system is permanently damaged and requires large scale rehabilitation.	Greater than 10 years/permanent	Regional	Impact significant which requires rehabilitation and mitigation application (12 - 16)		

CHAPTER 5: RESULTS AND DISCUSSION

The results of the current study are presented in chronological order in which data were obtained from the initial desktop stage towards the conceptualisation of the geological setting to present actual and applicable protection zones within the study area.

5.1 DESKTOP ASSESSMENT

The results of the desktop study proved to be valuable with an improved understanding of the existing aquifer status and groundwater use within the Sutherland area. It was clear that the municipal supply water restrictions and the ongoing drought conditions had resulted in a large increase in privately owned boreholes being established. Previous hydrogeological studies completed in the area indicated that the existing town supply, located in close proximity to the town area was experiencing dropping water levels and yields. Through basic lineament mapping on satellite imagery, clear trends were picked up in terms of fractured zones which could be associated with high potential areas for groundwater development. Furthermore, existing boreholes reported on in previous assessments showed potential for successfully developing high-yielding production boreholes.

5.2 STRUCTURAL MAPPING AND GEOPHYSICS

To confirm the major groundwater flow controlling geological structures within the study area, basic on-site geological mapping was completed as well as a geophysical survey. This aided in compiling a conceptual model, and selection of drill targets where exploration and aquifer recharge enhancement boreholes were drilled and recharge areas.

5.2.1 Structural mapping

The infield geological mapping confirmed the locations of major and minor geological structures as well as the occurrence and composition of bedding plane outcrops and estimated thicknesses of different rock types. Figure 22 shows the typical horizontal layered characteristics of the Abrahamskraal Formation with alternating layers of sandstone, shale, sandstone, mudstone, shale and sandstone. The grey arenaceous shale and purple mudstone show higher degrees of weathering at the surface.



Figure 22: Left: Bedding plane outcrops evident within the study area showing alternating sandstone and shale layers (left), and thick sandstone layer overlying mudstone and shale layers (right)

In the town area, the Abrahamskraal bedrock has been intruded by melilite basalt showing a low degree of metamorphism and associated radial fracturing evident on the sedimentary bedrock outcrop close to the intrusion (Figure 23).



Figure 23: Metamorphosed bedrock and linear fracturing evident on the surface

Dolerite is prominent in the higher lying areas towards the north and south of town in the form of a sill forming a cap on top of the Abrahamskraal Formation. Figure 24 shows the dolerite sill and Abrahamskraal contact zone evident in the road cutting of the Rooikloof towards the south of the town. A very sharp contact zone is evident, with signs of metamorphism and fracturing in the sedimentary bedrock.

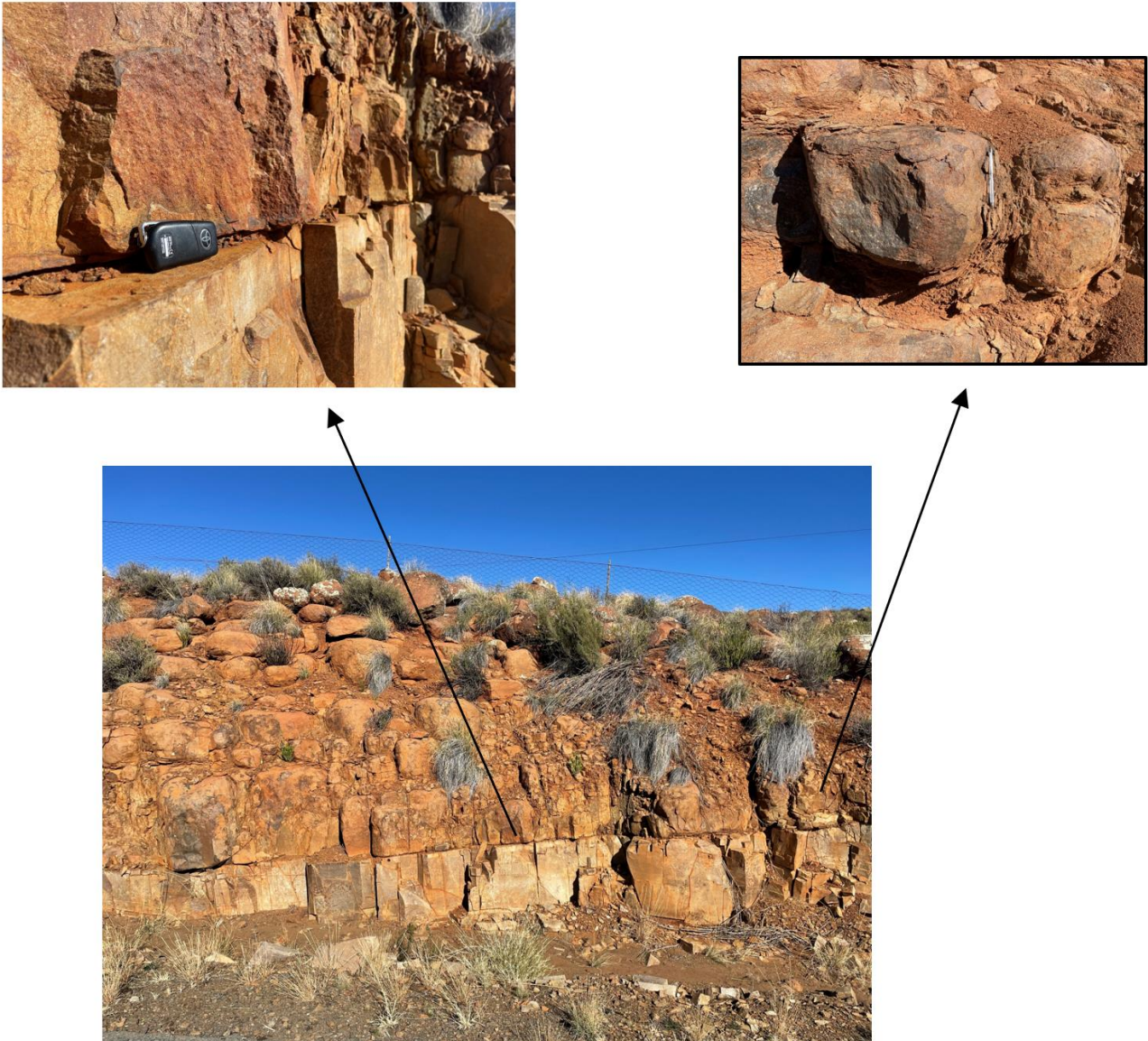


Figure 24: Dolerite and sedimentary bedrock contact zone located towards the southern higher lying areas (authors' own)

Major conduit zones within the Abrahamskraal Formation are associated with broad fractured zones, which are associated with general depressions in the topography where it crosscuts the bedrock. The centre of these structures appears to be highly damaged with no clear fracture orientation; however, moving outwards from the core, fracturing appears to have a preferred orientation parallel to that of the major structure itself. In the damaged zones Montmorillonite appears to be evident. This mineral

is also visible in the down-hole camera investigation discussed in Section 5.5. Figure 25 shows an example of major structure F3 in a road cutting towards the south-west of the town.



Figure 25: Fractured sandstone outcrop in a depression associated with major structure F3 (-32.446615°S, 20.619237°E) (Authors own)

In addition to major fractured zones, numerous lineaments were identified on aerial photographs and confirmed in the field. Major fractured zones are associated with open fractures where lineaments show similar open fracture characteristics. Some of the fractured zones appear closed towards the northwest, in the proximity of the melilite basalt intrusive body. Several structures within the study area were classified as major fractured zones and later referred to as conduit zones. These structures are summarised in Table 5 and shown spatially in Figure 26.

Table 5: Major geological fractured zones evident in the study area

ID	Type	Orientation	Strike length (m)
F1	Fracture zone	NE - SW	5 764
F2	Fracture zone	NE - SW	4 337
F3	Fracture zone	NE - SW	11 965
F4	Fracture zone	NE - SW	547
F5	Fracture zone	NW - SE	2 165
F6	Fracture zone	NE - SW	2 409
F2.1	Fracture zone	NE - SW	1 860
F7	Fracture zone	NE - SW	854
F5.1	Fracture zone	NW - SE	790

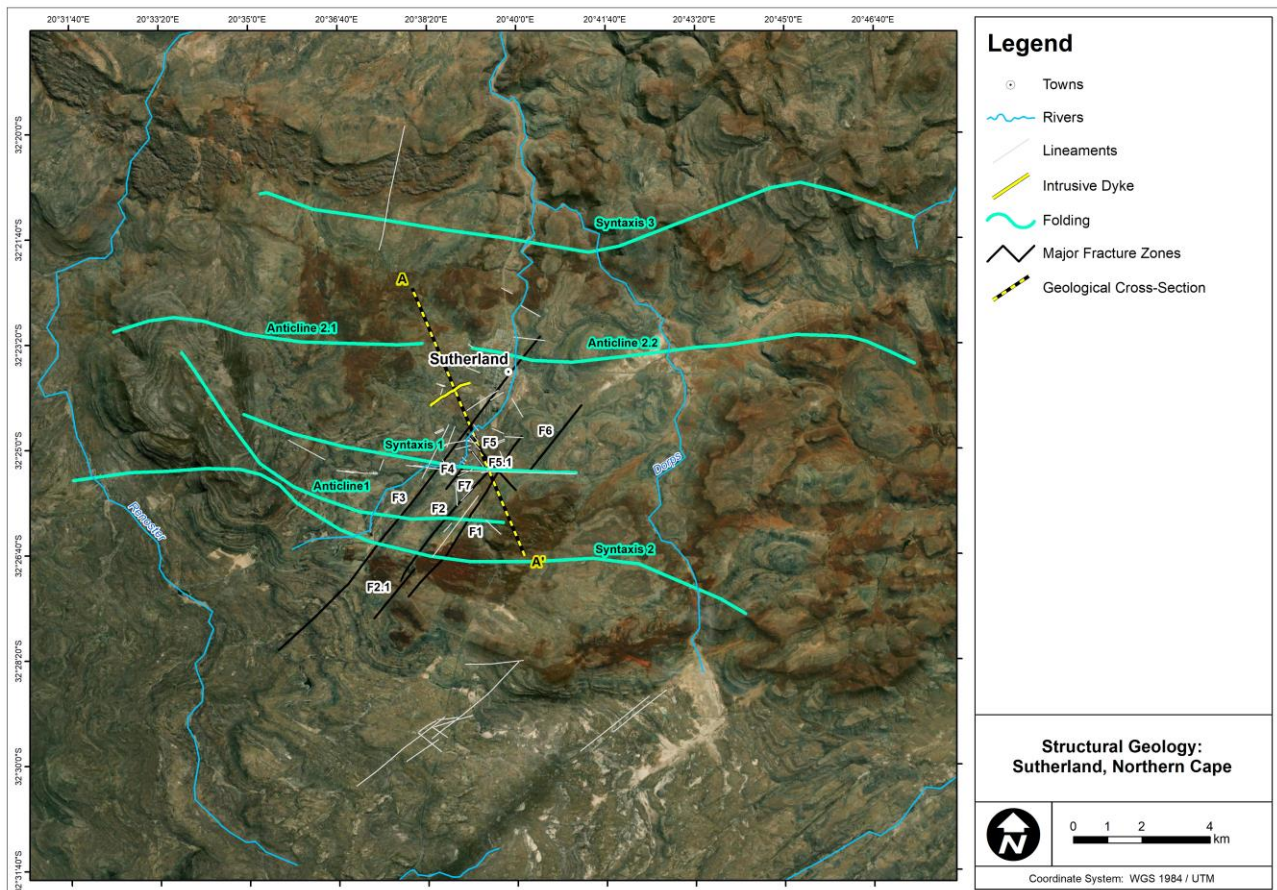


Figure 26: Map showing major and minor lineaments and folding axis evident in the area

5.2.2 Geophysics

The geophysics was completed along a total of six electromagnetic method (EM) traverses and a single electrical resistivity tomography (ERT) traverse within the study area. The EM method was used to confirm the locations of major linear features evident on aerial photographs, at the two depths of investigation allowed by surveying with two different loop orientations. The EM traverses crossed the major geological structures identified in the Southern Wellfield area. The surveys were done using a 40-meter coil spacing during the process of identifying drill targets for the production wells. The recorded apparent conductivity data revealed clear anomalies that coincided with the major structures within the Southern Wellfield, as discussed below.

The ERT survey was conducted in a south-east/north-west direction perpendicular to a north-east/south-west trending linear feature, and across an east/west trending syncline covered by alluvial and unconsolidated material as mapped in the 1:250 000 geology map series. The purpose of the ERT survey was to investigate these geological features in more detail to identify potential drilling targets. The positions and orientation of the geophysical traverses are shown in Figure 27 and summarised Table 6.

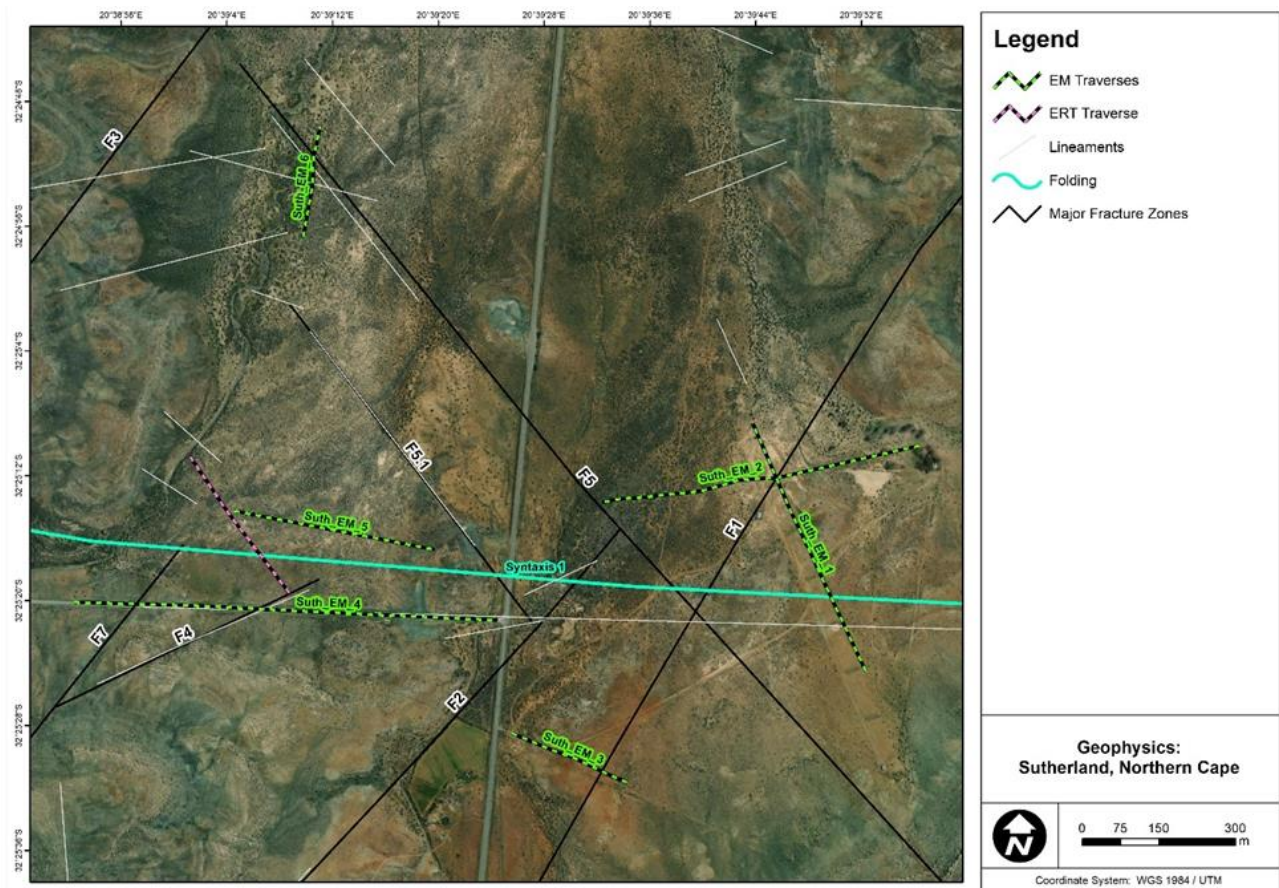


Figure 27: Positions and orientations of the geophysical traverses across the mapped geological structures

Table 6: Summary of geophysics completed

ID	Start		End		Length (m)
	Latitude (DD, WGS 84)	Longitude (DD, WGS 84)	Latitude (DD, WGS 84)	Longitude (DD, WGS 84)	
Electromagnetic method					
Suth_EM_1	-32.42353	20.66450	-32.41911	20.66212	540
Suth_EM_2	-32.41952	20.66563	-32.42052	20.65897	640
Suth_EM_3	-32.42461	20.65706	-32.42550	20.65948	250
Suth_EM_4	-32.42226	20.64787	-32.42261	20.65675	840
Suth_EM_5	-32.42064	20.65125	-32.42134	20.65545	400
Suth_EM_6	-32.41380	20.65309	-32.41577	20.65271	220
Electrical Resistivity Tomography method					
ERT Traverse 1	-32.422116	20.652402	-32.419662	20.650303	355

5.2.2.1 EM Traverses; Suth_EM_1, Suth_EM2 & Suth_EM_3

Three EM traverses were completed across major structure F1 visible on aerial photographs to confirm its location in the field, especially where it is not exposed on the surface due to surficial and alluvial cover.

The data for Suth_EM_1 were acquired from the south-south-west towards the north-north-east crosscutting major fractured zone F1. The area investigated is generally overlain by a thin alluvial

cover and weathered bedrock, with the occurrence of fractured sandstone bedrock towards the east of major structure F1 and the higher-lying areas. With the horizontal dipole (HD) orientation, an average apparent conductivity of 14.79 mS/m was measured, while the vertical dipole (VD) orientation revealed a slightly higher average of 15.11 mS/m (Figure 28). The HD measurements generally show similar conductivity values across most of the traverse, but a local increase in the apparent conductivity data is observed around stations 85 – 100, peaking near station 95. The VD data also reveal a more conductive zone towards the end of the traverse, measuring an amplitude high at station 90 of 24.88 mS/m. The conductive zones identified in the HD and VD data correlate well with the location of major structure F1 (Figure 28).

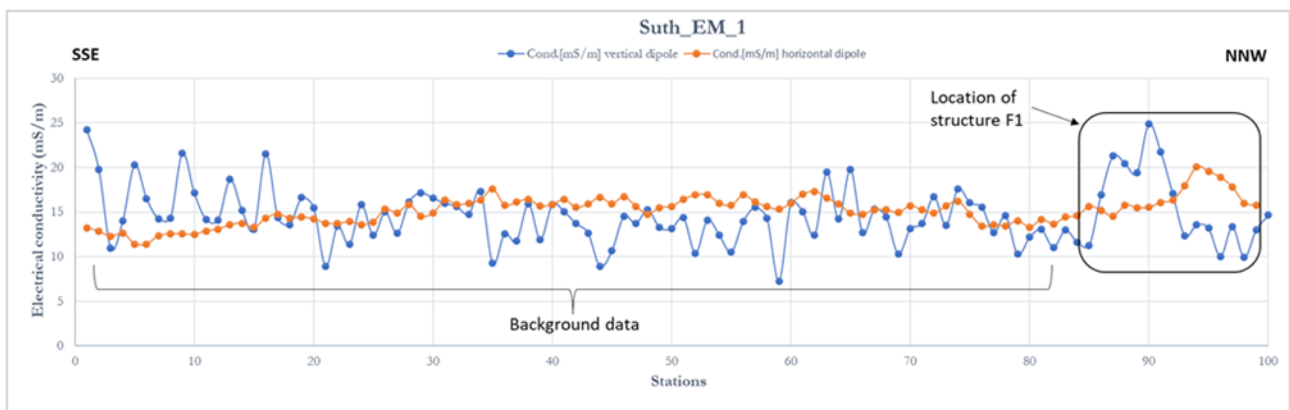


Figure 28: Apparent conductivity data recorded along traverse Suth_EM_1

The data for Suth_EM_2 were acquired from the east towards the west perpendicular to Suth_EM_1 (Figure 27), crosscutting major structure F1 to confirm its location and confirm the anomaly evident in the data of EM traverse Suth_EM_1. There is bluish grey fractured sandstone outcrop in the area investigated towards the east, likely covered by residual bedrock in line with major structure F1 and silt-rich alluvial material of the north draining non-perennial Dorps River. The average conductivity measured using the HD and VD orientations is around 18.88 mS/m and 15.39 mS/m, respectively, similar to the data of Suth_EM_1. In general, the data appear to be noisy; however, a definite anomaly is evident around stations 60 – 80, correlating with the location of major structure F1. The VD data show a general decrease in the measured apparent conductivity with an amplitude low at station 71 measuring 5.36 mS/m. The HD orientation shows a generally higher apparent conductivity in the larger area from stations 50 – 100; however, no clear anomaly is observed in this zone.

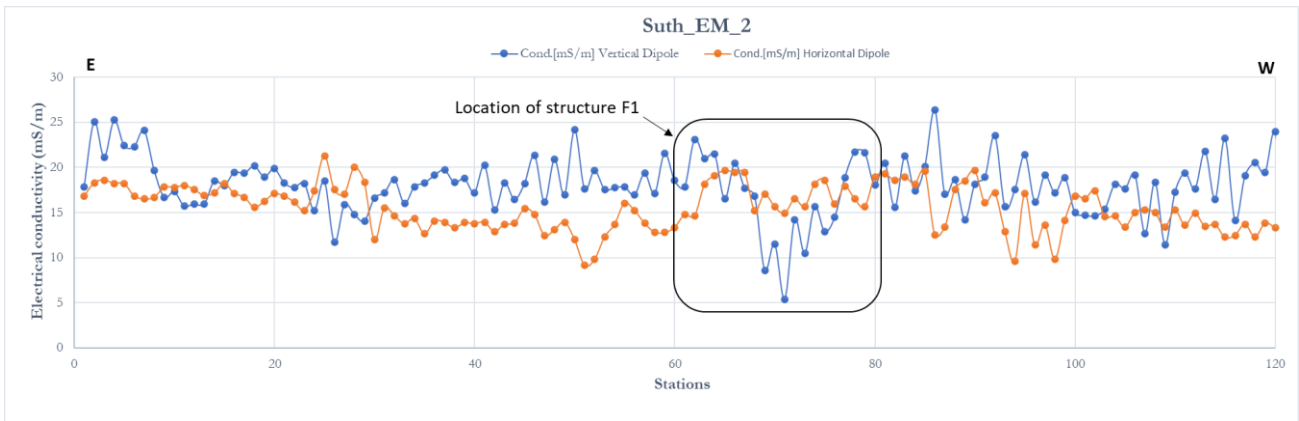


Figure 29: Apparent conductivity data recorded along traverse Suth_EM_2

The data for EM traverse Suth_EM_3 were recorded up-gradient (towards the south) from traverses Suth_EM_1 and Suth_EM_2, perpendicular to the major structure F1 (Figure 27). The data were acquired from west-north-west towards east-south-east. The recorded data show very similar trends to the previous two EM traverses, with average apparent conductivity values of 19.8 mS/m and 19.01 mS/m for the HD and VD orientations, respectively. Around stations 30 – 45 the data show a general increase in measured conductivity using the HD orientation and a correlating decrease using the VD orientation, measuring an amplitude high and low of 25.33 mS/m and 13.19 mS/m, respectively (Figure 30). This zone correlates well with the location of the major structure F1.

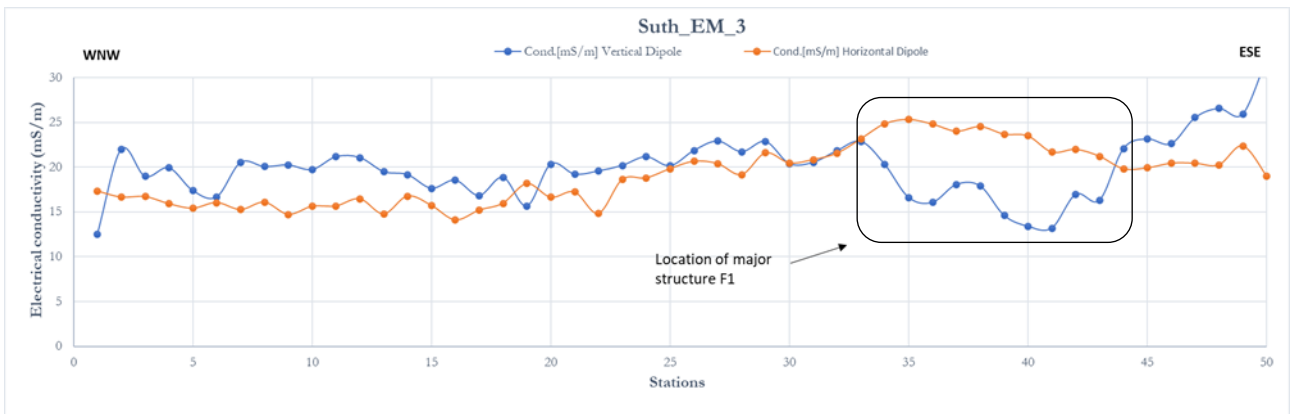


Figure 30: Apparent conductivity data recorded along traverse Suth_EM_3

5.2.2.2 EM Traverses; Suth_EM_4, Suth_EM_5 & Suth_EM_6

The data for EM traverses Suth_EM_4, 5 and 6 were acquired in an area generally overlain by surficial cover and alluvial material. The surveys on these traverses were conducted with the aim to confirm the location of major and minor structures F4 and F5.

The data for EM traverse Suth_EM_4 were acquired from the west toward the east along a gravel road. The data show a significantly higher apparent conductivity for the VD measurement compared to the other traverses, due to the cultural effect of a fence and old telephone line running parallel to

the traverse. Despite this effect, the data were not noisy and were still deemed usable for interpretation purposes. The HD orientation measured an average apparent conductivity of 16.83 mS/m, while the VD orientation measured an average apparent conductivity of 63.6 mS/m. The VD data show a large decrease around stations 60 – 90 which correlates with an increase in the HD data. These anomalies correlate well with the location of major structure F4.

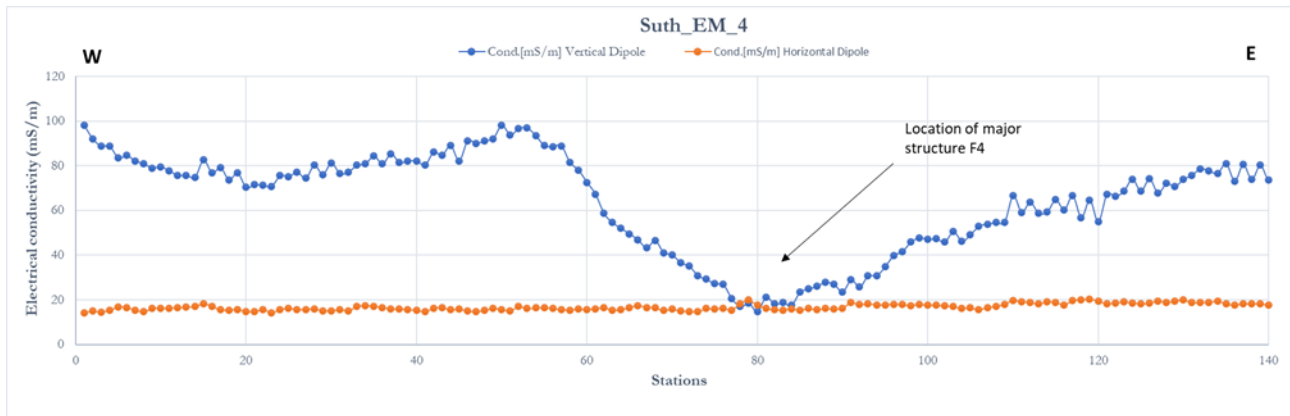


Figure 31: Apparent conductivity data recorded along traverse Suth_EM_4

The data for EM traverse Suth_EM_5 were acquired from the west towards the east, parallel to Suth_EM_4, crossing major structure F4. To minimise cultural effects in the data, this traverse was positioned farther to the north, away from any infrastructure. Average apparent conductivities of 17.0 mS/m and 15.8 mS/m were measured with the VD and HD orientations, respectively. The location of major structure F4 was confirmed around stations 60 – 75, where the VD data show a general decrease in measured conductivity corresponding to a slight increase in the HD data.

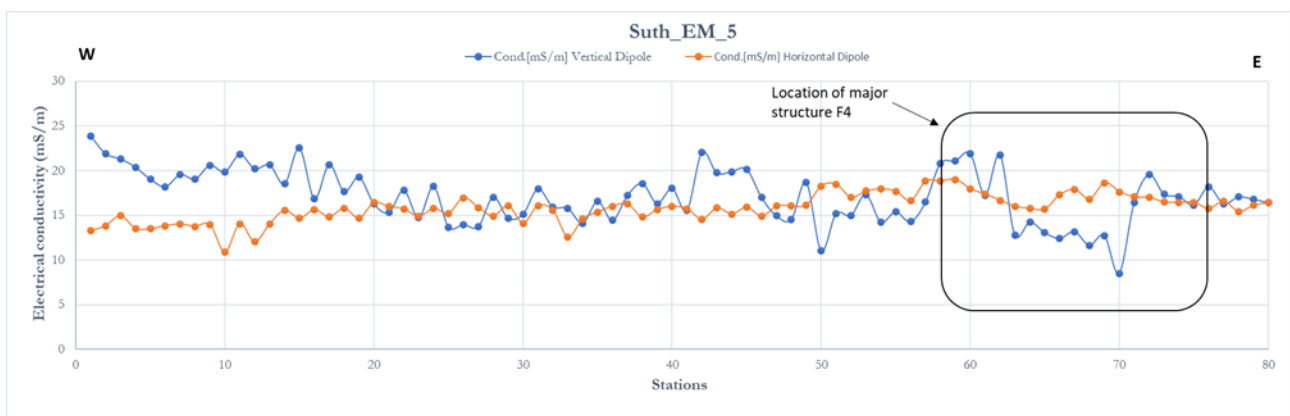


Figure 32: Apparent conductivity data recorded along traverse Suth_EM_5

The data for EM traverse Suth_EM_6 were acquired from the north to the south close to where major structure F5 outcrops in a dry riverbed. Structure F5 is traversed between stations 0 – 20, where the VD data show a local decrease in the measured apparent conductivity, corresponding to an increase in the HD data. Farther to the south, both the VD and HD data display gradually decreases towards

the end of the traverse. The average apparent conductivity value for the HD orientation is around 14.6 mS/m while the average for the VD orientation is 21.9 mS/m.

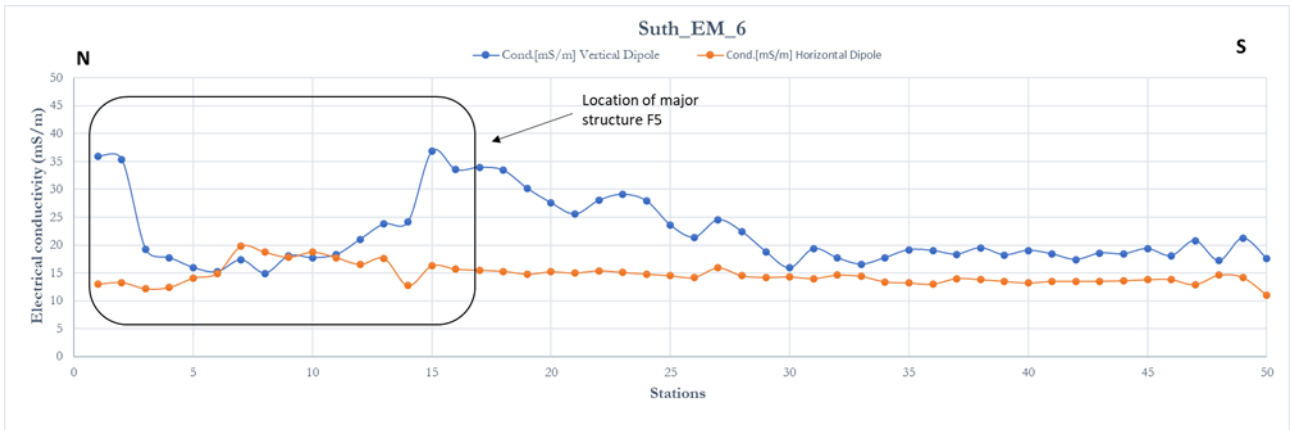


Figure 33: Apparent conductivity data recorded along traverse Suth_EM_6

5.2.2.3 ERT Traverse 1

The inverse resistivity model for the data recorded along ERT Traverse 1 is shown in Figure 34.

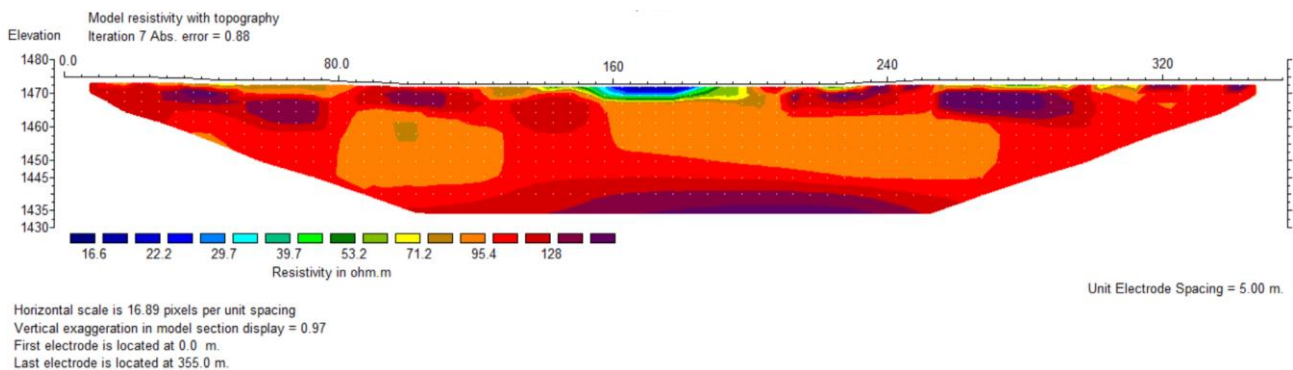


Figure 34: Data shown for ERT Traverse 1 completed in the Southern Wellfield area

Based on the modelled resistivity values, the subsurface can be divided into several homogenous zones with similar physical characteristics. The resistivity values are interpreted as follows:

- **Very low.** Dark blue to light blue contours values (16.6 Ωm – 6.51 Ωm) are likely indicative of clay-rich material and highly weathered bedrock at shallow depth (<10 m).
- **Low.** Green to yellow contour values (6.52 Ωm – 144 Ωm) at shallow depth are likely indicative of clay-rich unconsolidated material, grading into highly to moderately weathered bedrock with depth. Around stations 170 – 190 this extends to the full depth of investigation, likely indicative of moderately weathered and fractured gritstone.

- **Medium.** Brown to orange contours values (145 Ωm – 403 Ωm) values at shallow depth are likely indicative of moderately weathered siltstone, grading into competent bedrock with depth.
- **High.** Red to purple contours values (404 Ωm – 1135 Ωm) at shallow depth are likely indicative of sandy unconsolidated material. At depths >5 m this is likely indicative of gritstone with little to no weathering.

The inverse resistivity model obtained for ERT Traverse 1 shows a relatively uniform subsurface with no clear structures. The ERT method, therefore, appears not to be the ideal method for detecting and delineating the vertical structures that occur in the area. The inverse model shows a relatively shallow depth to bedrock across the traverse with a possible increase towards the centre of the modelled section, which correlates well with the topographic low and braided alluvial area visible in aerial photographs. The data show sub vertical steps in the data around 80 m – 85 m, 125 m – 135 m and 250 m – 260 m, likely associated with fractured zones within the bedrock.

5.3 HYDROCENSUS

The boreholes identified during the hydrocensus are shown spatially in Figure 35 and details pertaining to these boreholes are summarised in Table 7. A total of seven boreholes were identified within the area. Most of the boreholes are used for agricultural purposes supplying water for stock and some for-crop irrigation purposes. Two boreholes are existing production boreholes utilised for town supply, however, showing trends of dropping water levels and a general decline in yield. There is uncertainty with regard to the reliability of yields communicated by the landowners as no records are available for pumping tests completed.

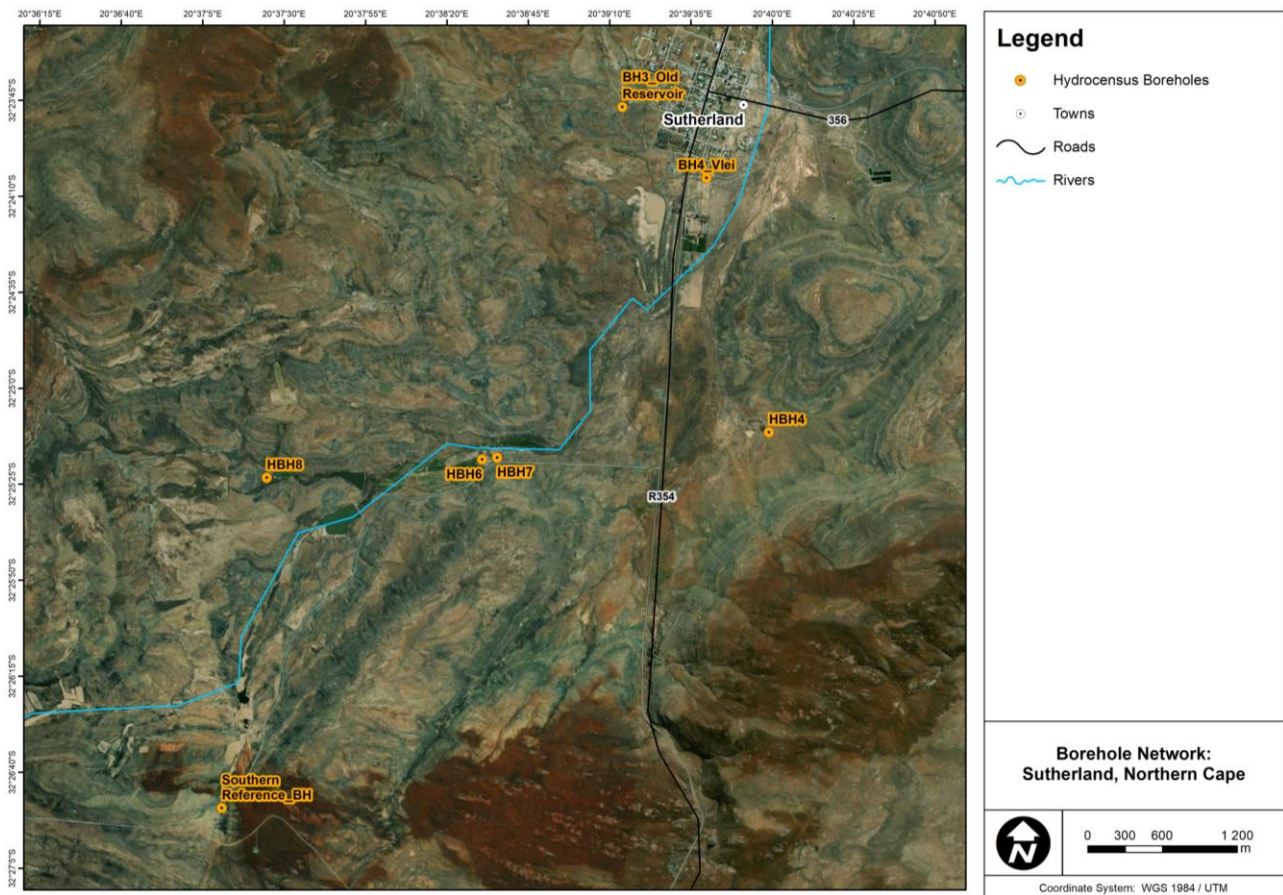


Figure 35: Borehole network around the Sutherland Southern Wellfield area

Table 7: Summary of boreholes in the study area

Site ID	Elev (mamsl)	Lat (WGS 84)	Long (WGS 84)	Depth (mbgl)	RWL (mbgl)	Yield (L/s)	EC (mS/m)	pH	TDS (mg/L)	Comment
BH4_Vlei	1469	-32.40162	20.66102	44	21.63	4.2	103	7.5	699	Used for town supply. Pumped 16 hours per day.
HBH4	1477	-32.42004	20.66628	-	12.20	1.2	178	7.6	910	Used for stock watering. Equipped with a "windpomp".
HBH6	1486	-32.42195	20.64179	150	22.50	22.0	177	7.0	850	Equipped with a submersible pump. No pumping test data available. Yield likely reported as airlift yield.
HBH7	1484	-32.42181	20.64308	150	23.00	17.0	179	7.0	860	Equipped with a submersible pump. No pumping test data available. Yield likely reported as airlift yield.
Southern Reference_BH	1595	-32.44710	20.61946	-	12.00	1.0	42	7.1	280	Equipped with a "windpomp".
HBH8	1517	-32.42321	20.62340	150	18.00	15.0	-	-	-	Yield likely the airlift yield. No pumping test data available.
BH3_Old Reservoir	1476	-32.39647	20.65387	120	72.39	3.0	112	8.3	757	Used for town supply with dropping operational water levels. Pumped 4 hours per day due to dropping water levels.

5.4 BOREHOLE DRILLING

During the drilling programme, 11 boreholes were drilled at selected locations. The boreholes served multiple purposes. First, all boreholes were considered *investigative boreholes* to gain information

on the geological and geohydrological conditions in the subsurface with the aim of improving the conceptual model of the area. Second, selected boreholes with adequate yields were subjected to hydraulic testing, while others simultaneously served as *observation boreholes*. Depending on the results of the hydraulic tests, some boreholes were selected to be used as *production boreholes*. Furthermore, three of the boreholes were drilled at suitable locations to act as *managed aquifer recharge (MAR) boreholes*, targeting the structures in which the production boreholes were drilled or the matrix adjacent to these structures. The positions of the boreholes drilled during the current study are shown in Figure 36 while Table 8 provides information on these boreholes.

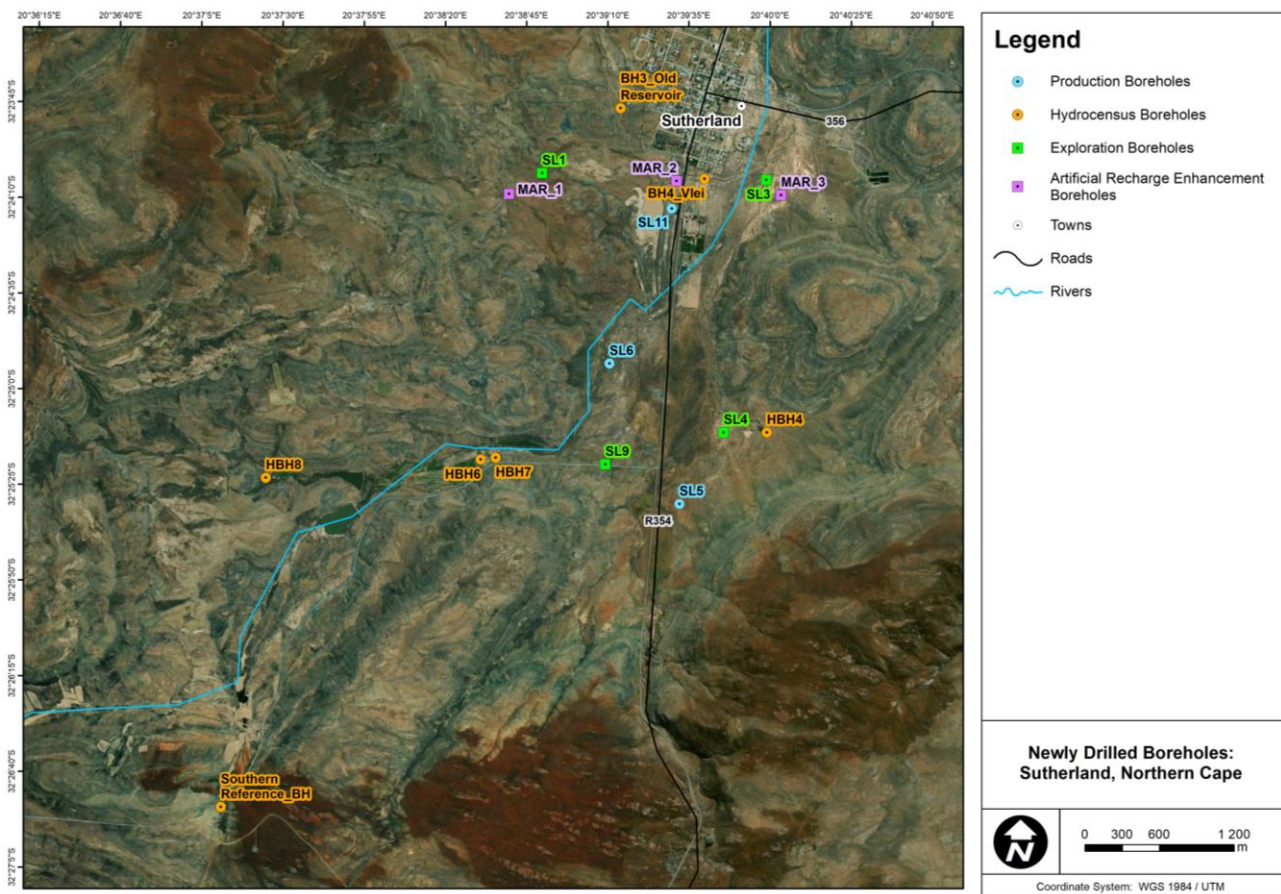


Figure 36: Positions of the newly drilled boreholes relative to the existing boreholes identified during the hydrocensus

All boreholes were drilled using down-the-hole (DTH) air percussion drilling, through overburden and residual bedrock followed by the installation of mild steel casing to prevent collapse in the shallow subsurface. The boreholes were then completed to their final depths by means of DTH air percussion drilling. If the borehole showed signs of collapse after drilling, an inner uPVC casing with screens at water-bearing zones was installed along with casing centralisers.

During drilling, geological drill samples were collected every meter along with the airlift yield and quality of groundwater intersected at different depths. Detailed geological logs pertaining to the

geology, airlift yields, drilling proceedings and borehole constructions are presented in **Appendix A**. The depths of the exploration boreholes ranged from 121 m to 151 m to intersect deeper fractured zones. The drilling depths of the MAR boreholes were based on the geological conditions intersected in the nearby exploration holes and ranged from 50 m to 90 m.

Table 8: Details pertaining to boreholes drilled during the study

BH	Latitude (DD, WGS 84)	Longitude (DD, WGS 84)	Depth (m)	Fracture depths (mbgl)	Main water strike/s (mbgl)	Airlift yield (L/s)	EC (mS/m)
SL1	-32.40117	20.64714	151	8,13, 103, 112, 122	112, 122	5.59	178
SL2	-32.38874	20.65532	151	25, 82	89	1.05	71
SL3	-32.40171	20.66632	151	85, 89, 132	89	3.88	78
SL4	-32.42004	20.66260	151	24, 47, 55,122	47	8.99	75
SL5	-32.42522	20.65880	121	21, 33, 56 - 59, 62, 67, 68, 82	62, 67, 68	11.94	59
SL6	-32.41500	20.65286	121	8, 17, 21, 34, 40, 55 – 71, 96, 107	97, 107	17.22	55
SL9	-32.42231	20.65247	100	69, 85	65	6.88	69
SL11	-32.40378	20.65822	103	13, 35, 57, 80, 100	82	11.94	74
MAR_1	-32.40266	20.64431	50	8, 13	13	1.2	60
MAR_2	-32.40177	20.65863	50	42	42	0.38	76
MAR_3	-32.40229	20.66646	90	-	-	0.23	74

5.5 DOWN-THE-HOLE CAMERA INSPECTION

The down-the-hole camera inspection provided useful information pertaining to the subsurface geological conditions. In general, all of the boreholes drilled were in good condition. During the inspections, some of the boreholes showed fragments of rocks stuck in the fractured zones. These were later opened up and uPVC casing was installed to keep the hole open. Most of the boreholes were open rock holes with the exception of SL3 and SL4, which already had an inner 127 mm ID uPVC casing installed from the top to the bottom of the hole due to the noticeable risk of collapse during drilling. A summary of the findings made during the down-the-hole camera inspection is provided in Table 9 and more detailed images of the down-hole camera logs are presented in **Appendix C**.

Table 9: Summary of down-the-hole camera inspection

BH	Depth (m)	Casing depth (m)	Casing type	Water level (m)	Fracture depths (m)	General condition	Comments
SL1	151.3	3.5	Steel	65.5	8,13, 103, 112, 122	Good	Water ingress at 8.26 m. Gas bubbles from 141.5 m
SL3	150.6	150.6	uPVC	21.03	85, 89, 132	Good	uPVC casing installed from the top to bottom of hole. Slight iron build up in borehole.
SL4	146.6	146.6	uPVC	12.89	24, 47, 55, 122	Good	uPVC casing installed from the top to bottom of hole. Slight iron build up in borehole.
SL5	121	6.97	Steel	23.46	15, 21, 33, 56 – 59, 61, 71, 82	Good	Main fractured zone 56 - 59.
SL6	121	5.8	Steel	24	21, 33, 56 - 59, 62, 67, 68, 82	Collapse issues, generally good	uPVC installed after camera log was completed
SL9	100	1.82	Steel	28.9	72, 85	Collapse issues at 73 m	Generally good with loose rock in fracture at 73 m.
SL11	2.71		Steel	23.5	13, 25, 35, 57, 80, 100	Good	Quartz crystal growth in cavities. Example included in pictures

The observations made during the camera inspections correlate well with the geological information logged during the drilling process. In terms of the hydrogeological conditions, the down-the-hole camera inspections confirmed the presence of a well-developed fractured network. All the boreholes intersected numerous fractured zones, rather than single fractures that were water-bearing. At shallow depths, above the water table, numerous fractures were observed, some with water seeping through the openings and others with water cascading down the borehole. The water entering the boreholes was likely associated with the precipitation event a few days before the inspection and was therefore probably a manifestation of recharge to the aquifer system. This was considered a positive sign considering the status of the aquifer during the study and further motivates the potential for establishing an artificial recharge enhancement scheme.

The horizontal nature of bedding is evident across all the boreholes and has been highly altered in some of the fractured zones. In general, water strikes intersected during drilling are associated with large open fractures, with the formation of cavities in some cases. Figure 37 shows screenshots from the camera inspection within borehole SL11. Fractures with apertures ranging between 1 cm and 5 cm are evident in these screenshots.



Figure 37: Screenshots of large open fractures in borehole SL11. Left: down-hole view of a fracture at 56.72 m, right: a side view of a fracture at 61.53 m

With the drilling of SL11, the water-bearing fractured zone was intersected at a depth of around 24 mbgl to 25.5 mbgl. The down-hole camera inspections showed that within the fractured zone, there was clear evidence of quartz crystal growth (Figure 38). Some of the quartz crystals on rock fragments were also found during the drilling process in the cuttings (Figure 39).



Figure 38: Fractured zone intersected with quartz growth in the fracture openings



Figure 39: Quartz crystals on fractured zone drill chips from the drilling of borehole SL11

5.6 GROUNDWATER LEVELS

Groundwater levels were measured at a total of 16 boreholes from the borehole network and converted to mamsl. In Figure 40, the surface elevation at each borehole is plotted against the measured hydraulic head. A generally good correlation between the topography and the head is observed. The only exceptions are at boreholes SL1 and BH3 where very deep water levels are observed. These two boreholes are likely hydraulically connected since they occur along the same fracture zone (F3). The deep water levels at these boreholes are likely due to groundwater abstraction from BH3 for municipal supply and therefore do not represent static conditions. Excluding boreholes, SL1 and BH3 give a linear correlation of 99.0% between the measured hydraulic heads and the topographic elevations of the boreholes (Figure 40).

To generate a groundwater level contour map and to determine the groundwater flow direction in the study area, the Tripol software package was used to perform a Bayesian interpolation of the groundwater level data. Boreholes SL1 and BH3 were excluded due to the very deep water levels at these boreholes. The hydraulic head contour map (Figure 41) indicates that groundwater flow is generally from the south-west towards the north-east, in the same direction as the general topographic gradient and the major north-east/south-west trending fractured zone.

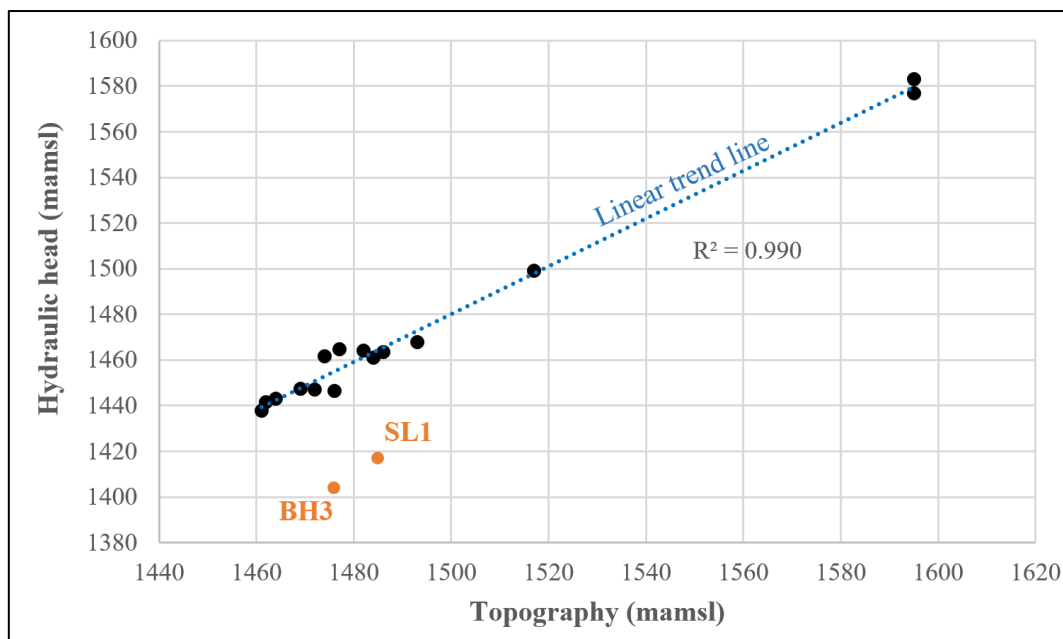


Figure 40: Correlation between topographic elevation and hydraulic head measured in the boreholes

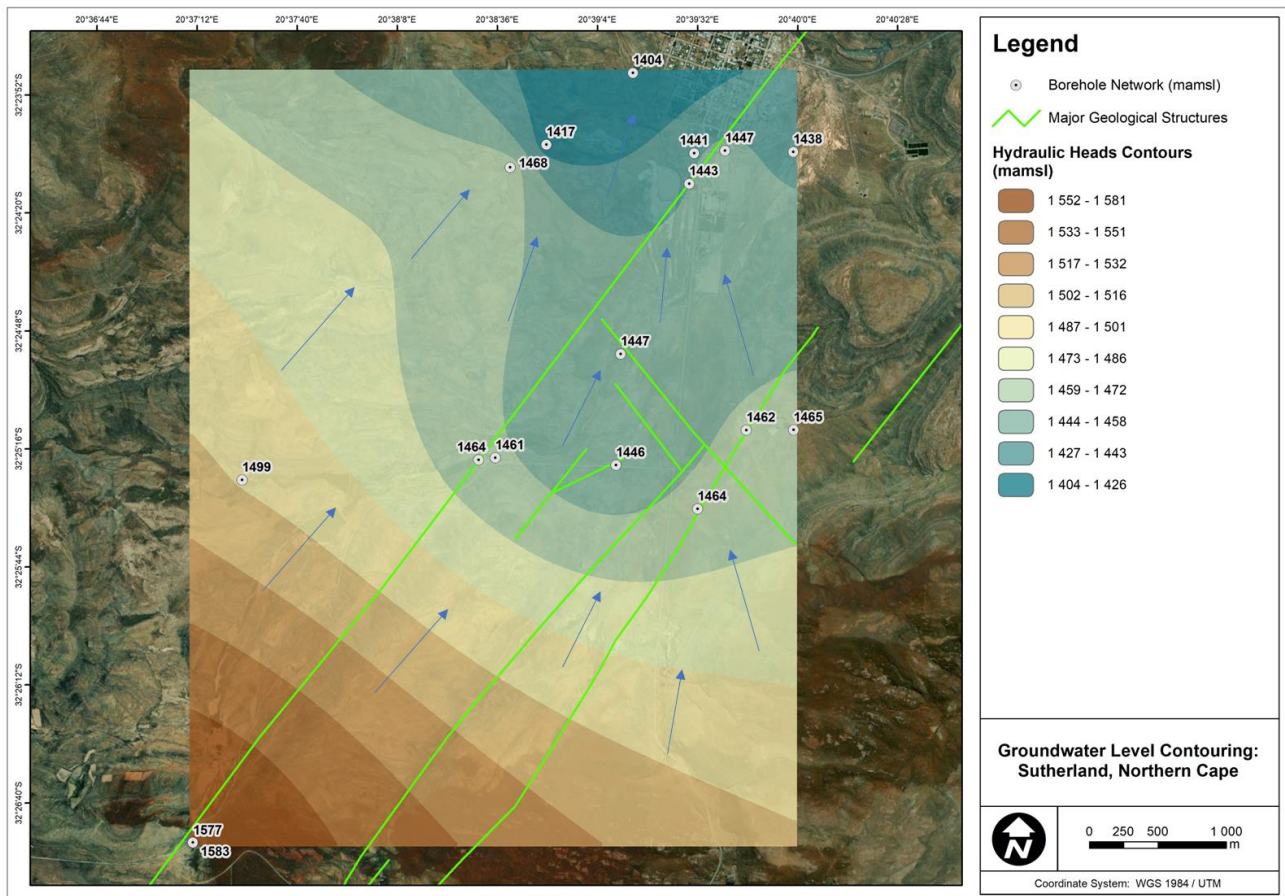


Figure 41: Groundwater level contour map and groundwater flow directions as determined from the interpolated groundwater levels measured at boreholes in the study area

5.7 HYDRAULIC TESTING RESULTS

The aim of the hydraulic tests was to 1) gain information on the aquifer hydraulic parameters, and 2) estimate the volume of water that could be sustainably abstracted from the respective boreholes, should recharge to the aquifer be minimal to zero for an extended period of time. An abstraction period of 10 years was considered.

Six exploration boreholes were hydraulically tested by means of pumping tests and a single modified injection test was completed at one of the potential MAR boreholes. During the pumping tests, the groundwater levels in nearby (observation) boreholes were monitored where such boreholes were available. The raw pumping test data used for the analysis are presented in the order of testing in **Appendix B**. Pumping test data were analysed in borehole clusters and individually. Where available, additional data were used to estimate aquifer parameters. Table 10 provides a summary of boreholes subjected to pumping tests and lists site-specific testing details.

Table 10: Summary of yield testing of individual boreholes

BH	Depth (m)	Discharge rates (L/s)						Duration of CDT (min)	Static water level (mamsl)	Step test max drawdown (mbgl)	CDT max drawdown (mbgl)
		Airlift yield	Step 1	Step 2	Step 3	Step 4	CDT				
SL1	150	5.59	0.8	2.5	5.0	3.5	3	4320	1417.00	120.09	107.23
SL3	150	3.88	3.0	4.1	-	5.0	2	4320	1437.75	95.98	59.44
SL4	147	8.99	3.1	5.1	6.2	6.2	6	4320	1461.73	15.81	18.00
SL5	121	11.94	4.6	9.2	13.8	15.2	14	3690	1464.00	23.52	28.49
SL6	121	17.22	3.0	4.0	5.5	5.5	5	4320	1447.00	27.49	28.62
SL11	121	11.94	3.4	9.1	14.1	18.1	16	4320	1443.00	24.08	26.17

5.7.1 Pumping tests on boreholes SL1

Borehole SL1 was drilled into a north-east/south-west trending linear feature, likely associated with dyke intrusion during the same time as the melilite basalt intrusion, located just towards the north. Figure 42 shows the testing rig set-up at the borehole during the testing.



Figure 42: Yield testing at SL1 (authors own)

The step test commenced on 14 November 2021. The test pump was installed at a depth of 120.83 mbgl. The rest water level (RWL) at the start of the test was 68.97 mbgl. During the step test, the water level was drawn down 51.12 meters below the rest water level (pump inlet) during the third step at a pumping rate of 5.0 L/s. Thereafter, the borehole was allowed to recover to 1.89 m below the RWL (70.86 mbgl), before a fourth step was started at a rate of 3.5 L/s where the water was drawn down to 17.70 m below the RWL (86.67 mbgl). The water level in the borehole was then allowed to recover to 0.88 m below the RWL (69.85 mbgl).

Figure 43 shows the drawdown over time during the different stages of the step and recovery tests. The pumping rates used during the step test are also indicated in this figure. The data show an early-time drop in water level in each step after which there is a small and gradual decline with time towards the end of the step. During the third step, the early-time drop in the water level continued until it reached the pump inlet, unlike the other steps.

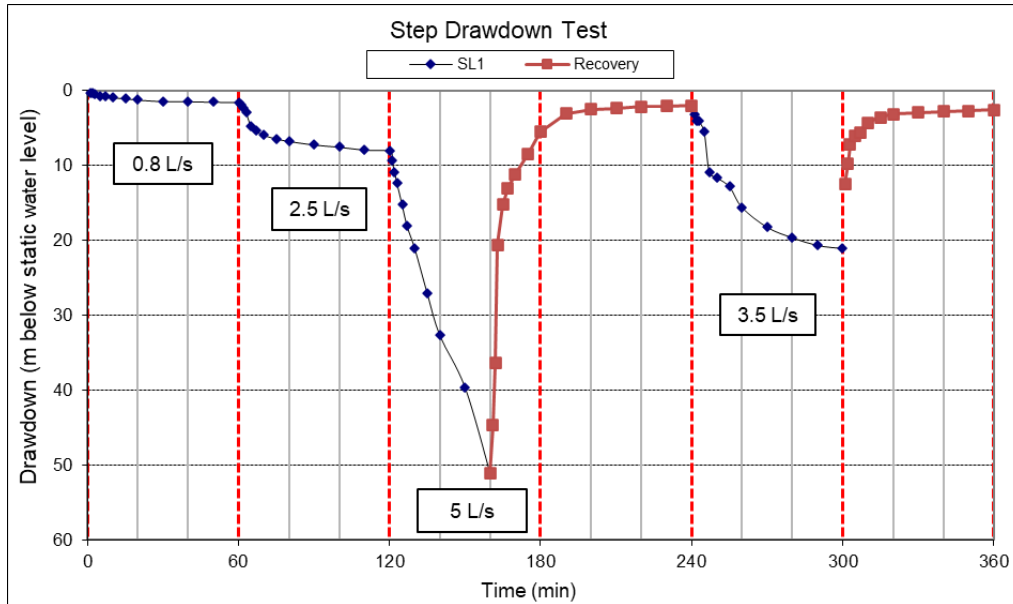


Figure 43: Step Test drawdown curve for SL1 and recovery

Based on the step test results, and by considering fracture depths and borehole construction, the CDT was conducted at a rate of 3 L/s. After the 72-hour period, the water level had drawn down to 38.26 m below the RWL (108.11 mbgl). The drawdown data along with the recovery data are presented in Figure 44. After 2040 minutes of pumping the water level in borehole SL1 shows a steeper drawdown curve towards the end of the test, likely associated with the dewatering of a fracture at a depth of 109 mbgl (Figure 44).

The aquifer parameters were estimated through drawdown response monitoring in the production borehole SL1, by fitting the Theis solution curve. The transmissivity obtained was correlated with the transmissivity estimated from the recovery data. In the semi-log plot of the drawdown data, a fit was obtained for the late-time data (720– 3000 minutes), which yielded an estimated T -value of 6.2 m²/day (Figure 45). This correlates well with the T -value calculated from the late-time recovery data (1080 – 1800 minutes) of 7.5 m²/day. During the late time fit (1000 – 4320 minutes) of the Theis solution to the drawdown data, a storativity of 1.63×10^{-2} was estimated. An available drawdown of 40 m was used for calculating the sustainable yield of the borehole.

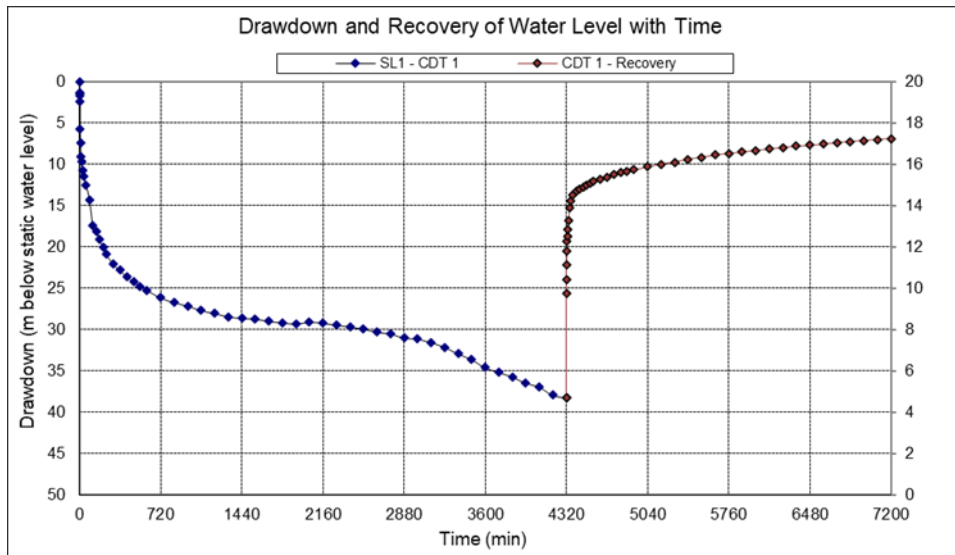


Figure 44: Time-series drawdown and recovery for SL1

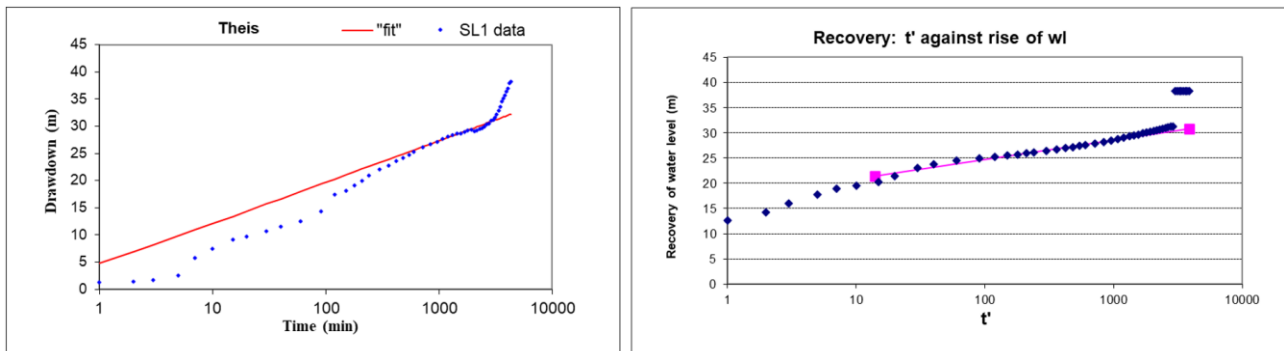


Figure 45: Left: Theis fit to the drawdown data recorded in borehole SL1 during pumping, right: recovery graph of SL1 applying Theis to determine Transmissivity.

5.7.2 Pumping tests on boreholes SL3

Borehole SL3 was drilled in a lower-lying area where the surface is largely covered by alluvial material that could potentially act as storage, retaining surface water flows and thus a good source of recharge to the underlying fractured bedrock. Figure 46 shows the testing at SL3 while the hydrogeologist is checking water levels during the CDT.

The step test commenced on 31 October 2021. The test pump was installed at a depth of 60.3 mbgl. The RWL at the start of the test was 21.66 mbgl. During the step test, the water level was drawn down 38.61 meters below the RWL (to the pump inlet) in the second step at a pumping rate of 4 L/s. Thereafter, the borehole was allowed to recover to 3.71 m below the RWL (25.37 mbgl). The pump was then re-installed to a depth of 96.73 mbgl, before a fourth step was started at a rate of 5.0 L/s where the water was drawn down to 95.98 mbgl (to the pump inlet).



Figure 46: Pumping test at SL3 (author's own)

Figure 47 shows the drawdown over time during the different stages of the step and recovery tests. The pumping rates used during the step test are also indicated in this figure. The data show an early-time drop in water level in each step after which there is a small and gradual decline with time towards the end of the step. Throughout the second step, there was a clear trend of the water level dropping towards the pump inlet. After the restart of the test with a greater pump depth installation a similar trend was observed.

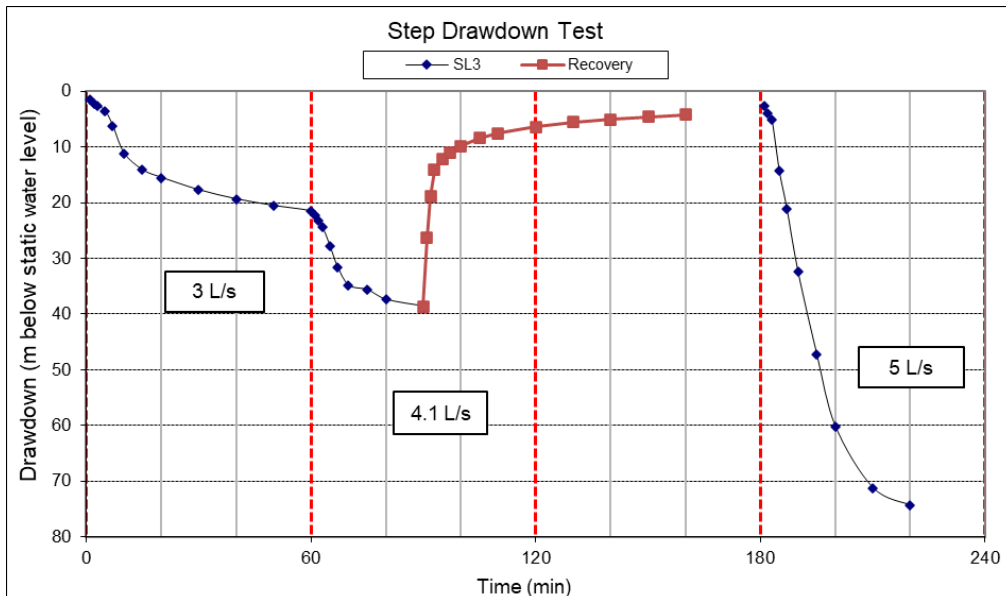


Figure 47: Step Test drawdown curve for SL3 and recovery

The water level recovered to 23.35 mbgl after the step test, before the CDT was started. Based on the results of the step test, the CDT was conducted at a rate of 2.0 L/s. During the CDT the water level

was drawn down to 37.78 m below the RWL (61.03 mbgl) after the 72-hour period of pumping. The drawdown and recovery data from the CDT are presented in Figure 48.

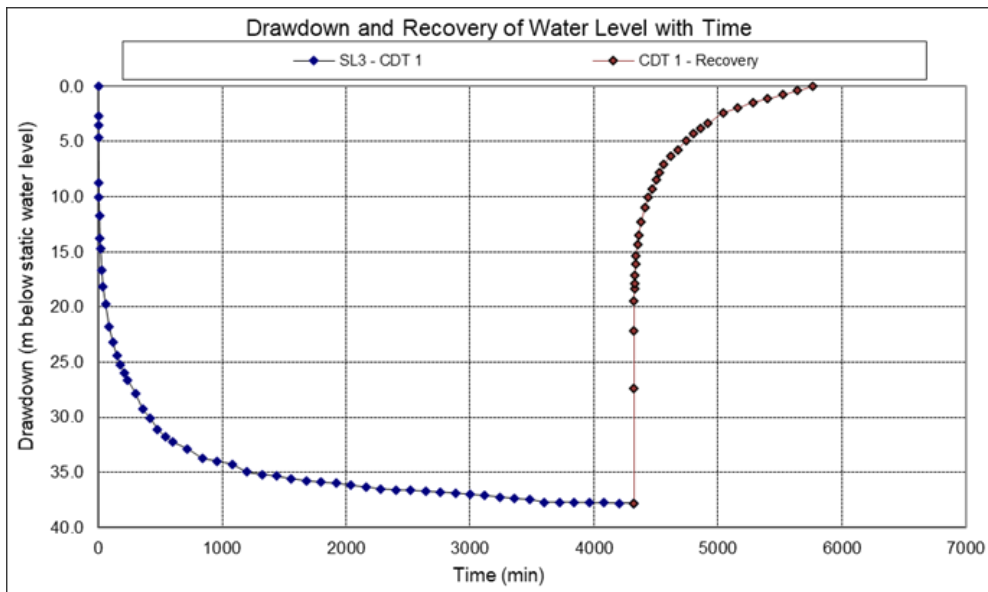


Figure 48: Time-series drawdown and recovery for SL3

The aquifer parameters were estimated through water level monitoring in the abstraction borehole by applying the Theis solution. The transmissivity thus obtained was correlated with the transmissivity estimated from the recovery data. In the semi-log plot of the drawdown data, a fit was obtained for the late-time data (480 – 3420 minutes), which yielded an estimated T -value of $2.8 \text{ m}^2/\text{day}$ (Figure 49). This correlates well with the T -value calculated from the late-time recovery data (120 – 1440 minutes) of $3.1 \text{ m}^2/\text{day}$. During the late time fit (480 – 3420 minutes) of the Theis solution to the drawdown data, a storativity of 4.11×10^{-3} was estimated. An available drawdown of 50 m was used for calculating the sustainable yield of the borehole.

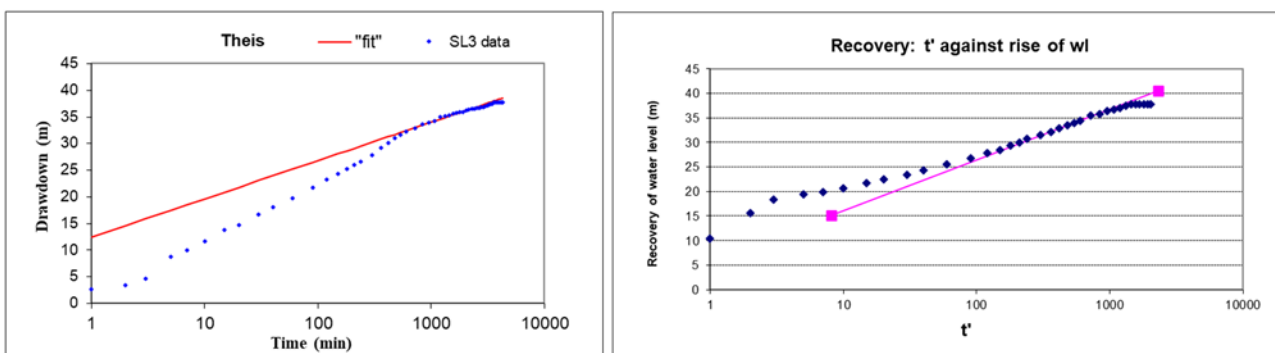


Figure 49: Left: Theis fit to the drawdown data recorded in borehole SL3 during pumping, right: recovery graph of SL3 applying Theis to determine transmissivity

5.7.3 Pumping tests on boreholes SL4 and SL5

Boreholes SL4 and SL5 were drilled into major structure F1 towards the far south of the town. These boreholes are separated by a distance of approximately 680 m. Borehole SL5 (1483 mamsl) is located 9 m higher in elevation than borehole SL4 (1474 mamsl) (Figure 50).

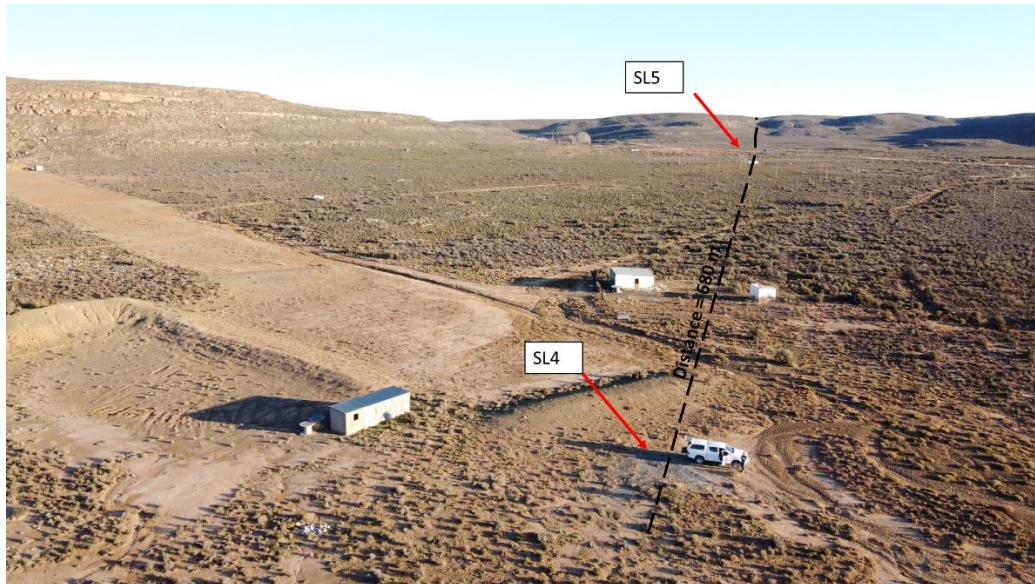


Figure 50: Positions of boreholes SL4 and SL5 on structure F1 (authors own)

5.7.3.1 SL4

The step test commenced on 8 November 2021. The test pump was installed at a depth of 72.20 mbgl, below the major water strike which occurred at 47 mbgl. The rest water level (RWL) at the start of the test was 12.27 mbgl. The pumping rate was limited by the inner diameter of the borehole (127 mm), resulting in the fourth step (extended third step rate) being completed at a rate of 6.2 L/s. For this step, the maximum drawdown in the borehole was 3.53 m below the RWL (15.8 mbgl). This drawdown was very small compared to the available drawdown in the borehole (~60 m to pump inlet). The water level in the borehole was then allowed to recover to 0.23 m below the RWL (12.5 mbgl).

Figure 16 shows the drawdown over time during the different stages of the step and recovery tests. The pumping rates used during the step test are also indicated in this figure. The data show an early-time drop in water level in each step after which there is a small and gradual decline with time towards the end of the step.

Based on the step test results, and by considering fracture depths and borehole construction, the constant discharge rate (CDT) rate for this borehole was chosen to be 6/0 L/s. This pumping rate was selected to stress the borehole. A very small response in relation to the available drawdown is evident in the data, where the water level was drawn down to 5.73 m below the RWL (18.0 mbgl) after the

72-hour pumping duration and allowed to recover for the time pumped (72 hours). During the testing of SL4 (1474 mamsl), water levels were monitored in borehole SL5 (1482 mamsl). Figure 52 shows the drawdown and recovery data for SL4 and the response measured in observation borehole SL5.

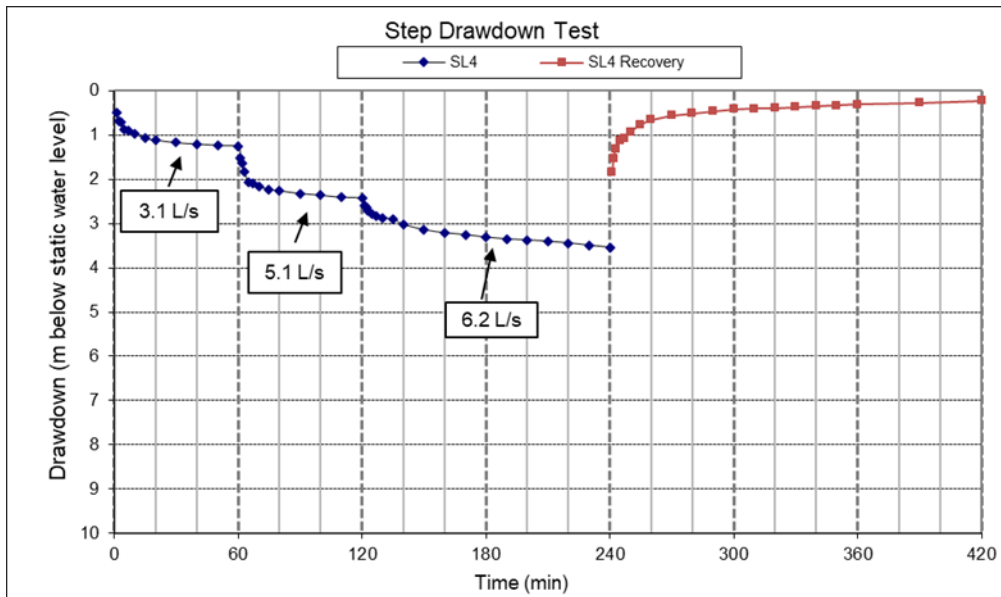


Figure 51: Step Test drawdown curve for SL4 and recovery

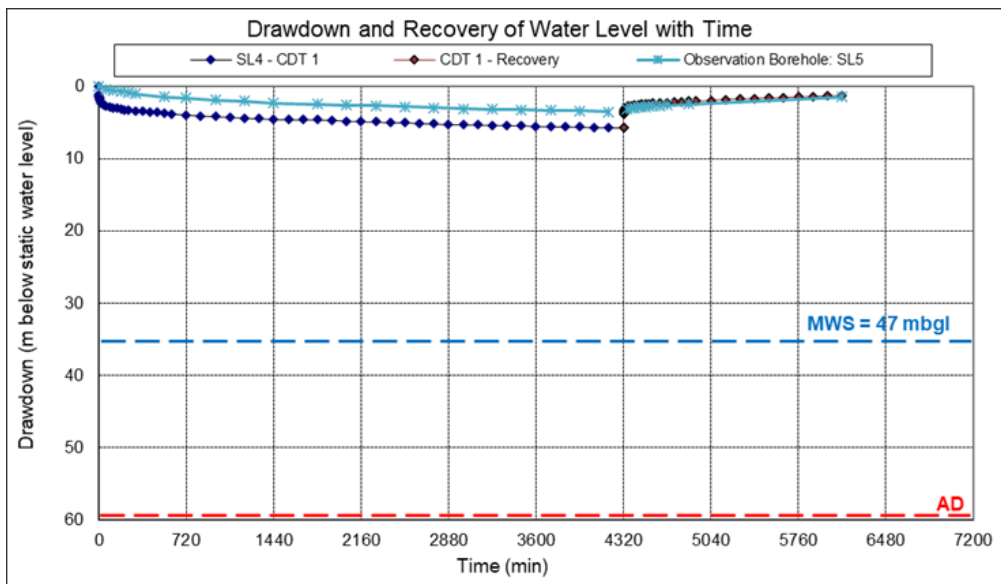


Figure 52: Time-series drawdown and recovery for SL4 and observation borehole SL5 in relation to main water strike (MWS) depth and available drawdown (AD)

The aquifer parameters were estimated through water level monitoring in observation borehole SL5 by applying the Theis solution. The transmissivity thus obtained was correlated with the transmissivity estimated from the recovery data. In the semi-log plot of the drawdown data, a fit was obtained for the late-time data (1000 – 4320 minutes), which yielded an estimated T -value of $33.7 \text{ m}^2/\text{day}$ (Figure 53). This correlates well with the T -value calculated from the late-time recovery data (1080 – 1800 minutes) of $36.1 \text{ m}^2/\text{day}$. During the late-time fit (1000 – 4320 minutes) of the

This solution to the drawdown data, a storativity of 1.25×10^{-5} was estimated. A conservative 15 m available drawdown was used for calculating the sustainable yield of the borehole.

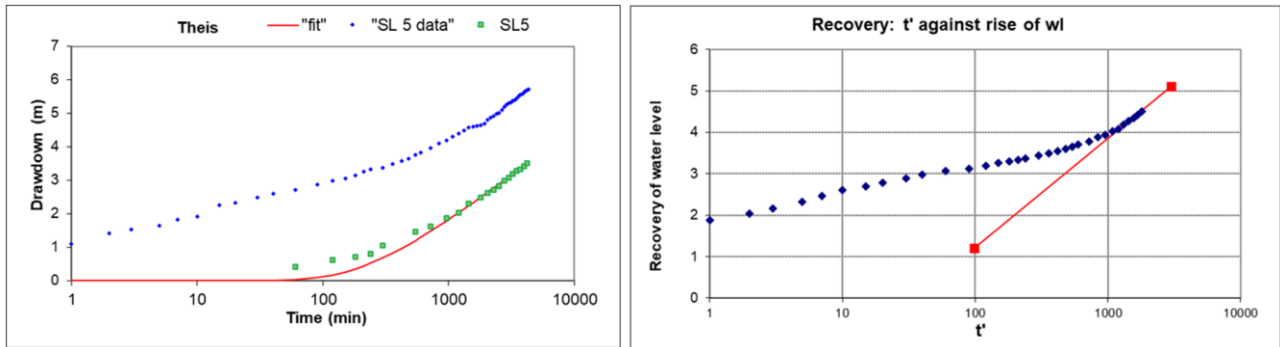


Figure 53: Left: Theis fit to observation borehole SL5 during pumping of borehole SL4, right: recovery graph of SL4 applying the Theis solution to determine the transmissivity

5.7.3.2 SL5

The testing of borehole SL5 was done between 31 October and 6 November 2021. The test pump was installed at a depth of 82.26 mbgl, below the major water fractured zone occurring 56–71 mbgl. The RWL at the start of the test was 17.91 mbgl. The water level was drawn down 5.61 m below the RWL during the fourth step at a rate of 15.2 L/s and allowed to recover to 0.53 m below the RWL (18.44 mbgl). Minimal drawdown was observed in comparison to the 64 m of available drawdown (to pump inlet) despite a higher fourth step rate (7 L/s) than that used during the testing of SL4. Figure 54 shows the time-series drawdown and the different pumping rates used during the step test. For all four steps, the data show an early-time drop in water level after which there is a small and gradual decline with time towards the end of the step.

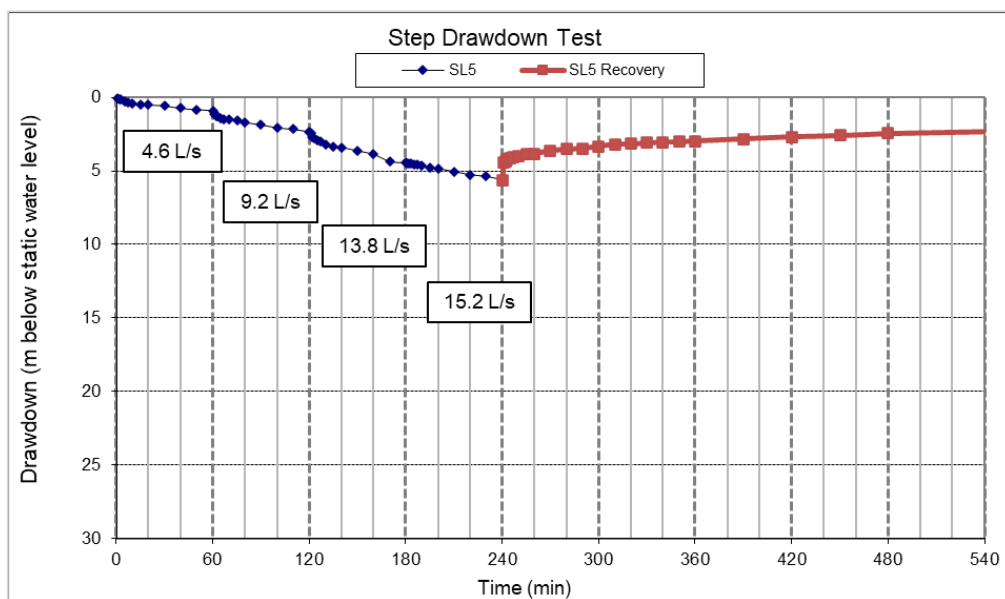


Figure 54: Step Test drawdown curve for SL5 and recovery

Based on the step test results, and by considering the fracture depths, the constant discharge rate (CDT) rate was chosen to be 14 L/s with the aim to stress the borehole. A very small response in relation to the available drawdown was evident in the data. The water level was drawn down to 10.58 m below the RWL (29.0 mbgl) after the 66-hour pumping duration (when the power source of the mono pump failed) and allowed to recover for the time pumped (66 hours). During the testing of SL5, water levels were monitored in borehole SL4 located downgradient. Figure 55 shows the drawdown and recovery data for SL5 and the response measured in observation borehole SL4.

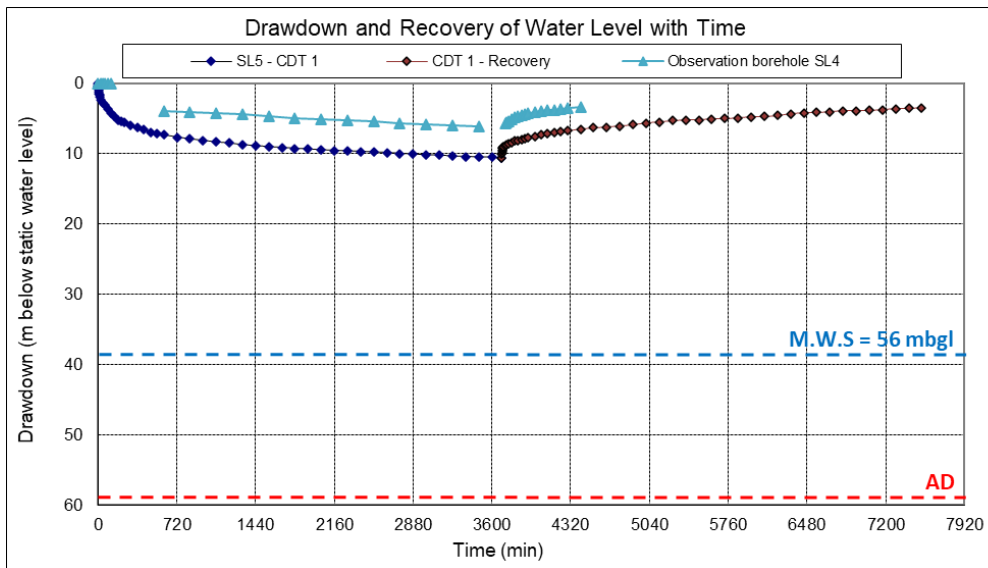


Figure 55: Time-series drawdown and recovery for SL5 and observation borehole SL4 in relation to main water strike (MWS) depth and available drawdown (AD)

Aquifer parameters were calculated based on the response of the water level in observation borehole SL4 during the pumping of SL5. The Theis curve was fitted to the late-time (1000 – 3480 minutes) drawdown data of the observation borehole data to estimate a T -value for the aquifer of $54.9 \text{ m}^2/\text{day}$ (Figure 56). This correlates well with the T -value of $41.6 \text{ m}^2/\text{day}$ calculated from the late-time (1080 – 3600 minutes) recovery data (Figure 56). During the late-time fit (1080 – 3600 minutes) of the Theis solution to the drawdown data, a storativity of 2.00×10^{-5} was estimated. A conservative 20 m available drawdown was used for calculating the sustainable yield of the borehole.

The drawdown data for boreholes SL4 and SL5 are displayed in a single graph in Figure 57. The data for both combinations of abstraction and observation boreholes (SL4 pumped with SL5 observed; SL5 pumped with SL4 observed) are shown. It is seen that the monitoring boreholes show a good correlation in hydraulic head response to pumping. Furthermore, the recovery curves of the observation boreholes are very similar to those of the corresponding abstraction boreholes.

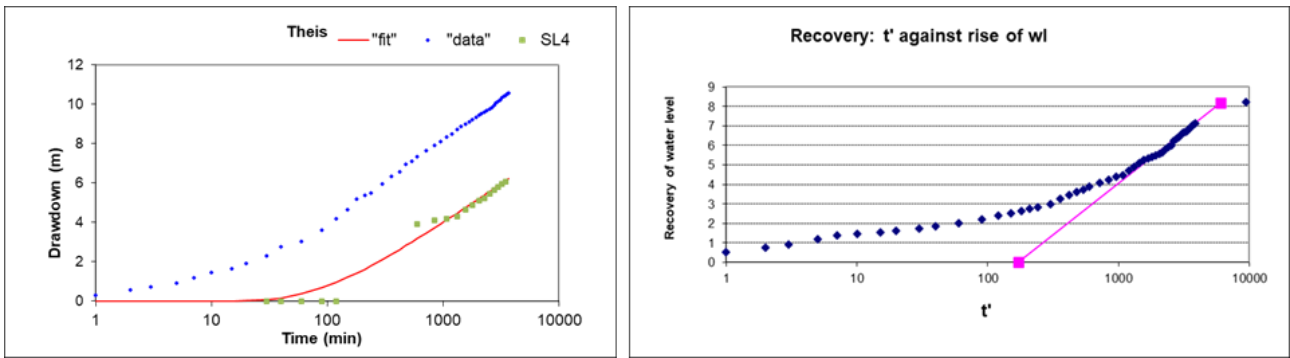


Figure 56: Left: Theis fit to observation borehole SL4 during pumping of SL5, right: recovery graph of SL5 applying Theis to determine the transmissivity

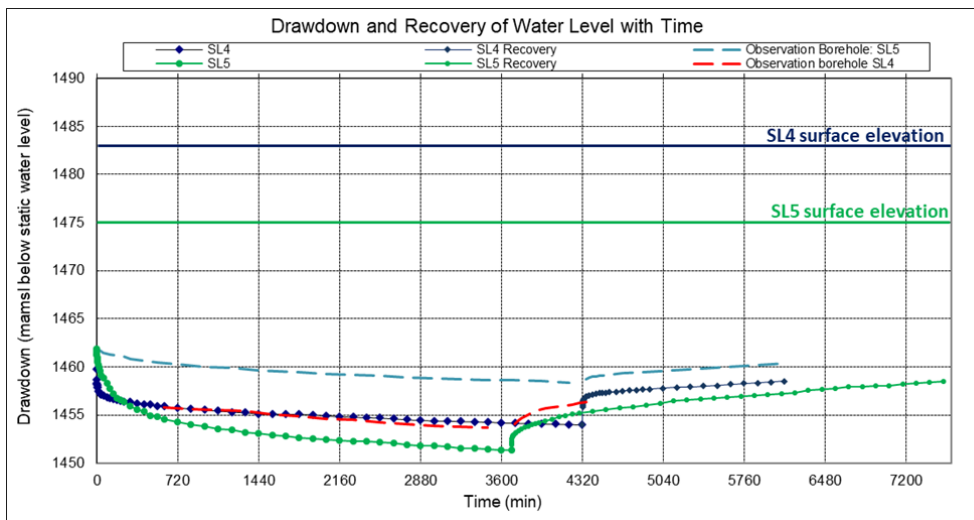


Figure 57: Constant discharge tests – water level drawdown and recovery responses in pumping boreholes SL4 and SL5 and the corresponding observation boreholes

5.7.4 Pumping test on borehole SL6 with observation borehole SL9

Borehole SL6 was drilled into major structure F5 crosscutting the flood plains of a south to north draining non-perennial river (Figure 58). Observation borehole SL9 (F5) is located towards the southeast and upgradient from SL6, drilled into major structure F4. Both boreholes intersected horizontal fractured zones at similar depths. SL6 also intersected numerous sub-vertical fractured zones in addition to horizontal fracturing. The surface distance between the pumping and observation borehole is approximately 818 meters, with a 5-meter difference in elevation between SL9 (1475 mamsl) and SL6 (1470 mamsl) (Figure 58).

The pumping test was conducted between 21 and 26 November 2021. The pump was installed at a depth of 90.83 mbgl. The RWL at the start of the test was 24.66 mbgl. The pumping rate was limited by the inner diameter of the borehole (127 mm). As a result, the first and second steps were completed at a rate of 3 L/s, and the fourth step at a rate of 5.5 L/s, resulting in a total drawdown of 2.83 m below the RWL (27.49 mbgl). The groundwater level was then allowed to recover to 0.18 m below the RWL (24.84 mbgl). Minimal drawdown was observed in comparison to the 66 m of available drawdown

(to pump inlet). Figure 59 shows the time-series drawdown relative to the different pumping rates used during the step test. For all steps, the data show an early-time drop in water level after which there is a small decline with time towards the end of the step.



Figure 58: Aerial photograph showing the location of SL6 in relation to SL9 and SL11, with major fractured zones (authors own)

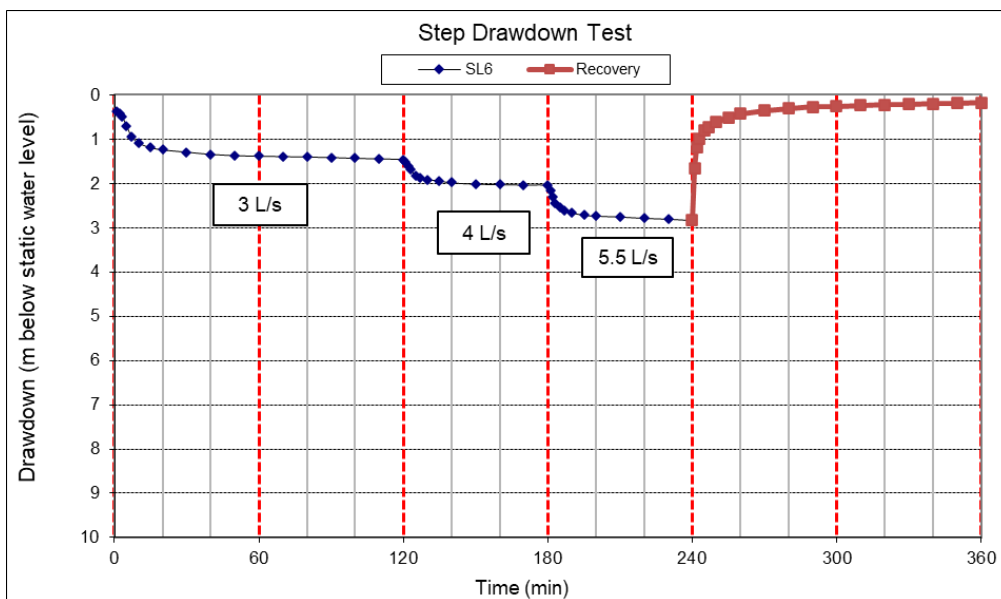


Figure 59: Step Test drawdown curve for SL6 and recovery.

Based on the step test results, and by considering the fracture depths, the constant discharge rate (CDT) rate was chosen to be the maximum flow rate of the pump (5 L/s). Using this pumping rate, a drawdown of only 3.96 m below the RWL (28.77 mbgl) was observed after 72 hours of pumping. This drawdown is very small compared to the available drawdown of 66 m. During the pumping of SL6, water levels in observation borehole SL9 showed a late time response, with a drop of 0.57 m

below the RWL (29.56 mbgl). This is likely associated with fracture depressurisation within the aquifer. Figure 60 shows the drawdown and recovery data for SL6 and the response measured in observation borehole SL9. Recovery is considered slow, attaining only 81% recovery after 42 hours.

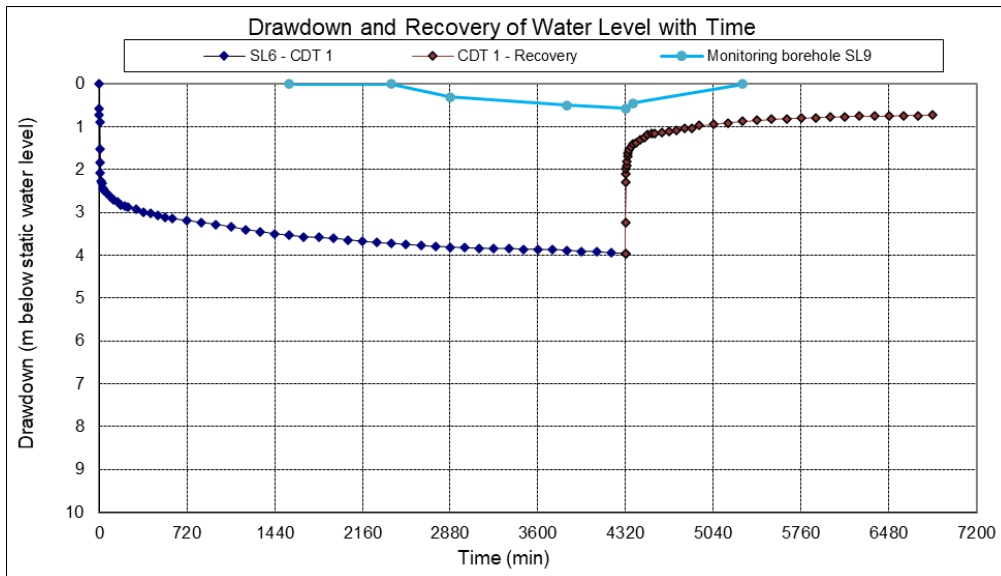


Figure 60: Time-series drawdown and recovery for SL6 and observation borehole SL9 with minimal water level response

Aquifer parameters were estimated through water level monitoring in observation borehole SL9 fitting the Theis curve. The estimated T -value was then correlated with the transmissivity estimated from the recovery data. The semi-log plot of the drawdown data was fitted to 1000 – 4320 minutes, calculating a transmissivity (T) of $79 \text{ m}^2/\text{day}$ (Figure 53). The T -value calculated from the recovery data (fitted to 480– 4320 minutes) is $148 \text{ m}^2/\text{day}$. The storativity was calculated at 1.10×10^{-4} through fitting the Theis solution to the drawdown response between 1000 – 4320 minutes. A conservative 16 m available drawdown was used for calculating the sustainable yield of the borehole.

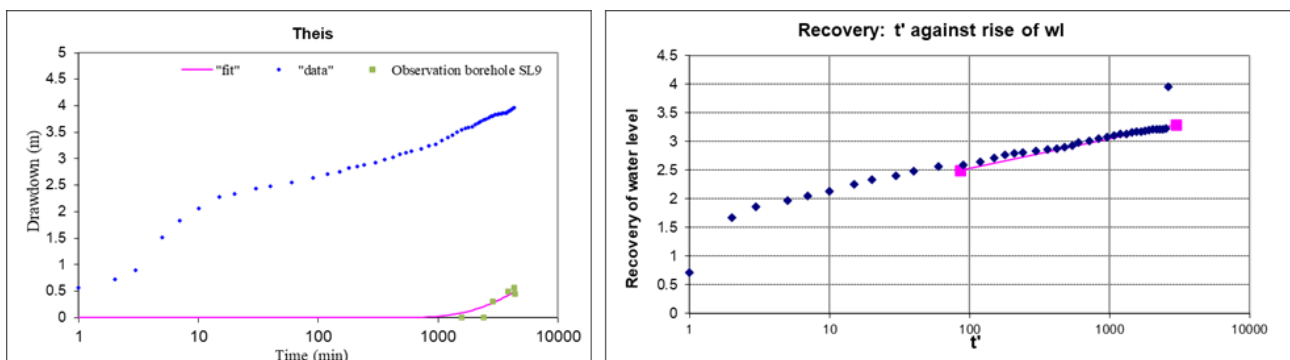


Figure 61: Left: Theis fit to observation borehole SL9 during pumping, right: recovery graph of SL6 applying Theis to determine the transmissivity

5.7.5 Pumping test on borehole SL11 with observation boreholes BH4_Vlei and MAR2

Borehole SL11 (1463 mamsl) was drilled into major structure F1 towards the far south of town and MAR2 (1462 mamsl) 240 meters north of the major structure into the bedrock matrix. An existing borehole, BH4_Vlei (1461 mamsl) is located approximately 340 m towards the north-east with a depth of 44 m. Both MAR2 and BH4_Vlei were monitored during the testing of SL11 (Figure 62).



Figure 62: Borehole locations of SL11, MAR2 and BH4_Vlei pumped and monitored during the testing of borehole SL11 (authors own)

The pumping test was conducted between 17 and 23 November 2021. The pump was installed at a depth of 98.40 mbgl. The RWL at the start of the test was 21.00 mbgl. The step test was completed at abstraction rates of 3.4 L/s, 9.1 L/s, 14.1 L/s and 18.1 L/s during the four steps. The final drawdown was 3.08 m below the RWL (24.08 mbgl). Thereafter, the borehole was allowed to recover to 0.16 m below the RWL (21.16 mbgl) (Figure 63). Very little drawdown was observed in comparison to the total available drawdown.

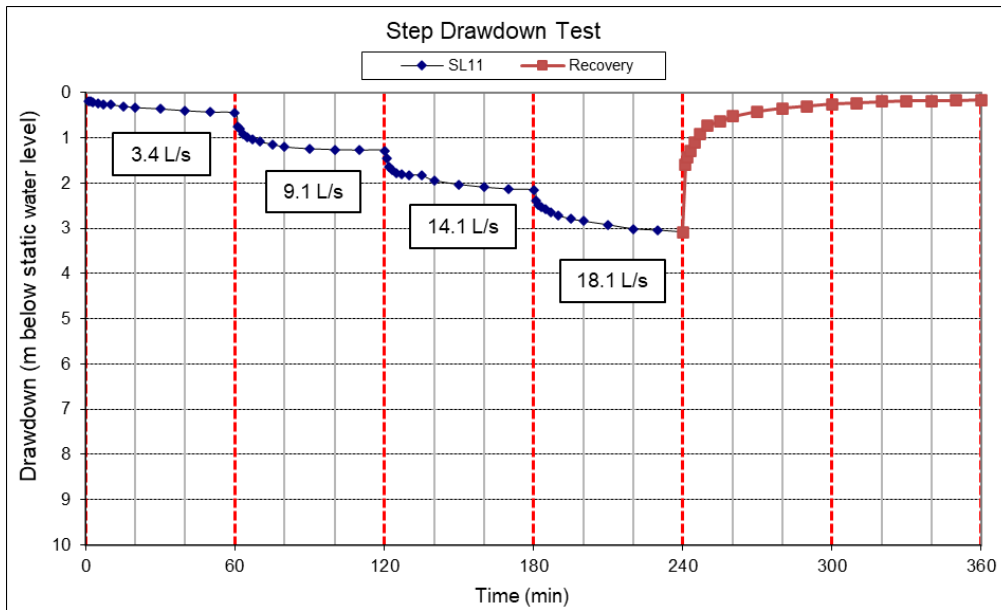


Figure 63: Step Test drawdown curve for SL11 and recovery

Based on the step results, and by considering the fracture depths, the constant discharge rate (CDT) rate was chosen to be the maximum flow rate that the pump could sustain for 72 hours (Figure 64). The CDT was therefore completed at a rate of 16 L/s. Very little drawdown was observed in relation to the total available drawdown. The water level was drawn down to 5.17 m below the RWL (26.17 mbgl) after the 72-hour pumping duration and allowed to recover for the time pumped (42 hours). During the testing of SL11 water levels were monitored in MAR and BH4_Vlei, located downgradient from SL11. The water level in MAR2 was monitored by means of an automated logger, while BH4_Vlei was monitored with hand measurements. The rest water levels for MAR2 and BH4_Vlei were respectively 20.17 mbgl and 21.14 mbgl before the testing started. Pumping was ceased at BH4_Vlei the day before the testing started; however, the water level at this borehole initially still showed recovery trends during the early time of the CDT.

Aquifer parameters were estimated through water level monitoring in observation borehole MAR2 fitting the Theis curve and correlated transmissivity estimated with water level recovery observed. The semi-log plot of the drawdown data was fitted to 540 – 4320 minutes calculating a transmissivity (T) of $54 \text{ m}^2/\text{day}$ (Figure 65). The T -value calculated from the recovery data, fitted to 480 – 4320 minutes, is $165 \text{ m}^2/\text{day}$. The storativity was calculated at 1.98×10^{-3} . A conservative 16 m available drawdown was used for calculating the sustainable yield of the borehole.

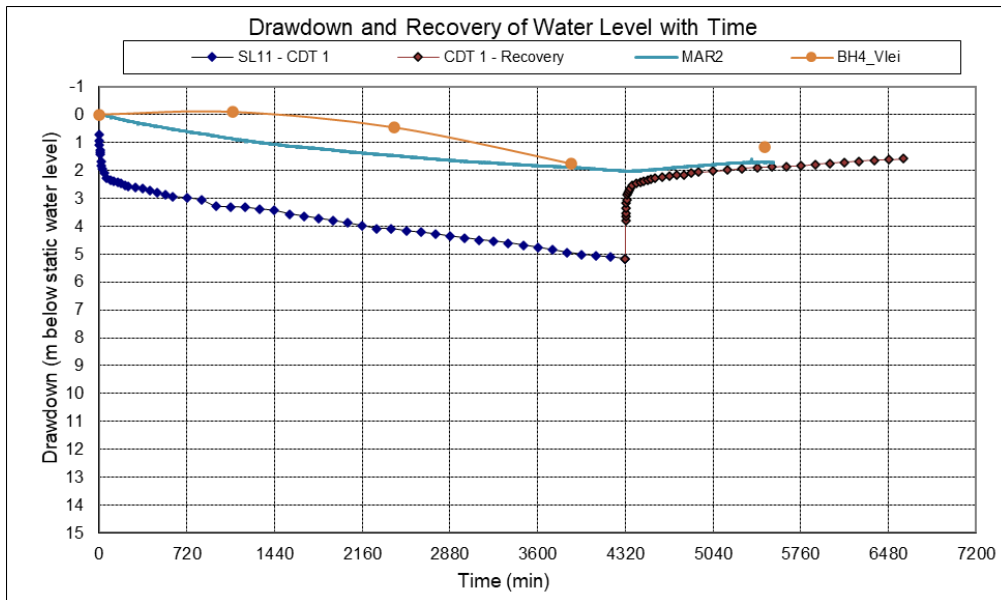


Figure 64: Time-series drawdown and recovery for borehole SL11 and observation boreholes MAR2 and BH_Vlei

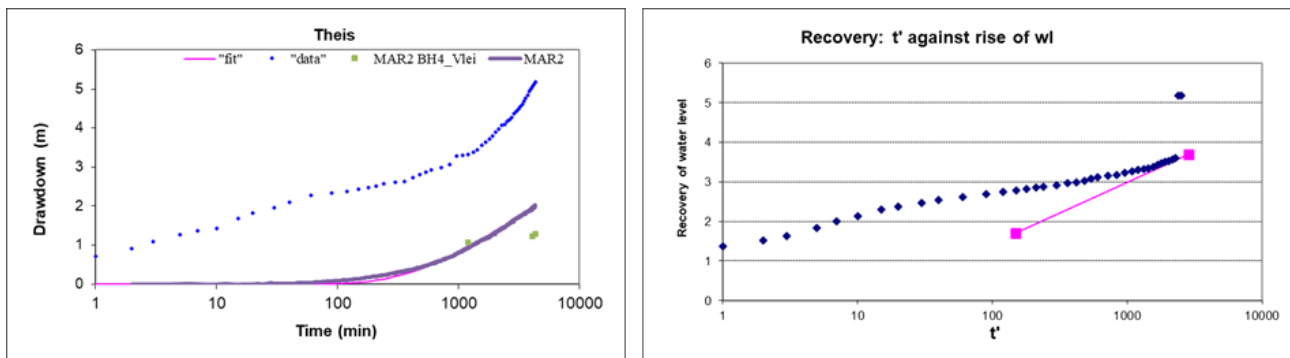


Figure 65: Left: Theis fit to observation borehole MAR2 during pumping, right: recovery graph of SL11 applying Theis to determine transmissivity.

5.7.6 Falling head test on borehole MAR2

During the testing of SL11 a modified falling head test was completed at MAR2 to collect preliminary data on the aquifer matrix acceptance capacity. The falling head test involved repeated injection of a known volume of water into the borehole. The injection of water causes a sudden rise in the water level head (positive displacement). The subsequent falling water level response is then measured with time to estimate the hydraulic properties (Copper *et al.*, 1967; Barker and Black, 1983).

The falling head test was conducted in MAR2 during the step test of SL11 (discussed in Section 5.7.5). Water was injected into the MAR2 borehole at rates of 3.43 L/s, 9.12 L/s, 14.12 L/s and 18.18 L/s until overflow to the surface occurred. The volumes injected were calculated based on the response time measured on a stopwatch from the start of the injection to overflow. For example, the water level raised to the surface within 141 seconds at an injection rate of 3.34 L/s. Figure 66 depicts the time series data for the water level reaction and volume injected into MAR2 during the falling

head test. Prior to the start of the injection of water into MAR2 the RWL was 20.6 mbgl. Photos of the testing are shown in Figure 67.

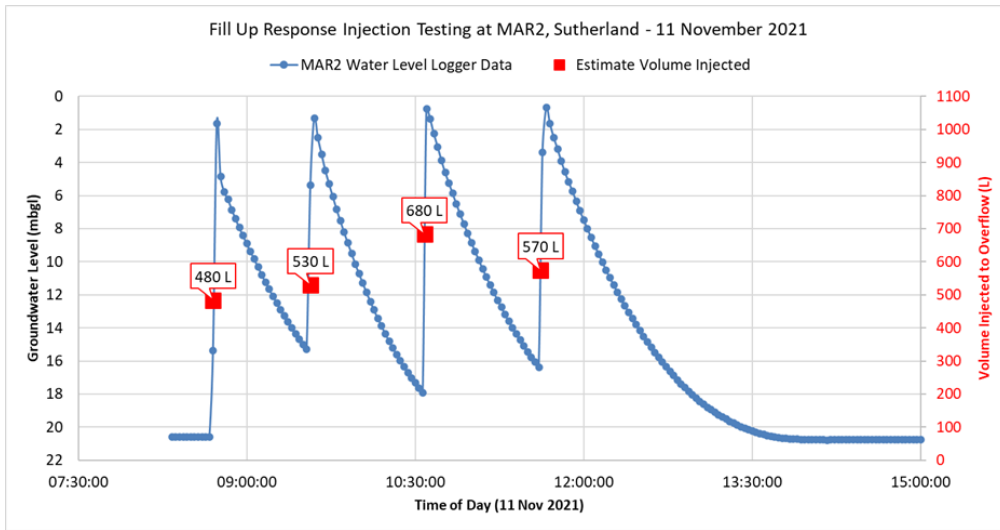


Figure 66: Time series data for water level and volume injected into MAR2



Figure 67: Photographs of the modified falling head test conducted on borehole MAR2, injection (left) to overflow (right) (author's own)

Based on the results of the test it is expected that the single borehole MAR2 can sustain an injection rate of 0.2 L/s without the water level rising above ground level and overflowing. The hydraulic conductivity calculated from these tests is indicated in Table 11.

Table 11: Hydraulic parameter estimation and potential injection rate for MAR2

Site	RWL (mbgl)	K (m/d)	Injection rate (L/s)	Aquifer thickness (m)
MAR_2	20.6	0.02	0.19	30

Minimal fractures were intersected during the drilling of MAR2. However, based on the falling head test and water level monitoring during the testing of SL11, it is clear that the borehole has the capacity

to enhance natural recharge to the local area. It is likely that the potential injection rate at this borehole is a reflection of the hydraulic conductivity of the Abrahamskraal Formation.

5.7.7 Estimated hydraulic parameters

Flow characteristics and regimes for the fractured aquifer of the Southern Wellfield area were estimated by means of the Cooper Jacob and Theis methods. The analysis of data was completed with the FC data analysis tool through drawdown observations and first and second derivate plots. A double porosity medium approach was adopted, based on the assumption that the fractured aquifer is associated with a uniform network of fissures and matrix blocks (Woodford and Chevallier, 2002). The transmissivity for MAR_2 was determined considering the aquifer thickness and fracture depths. The estimated aquifer parameter values are summarised in Table 12 as well as the method used to obtain these estimates. The aquifer parameter estimates for BH4_Vlei were obtained from a previous pumping test completed in 2020 (GEOSS, 2020).

Table 12: Summary of aquifer parameter estimates from the hydraulic tests

Site ID	T (m ² /d)	Recovery T (m ² /d)	Storativity	Methods
Conduit zone boreholes				
SL11	54.8	130	5.88E-04	Theis and recovery
SL6	79.7	148.7	1.10E-04	Theis and recovery
SL4	38.3	35.1	1.25E-05	Theis and recovery
SL5	54.9	40.4	2.00E-05	Theis and recovery
BH4_Vlei	55.0	42.2	5.88E-04	Cooper-Jacob and recovery
Average	49.4	39.2	1.83E-04	
Matrix boreholes				
MAR_2	0.5	0.4	4.71E-03	Cooper-Jacob and recovery
SL1	6.2	7.5	0.01631	Cooper-Jacob and recovery
SL3	2.8	3.1	4.71E-03	Cooper-Jacob and recovery
Average	3.2	3.7	8.58E-03	

Higher transmissivities were observed at boreholes drilled into or located close to major fractured zones, with correlating higher observed yields. As expected, the transmissivity values for the conduit zone boreholes (SL4, SL5, SL6 and SL11) are generally high in comparison to those of the matrix boreholes (SL1, SL3 and BH4_Vlei).

5.7.8 Estimated sustainable yields for the new production boreholes

Several methods were used to assess the sustainable yields of the boreholes. These are summarised in Table 13. The average of the sustainable yields obtained with the different methods used in a single

borehole was then recommended as the potential sustainable abstraction rate. This was done for all the boreholes tested, from which three were identified that were commissioned as production boreholes. Based on the spatial positions, borehole yields and the low-risk potential for interaction with other boreholes, boreholes SL5, SL6 and SL11 were chosen to be utilised as production boreholes for town water supply.

Table 13: Yield determination for the tested boreholes

BH ID	Borehole depth (m)	Method					Recommended abstraction rate (L/s)
		Basic FC	FC inflection point	Cooper-Jacob	FC Non-Linear	Barker	
SL1	150.1	0.3	-	1.1	0.9	0.4	0.7
SL3	150	1.1	0.9	0.9	-	0.9	1.0
SL4	146.6	2.5	-	2.1	-	2.3	2.3
SL5	121	5.1	3.9	4.5	5	5	4.7
SL6	121	5.4	-	5.8	5.1	5.1	5.4
SL11	121	5.3	4.9	6.4	5.1	4.2	5.2

In the process of estimating the sustainable yields of the production boreholes, critical operation water levels were determined. This includes the baseline rest water levels measured before the pumping tests started, predicted dynamic water levels and a critical water level in a borehole which may not be exceeded. Table 14 lists these water levels for the different boreholes along with the recommended duration for the abstraction and recovery.

Table 14: Borehole abstraction rate and management levels

BH ID	Borehole depth (m)	Recommended abstraction rate (L/s)	Recommended abstraction duration (hrs)	Recommended recovery duration (hrs)	Recommended pump installation depth (mbgl)	Critical water level (mbgl)	Dynamic water level (mbgl)	Rest water level (mbgl)
SL1	150.1	0.7	24	0	141	136	116	69.85
SL3	150.0	1.0	24	0	94	89	69	23.25
SL4	146.6	2.3	24	0	45	43	24	12.27
SL5	121.0	4.7	24	0	55	50	30	17.91
SL6	121.0	5.4	24	0	72	65	35	24.66
SL11	121.0	5.2	24	0	75	70	30	21.00

The abstraction durations were chosen to be 24 hours of pumping with zero hours of recovery in all the boreholes. The reason is two-fold. First, the chemistry data (refer to Section 5.8) show slightly elevated concentrations of dissolved iron, which in the past resulted in iron bio-fouling and clogging of the boreholes in the area. By maintaining a 24-hr pumping regime, bio-fouling of the borehole can be avoided. Second, a 24-hr pumping regime will ensure that the reservoir remains full at all times.

Should the reservoir reach its maximum capacity one of the boreholes could be switched off to maintain the level.

5.8 HYDROGEOCHEMICAL CHARACTERISATION

Six representative groundwater samples were taken from selected boreholes after the full duration of the CDT conducted on these boreholes. Samples were collected from boreholes SL1, SL3, SL4, SL5, SL6 and SL11. All of the samples were submitted for physicochemical analyses at an accredited laboratory. Based on the results of the analyses, the samples were classified according to the Drinking Water Guidelines specified by DWAF (1998) (Table 15). The classification system used to evaluate the water quality is explained in Table 15 while the results of the chemical analyses performed on the groundwater samples for selected parameters are presented in Table 16. For a complete listing of the chemical analysis results, refer to **Appendix D**.

Table 15: Classification table for specific drinking water limits according to DWAF (1998)

Class 0	Ideal water quality - Suitable for lifetime use.
Class 1	Good water quality - Suitable for use, rare instances of negative effects.
Class 2	Marginal water quality - Conditionally acceptable. Negative effects may occur in some sensitive groups
Class 3	Poor water quality - Unsuitable for use without treatment. Chronic effects may occur.
Class 4	Dangerous water quality - Totally unsuitable for use. Acute effects may occur.

From the chemical results, the groundwater from the boreholes is seen to be predominantly good to marginal in quality in terms of dissolved mineral concentrations. All of the boreholes have elevated concentrations of dissolved fluoride and slightly elevated iron concentrations. The fluoride concentrations are all in a range that is not safe for human consumption and thus treatment is required. All boreholes have some degree of turbidity within a reasonable range that requires minimal filtering. The turbidity may also naturally decline under production conditions, which employ lower flow velocities than under testing conditions. Water from all the boreholes requires treatment prior to human consumption.

Table 16: Water chemistry of boreholes tested classified according to the DWAF (1998) standards for domestic drinking water

Parameter	Sample					
	SL1	SL3	SL4	SL5	SL6	SL11
pH	7.7	8.9	8.1	8.2	7.7	7.9
Conductivity (mS/m)	174.6	94.6	68.6	68.4	64.0	63.7
Turbidity (NTU)	9.16	8.96	1.06	0.97	1.12	1.52
mg/L						
Total Dissolved Solids	1183.79	641.39	465.11	463.75	433.92	431.89
Sodium (as Na)	261	204	116	104	71	92
Potassium (as K)	2	4	4	2	1	4
Magnesium (as Mg)	2	1	7	9	5	4
Calcium (as Ca)	82	3	24	30	50	38
Chloride (as Cl)	476.61	126.78	77.42	75.15	69.57	71.03
Sulphate (as SO ₄)	6.84	8.78	<4.00	<4.00	13.36	11.34
Nitrate& Nitrite (as N)	<1.05	<1.05	<1.05	<1.05	<1.05	<1.05
Fluoride (as F)	2.11	7.66	2.00	2.07	0.94	1.34
Manganese (as Mn)	0.035	<0.018	0.020	0.009	0.025	0.024
Iron (as Fe)	0.419	0.025	0.026	0.094	0.041	0.036
Copper (as Cu)	0.005	0.011	0.016	0.014	0.004	0.017
Zinc (as Zn)	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008
Arsenic (as As)	<0.010	<0.010	<0.010	<0.010	0.013	<0.010
Cadmium (as Cd)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Hardness (as CaCO ₃)	213.200	11.15	88.70	111.90	145.50	111.40
Charge Balance %	0.1	4.6	4.5	2.5	1.2	4.2

To assist with the chemical characterisation of the groundwater, the groundwater chemistry was plotted on Piper and Stiff diagrams. These diagrams provide visual representations of the chemistry of the groundwater.

The Piper diagram for the groundwater samples from the Sutherland boreholes is presented in Figure 68. The diagram shows the distribution of cations and anions in separate triangles and then a combination of the chemistry in the central diamond. Water with similar chemical signatures will plot in close proximity to one another in the diagram. From the central diamond of the Piper diagram in Figure 68, it is seen that the groundwater samples can be classified as being of calcium, sodium-chloride and sodium-bicarbonate waters. Boreholes SL3, SL4, SL5, SL6 and SL11 are classified as having sodium-bicarbonate hydrofacies (bottom of the central diamond) linked to the Abrahamskraal Formation which provides aquifer storage in bedding planes and bedding plane fractures. The clustering of boreholes SL4, SL5, SL6 and SL11 are expected as all of the boreholes are located within a good fractured network, some drilled into the same geological structures. The bicarbonate-type samples are likely a result of interaction with carbonate minerals, often found on drill chips. Field observations of the drill chips and downhole camera logging have shown that calcite or dolomite crystal growth is present in fractures and voids, as well as some instances of quartz crystal growth.

Groundwater from borehole SL1 is classified as a sodium chloride hydrofacies (right corner of the central diamond). The chemical character of the groundwater from this borehole is likely linked to the presence of an intrusive body, which was targeted for the drilling of SL1. This intrusive structure may be a dolerite dyke or a fractured zone connected with the melilite basalt intrusion towards the west of the town.

From the bottom triangles, no clear distinction is made in the cation ratios (left triangle) between the groundwater samples of different areas or clusters; however, a clear difference is seen in the anion ratios (right triangle) between the samples from boreholes SL3, SL4, SL5, SL6 and SL11, and the sample from borehole SL1.

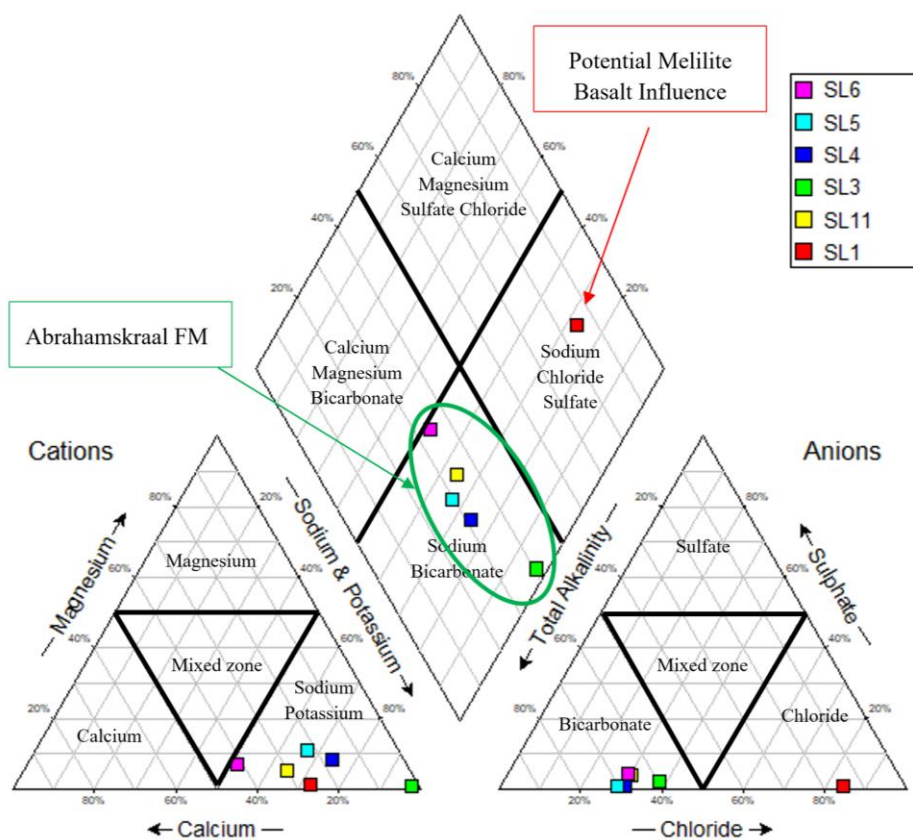


Figure 68: Piper diagram for the groundwater samples from boreholes in the area

A Stiff diagram is a graphical representation of the relative concentrations of the cations (positive ions) and anions (negative ions). This diagram shows concentrations of cations and anions relative to each other (not as a percentage, as is the case for the Piper diagram) and direct reference can be made to specific salts in the water. The Stiff diagrams for the samples from the Sutherland boreholes are shown in Figure 69. These diagrams confirm the same clustering as observed in the Piper diagram (boreholes SL3, SL4, SL5, SL6 and SL11), but now provide magnitude to the variability. SL1 has a brackish sodium–chloride type water, associated with the formations of the Abrahamskraal

Formation. The chemical character of the water from SL1 may also be associated with limited recharge and possible over-abstraction of groundwater in the area (western side of town). This would explain the higher dissolved concentrations of sodium and chloride in the groundwater.

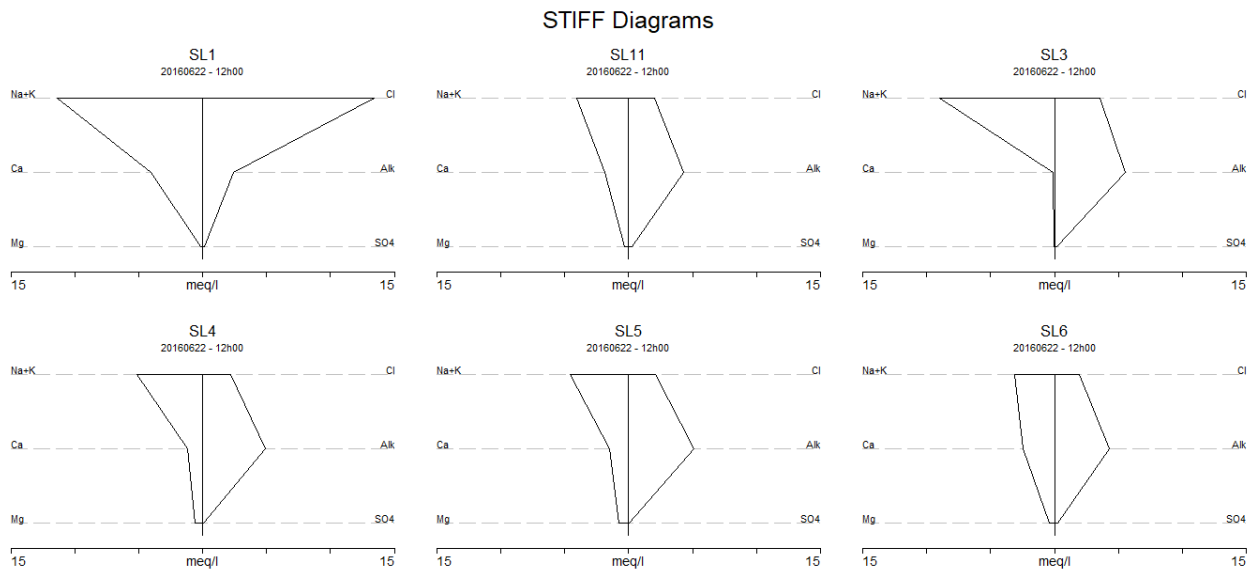


Figure 69: Stiff diagrams for the groundwater samples from boreholes in the area

5.9 HYDROGEOLOGICAL PROCESSES IN THE SUTHERLAND AREA

5.9.1 Land use and potential contaminants

The Southern Wellfield area is generally undeveloped in terms of infrastructure and is currently only used for grazing purposes. Potential contaminant sources are limited to single pit latrines and small-scale irrigation farming activity with minimal pesticide application towards the south and far south-west. The potential for sporadic contamination due to activities associated with the R356 access road also exists. The other major activity in the larger study area is the town of Sutherland towards the north and its associated activities. This includes two filling stations with on-surface and subsurface storage tanks, the Wastewater Treatment Works, the town cemetery and the landfill site (Figure 70).




Image	Land use
	<p>Visual of the typical land use in the Southern Wellfield area. Production borehole SL5 is seen at the bottom of the picture with a small patch of lucerne being irrigated. The homestead is also visible where there is a pit latrine system. Generally undisturbed vegetation surrounding the production borehole.</p> <p>(-32.428688 S, 20.657290 E)</p>
	<p>Landfill located towards the far north-east of the Southern Wellfield area.</p> <p>(-32.398824 S, 20.672503 E)</p>
	<p>Waste Water Treatment Works with lined evaporation ponds located towards the far north-east of the Southern Wellfield area.</p> <p>(-32.401628 S, 20.675988 E)</p>

Figure 70: Images of the higher risk land uses that could result in point source contamination

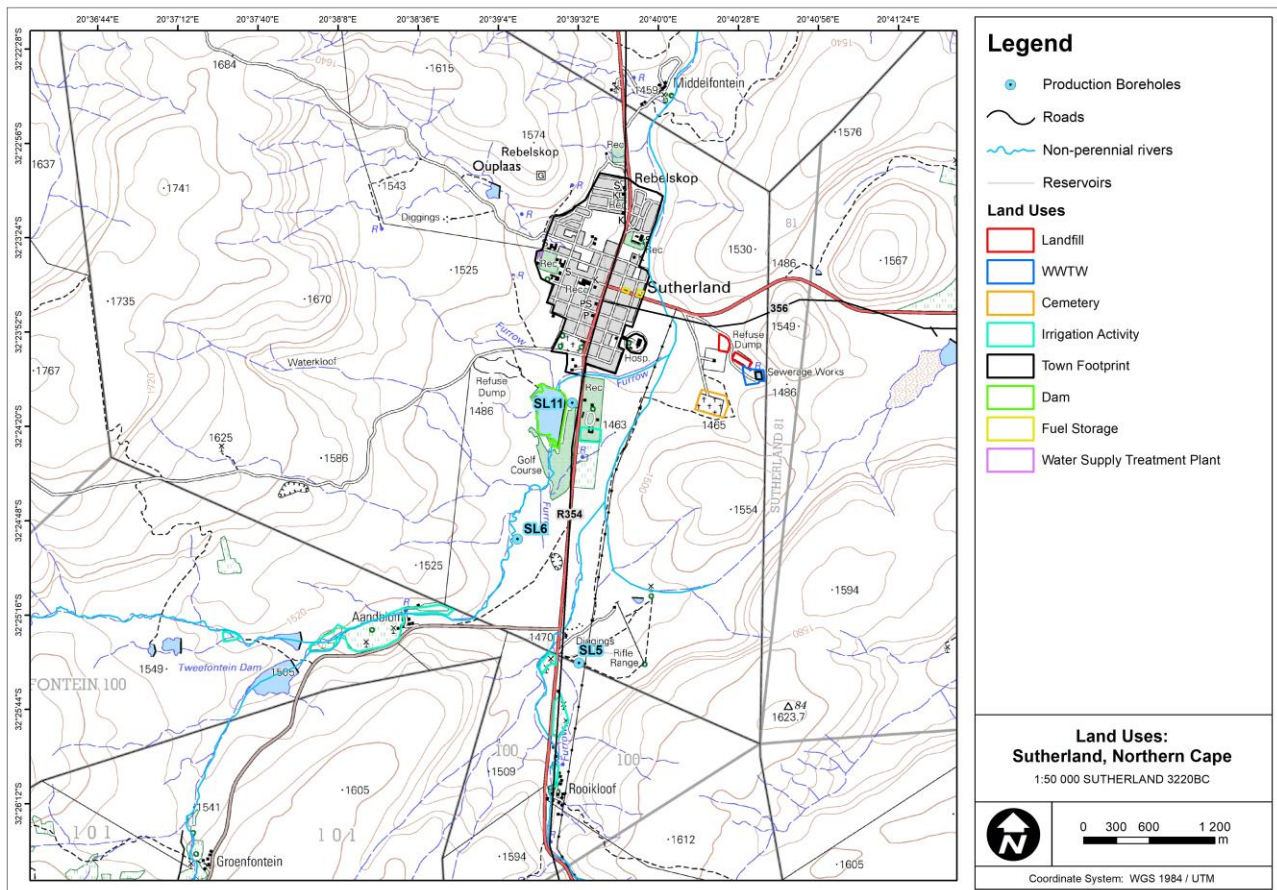


Figure 71: Land use in the study area in relation to the production boreholes.

5.9.2 Aquifers and aquitards

The lithostratigraphy of the study area comprises predominantly sedimentary successions of the Beaufort Group, consisting of alternating layers of siltstone, mudstone, shale and occasional sandstone, cross-cut by major north-east and south-west trending fissures, minor north-west/south-east and east/west fractured zones. The sedimentary bedrock is capped by a dolerite sill which is generally eroded away, but still evident on the topographical highs surrounding the Southern Wellfield area. This sill emulates the dip of the underlying sedimentary bedrock. There is evidence of north-west/south-east trending dyke structures consisting of dolerite or melilite intrusions. A basalt intrusive body located towards the north-west of the study area is largely capped by the Abrahamskraal host rock, showing clear signs of low degree metamorphism and linear fractured zones within the parent rock.

The principal aquifer in the study area is fractured zones within the bedrock of the Abrahamskraal Formation, with minor aquifers associated with the baked and fractured zones between intrusive bedrock and the parent sedimentary bedrock, i.e., the contact zone between dolerite and shale bedrock and the metamorphosed zone between the parent rock and melilite basalt. The Abrahamskraal fractured aquifer comprises a high percentage of relatively impermeable mudstone and siltstone

layers, with good fractured shales and gritstone. Prominent bedding plane fracturing occurs at the transition from mudstone to sandstone. The fractured sandstone, shale and gritstone layers within the geological succession represent the major aquifer and matrix for groundwater storage. Highly transmissive zones are associated with subvertical and vertical linear fissures crosscutting the bedrock. Locally, intrusive bedrock is considered an aquitard with low permeability. However, the parent bedrock (i.e., mudstone, siltstone or sandstone) has been baked and fractured due to the intrusion, and is therefore associated with aquifer characteristics.

5.9.3 Boundaries

The Southern Wellfield area occupies a structural embayment of the Sutherland Suite associated with north-east/south-west trending fissures resulting in clear fractured zones within sediments of the Beaufort Group. The fissures are not associated with any significant displacement; however, there is evidence of displacement with the north-western section of structure F5. Structure F5.1 has been downthrown in the centimetres to meters range. Camera inspections in boreholes showed rather damaged zones in SL11 with minor displacement in boreholes SL5, SL6 and SL9 which targeted structures F5 and F5.1.

Boundaries within the aquifer for the southern well field include the following:

- Seasonal recharge boundaries, comprising streams generally draining towards the north with a meandering stream originating from the south-west with major flows captured by two in-stream dams. Flows are rather episodic with sporadic rainfall and associated with the melting of snow during the wet season. The non-perennial Dorps River crosscuts the major fractured zones, covered by silty alluvial material with floodplains in the proximity of SL3. The alluvial cover has a low permeability with ponding occurring during wet seasons. The contribution to groundwater recharge through these surface water features is rather sporadic and seasonal, materials are likely to rather be transported towards the floodplains.
- Conduit zones within the aquifer are likely to occur along the major north-east/south-west fractured zones. Furthermore, single bedding plane fractures are evident within the study area, which is often associated with the geological contact zones between mudstone and sandstone layers.
- No flow boundaries are formed by the topographical highs surrounding the study area, dolerite sills and melilite basalt intrusion towards the north-west, and a north-west/south-east trending dyke structure, either associated with the melilite basalt intrusion or a younger dolerite intrusion.

- The bedrock matrix of the Abrahamskraal Formation is associated with aquifer storage.

5.9.4 Hydraulic characteristics

Information on the hydraulic characteristics of the Southern Wellfield area is based on literature of the typical Karoo aquifer and results from aquifer parameter determination through the analysis of hydraulic test data (Section 5.7). The lithostratigraphic units of the Abrahamskraal Formation are associated with a double porosity aquifer. The rock mass matrix has sufficient inherent porosity for groundwater storage; however, it is not very transmissive. The transmissivity of the aquifer is enhanced by fractured zones associated with north-east/south-west trending fissures on a micro scale. Although these zones facilitate the rapid movement of groundwater, they do not allow for major storage. Linear flow and bi-linear flow are expected to be the dominant flow regimes due to the highly transmissive and fractured characteristics of the major fractured zones in which the majority of boreholes were drilled.

5.9.5 Recharge areas

The area is characterised by minimal alluvial cover and intergranular primary aquifers are essentially absent. However, in the lower-lying areas towards drainage channels and non-perennial rivers, 2 m–3 m of sandy alluvium receives recharge from direct precipitation and from the baseflow component of episodic stream flow events. This in turn then recharges the underlying residual and fractured bedrock.

The largest percentage fractured aquifer recharge is from precipitation and snow melt during winter months along fractured bedrock outcrop in the higher-lying areas. Preferential recharge is expected along major fractured zone structures. The zone with the largest contribution is towards the south-west where the area has the highest rainfall and thickest snow cover during precipitation events (personal communication, Awie Vlok, 2021). Furthermore, this zone forms a catchment area draining towards the north-east, with major structure F3 cutting through the catchment area along with several other minor structures and lineaments.

5.9.6 Recharge calculation

The input data and recharge value calculated for the Sutherland area based using the CMB method are summarised Table 17. The calculated recharge value is significantly lower than indicated in the groundwater maps (Vegter, 1995) which shows a recharge value of 120 mm/a, corresponding to a

recharge percentage of 38.6%. Using the CMB method (Section 2.11.1), the recharge calculated for the study area is 22.4 mm/a, or 7.2% of the 311 mm annual precipitation.

Table 17: Summary of the input and calculated parameter values for recharge calculations using the CMB method

Parameter	Value
Input	
Surface area (km ²)	45.7
Chloride concentration - rainfall (harmonic mean) (mg/L)	6.1
Dry deposition of Cl (mg/L)	0.1
Chloride concentration - groundwater (harmonic mean) (mg/L)	86.2
Average annual rainfall (mm/a)	311
Output	
Recharge (%)	7.2
Annual recharge (m ³ /a)	1005400

5.10 CONCEPTUAL HYDROGEOLOGICAL MODEL

A conceptual model is a graphical representation of the groundwater system in terms of the different hydrogeologic units, system boundaries, inputs and outputs, and hydraulic and transport properties. Conceptual models are constructed to simplify the field problem and organise the associated field data so that the system can be more readily analysed (Izady *et al.*, 2014).

The data and information on the hydrogeological process in the Sutherland area were described in Section 5.9. These data and information were obtained during the desktop assessment, literature review and field surveys in the Sutherland area and inform the conceptual hydrogeological model of the study area shown in Figure 72. The conceptual model is based on the geological cross-section described in Section 3.4.3. The conceptual hydrogeological model assumes that similar conditions exist laterally across the study area. It shows the different geological formations, geological structures, groundwater flow directions, the hydraulic head (potentiometric surface) and recharge areas.

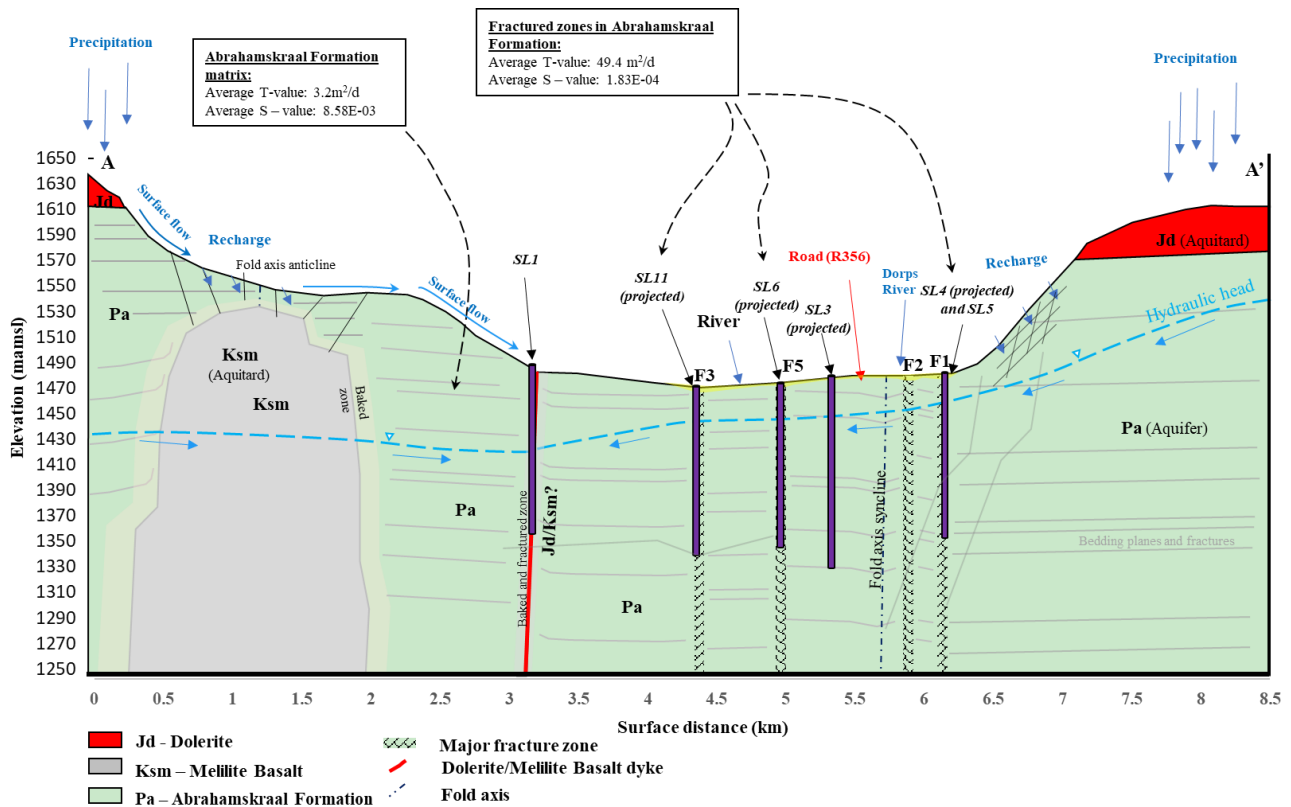


Figure 72: Conceptual hydrogeological model

5.11 WATER BALANCE WITHIN THE GROUNDWATER RESPONSE UNIT

The town water demand for the Sutherland area was estimated at 0.274 Mm³/a in 2020, and it is projected to increase to 0.287 Mm³/a and 0.343 Mm³/a by 2030 and 2040, respectively (DWS, 2021a). The annual average daily demand is currently 751 m³/day which is projected to increase to 785 m³/day and 939 m³/day in 2030 and 2040, respectively. During 2020, the peak daily demand of 1882 m³/day was not met by the existing production boreholes which could sustainably produce 583.2 m³/d (GEOSS, 2020).

During the current study, three additional production boreholes (SL5, SL6 and SL11) were drilled and developed to form part of the Southern Wellfield to make up the difference between the water demand and supply (Section 0). Minimal to no groundwater development had previously taken place in this area. These boreholes were hydraulically tested to estimate their hydraulic parameters and calculate their sustainable yields (Section 5.7). Information on these boreholes, their estimated sustainable yields, and proposed pumping regimes is provided in Table 18.

Table 18: Summary of production boreholes, yields and abstraction durations

BH	Latitude (°S)	Longitude (°E)	Pump depth (mbgl)	Critical water level (mbgl)	Dynamic water level (mbgl)	Rest water level (mbgl)	Proposed abstraction rate (L/s)	Proposed abstraction duration (hr)	Proposed recovery duration (hr)	Daily volume abstracted (m ³ /day)
SL5	-32.42522	20.65880	55	50	30	18	4.69	24	0	405.2
SL6	-32.41500	20.65286	72	65	35	25	5.36	24	0	463.1
SL11	-32.40378	20.65822	75	70	30	21	5.2	24	0	449.3
										1317.6

The study area is located in the D51 quaternary catchment. The hydrogeological parameters for this catchment area are listed in Table 19. These values were used as inputs for calculating the firm yield of the aquifer in the catchment using the AFYM described in Section 2.10.1. The results of this calculation are presented in Table 20. It is seen that the aquifer can sustain an abstraction rate of approximately 102 L/s.

Table 19: Hydrogeological parameters for quaternary catchment D51 (Murray *et al.*, 2012)

Parameter	D51A
Groundwater Level (mbgl)	11.8
Max Drawdown (m)	5
Specific Yield	1.34E-03
Firm Yield (L/s)	359.6
Firm Yield (L/s/km ²)	0.4512
Recharge % (CMB)	7
Recharge Threshold (mm)	13
MAP (mm)	311
Hydrological MAR (mm)	11.9
Hydrological MAE (mm)	1950
Baseflow: Default (Mm ³ /a)	4.86
ET Model	Linear
ET Extinction Depth (m)	2
Riparian Zone (%)	2.7

Table 20: Results of the Aquifer Firm Yield Model for the relevant Quaternary Catchments.

Name	Q (L/s)	Q (m ³ /month)	Q (m ³ /a)
D51A	102.6	265939.2	3237809.76

5.11.1 Sutherland Town Area– Groundwater response unit (GRU)

Only three of the eight boreholes drilled as part of this study have been commissioned to act as production boreholes in the short to medium term. However, some of the other boreholes can also in

future be commissioned to increase the volume of water abstracted from the Southern Wellfield, if needed. The area in which Southern Wellfield is located is relatively unutilised and undeveloped in terms of groundwater. However, there is potential for agricultural expansion, and hence, increased private groundwater use.

To estimate the aquifer firm yield for the area surrounding the Southern Wellfield, a groundwater response unit (GRU) was delineated for the large area. The boundary of the GRU lies on the topographical highs surrounding the basin of the Sutherland area where bedrock outcrop is evident (Figure 73).

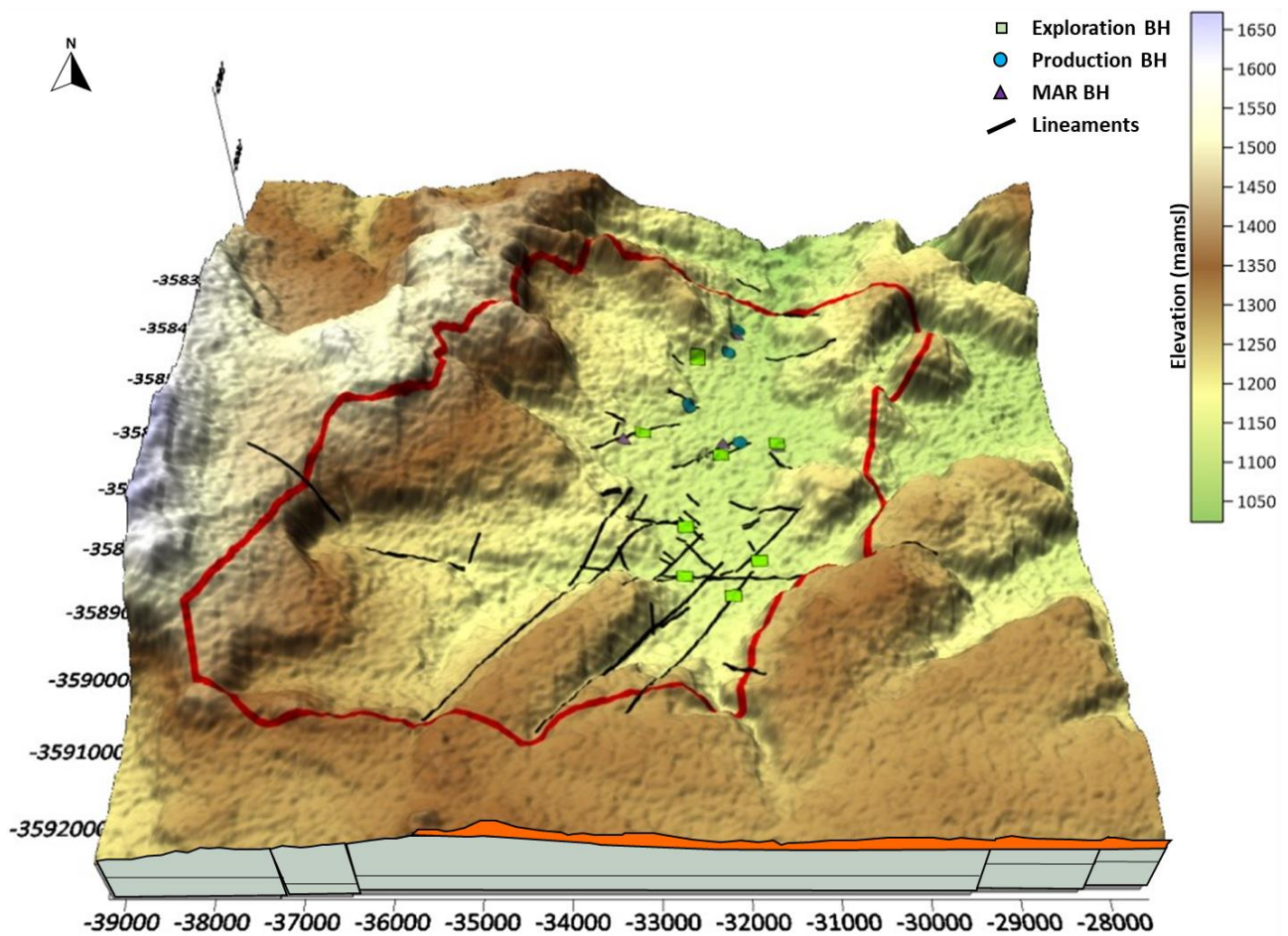


Figure 73: DEM model of the town GRU area using a 30 m DEM (ESRI, 2018)

The north-eastern and south-western highs of the GRU are characterised by outcrops of the Abrahamskraal Formation, comprising alternating layers of sandstone, siltstone, mudstone and gritstone. The north-western and south-eastern highs, on the other hand, are characterised by dolerite sill outcrops. The dolerite sills are unlikely to limit vertical recharge to the GRU as they are crosscut by drainage channels, associated with major linear geological structures. These structures are in turn associated with fractured bedrock. The basalt intrusion associated with a topographical high is also

unlikely to limit vertical recharge and may in fact enhance it since the parent bedrock hosting the basalt is highly fractured and contains west to east draining channels. The south-western portion of the GRU is likely to have the highest contribution to recharge from the upper escarpment and mountainous area, forming a small catchment draining generally towards the north.

The delineated GRU has an extent of approximately 45.7 km² and is predominantly in quaternary catchment D51A. Using the recharge value calculated with the CMB method (7.0% of MAP) the direct vertical recharge is calculated to be 994 889 m³/a, while the firm yield is calculated to be 650 782.74 m³/a, which is estimated to be 65.41% of the total recharge to the GRU. This translates to a yield of approximately 20.63 L/s for the GRU (averaged over a period of a year). The GRU does extend beyond the capture zones (discussed in Section 5.12) of the boreholes located within the Southern Wellfield area and there are other groundwater users within this extent. However, for this study groundwater use other than the three new production boreholes is assumed to be zero as it is difficult to quantify the volumes abstracted by the private groundwater users.

5.12 DELINEATION OF PROTECTION ZONES

As outlined by DWS (2021) decline in groundwater levels is a major risk for aquifer deterioration physically and in terms of quality. Protection zones within the Southern Wellfield were delineated by incorporating the total volume that can be sustainably abstracted from the three new production boreholes. from the three abstraction boreholes (SL5, SL6 and SL11). The total abstraction of approximately 1315 m³/day is distributed across a relatively undeveloped area in terms of groundwater utilisation. The delineation of protection zones was based on sound hydrogeological input and a good conceptual understanding, developed through the borehole network established as outlined in previous sections of this study. Aquifer parameters calculated from the pumping test data in Section 5.7 were assigned to the conduit zones associated with major structures and average hydraulic parameter values were assigned to the bedrock matrix within the model domain.

Four different protection zones corresponding to four different levels of protection were delineated, namely: 1) the wellhead protection zone around the production boreholes, 2) an inner protection zone, 3) an outer protection zone, and 4) the source catchment zone considering the entire GRU from which recharge is derived.

5.12.1 Wellhead protection zone

As described in Section 2.9, wellhead protection areas are generally for protection of the physical borehole from point source pollution through fencing off the area surrounding the borehole and its

associated headworks. No activities other than routine monitoring and maintenance of borehole infrastructure are permitted in this zone. This then acts as protection against potential pollution of activities around the boreholes and vandalism or theft. This level of protection has already been implemented at three of the new production boreholes. The other newly-drilled boreholes and decommissioned production boreholes have been sealed and shut with a lockable cap and surrounding sanitary seal. Figure 74 shows an example of a newly established production well (SL11).



Figure 74: Wellhead protection at SL 11 with a fenced zone around the production hole and associated headworks

5.12.2 CJWFM to delineate the inner and outer protection zones

The CJWFM was used to delineate the inner and outer protection zones by modelling the decrease in the hydraulic head of the aquifer as a function of time and distance from the abstraction boreholes. The CJWFM uses the Cooper-Jacob approximation of the Theis equation describing radial confined

groundwater flow in a uniformly thick horizontal, homogeneous, isotropic aquifer of infinite areal extent. Although the characteristics of the fractured rock aquifer in the Sutherland area do not generally conform to these assumptions, the CJWFM can still be used to model the groundwater response of the Sutherland aquifer by taking the geometry of the aquifer into account and by making additional assumptions.

First, it should be noted that the three production boreholes in the Southern Wellfield were all drilled into linear fracture zones that occur within the fractured hard rock aquifer. Groundwater abstraction from these boreholes will cause a decrease in the hydraulic head along the fracture zones, with the largest decrease occurring at the abstraction boreholes. The decrease in hydraulic head will decrease with distance from the boreholes. Groundwater flow will take place from the matrix towards the fracture zone, with larger flows occurring closer to the boreholes where the largest hydraulic gradients between the matrix and the fracture zones are present. It is therefore expected that the cone of depression around a borehole will not be circular, but will be elongated in the direction of the strike of the fracture zone.

For the current study, it is assumed that each position along the fracture zone acts as an abstraction borehole. It is further assumed that abstraction at a specific borehole takes place at a rate proportional to the decrease in hydraulic head at that borehole. The total decrease in hydraulic head around the wellfield is then assumed to be the superposition of all the individual cones of depression around these virtual boreholes in the fracture zone.

Since it is not possible to model the response from an infinite number of virtual boreholes along the fracture zone, a finite number of boreholes was considered by placing virtual boreholes every 50 m along the strike of the fracture zone. The above approach to simulate the flow and drawdown in the matrix using virtual boreholes is explained graphically in Figure 75.

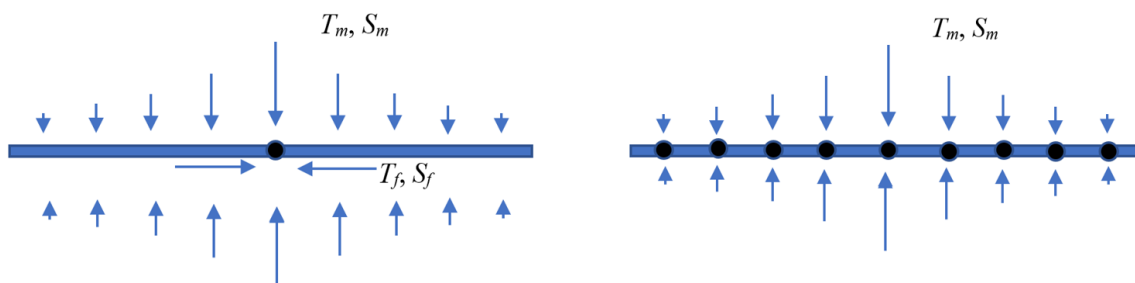


Figure 75: Left: fracture and matrix flow in the vicinity of an abstraction borehole (black circle) in a fracture zone; right: virtual borehole approach to simulate matrix flow

To illustrate the above approach, consider the pumping test data recorded for production borehole SL5 using borehole SL4 as an observation borehole. Using the FC method, the late-time T - and S -values of the aquifer were estimated from the response measured at SL4 (Figure 76, lefthand graph). With these calculated values for the hydraulic parameters, the corresponding drawdown in a virtual borehole 50 m from borehole SL5 could be calculated (Figure 76, righthand graph).

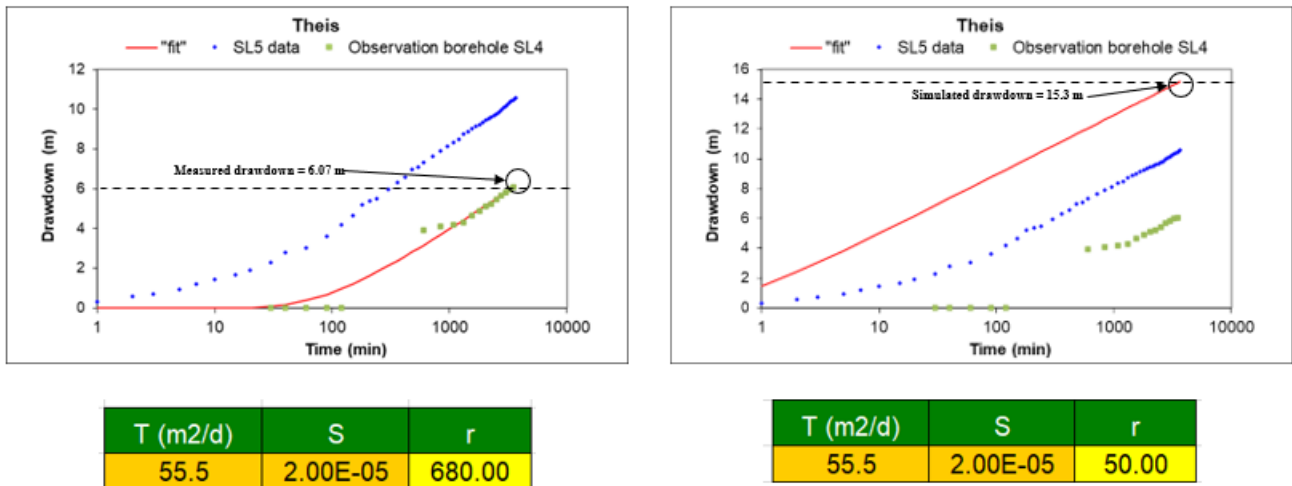


Figure 76: Theis fit for late time drawdown. Left; water level response at observation borehole SL4 distance 680 m, right; water level response prediction at a distance of 50m.

Using this approach, drawdowns were simulated for all the virtual boreholes along the fracture zone in which SL5 occurs. The drawdowns were then used to weight the pumping rates at the virtual boreholes. The total of the weighted distribution is equal to one (1), while the abstraction rate at borehole SL5 was 4.69 L/s. To calculate the abstraction rates at the virtual boreholes, the ratio of the drawdown at each virtual borehole to the total drawdown was then multiplied by the abstraction rate at SL5 (Table 21).

To delineate the inner and outer protection zones using the CJWFM, the abstraction rates at boreholes SL5, SL6 and SL7 were set to their estimated sustainable yields of 4.69 L/s, 5.36 L/s and 5.20 L/s, respectively (refer to Section 5.7.8). The hydraulic parameters assigned to the aquifer were the averages of the values estimated for the matrix (Section 5.7.7), i.e., a T -value of 3.67 m²/day and an S -value of 8.58×10^{-3} .

Table 21: Weighted abstraction rates for virtual boreholes along the fracture zones in which production boreholes are drilled

Number of points	Distance (m)	Simulated drawdown (after 3 days of pumping) (m)	Weighted distribution based on drawdown	Abstraction distribution along conductive zone (L/s)	Percentage abstraction
1	0.1	37.2	0.228	1.07	22.8
2	50	15.3	0.094	0.22	4.7
2	100	12.8	0.078	0.18	3.9
2	150	11.5	0.071	0.17	3.5
2	200	10.5	0.064	0.15	3.2
2	250	9.7	0.059	0.14	3.0
2	300	9.1	0.056	0.13	2.8
2	350	8.4	0.052	0.12	2.6
2	400	8.1	0.049	0.12	2.5
2	450	7.6	0.047	0.11	2.3
2	500	7.2	0.044	0.10	2.2
2	550	6.9	0.042	0.10	2.1
2	600	6.6	0.040	0.09	2.0
2	650	6.3	0.039	0.09	1.9
2	700	6.0	0.037	0.09	1.8
Totals	Totals	163.06	1.000	4.69	100.00

5.12.2.1 Inner protection zone

For the current study, this zone is defined as the area within which the groundwater drawdown in the aquifer is predicted to be 5 m after 50 days of pumping, changing the hydraulic gradient towards the pumping borehole. Water particles within this zone are drawn towards the borehole. Additional groundwater abstraction in and around this zone could potentially lower the groundwater level below the 5 m drawdown limit of this protection zone. Furthermore, activities within this zone that could result in aquifer deterioration in terms of groundwater quality through chemical or microbial contamination are not permitted. Prohibited activities are discussed in Section 6.2.3 and listed in Table 23. The inner protection zone delineated around the Southern Wellfield is shown in Figure 77.

5.12.2.2 Outer protection zone

This zone is delineated by the 5-m drawdown contour as it occurs after 365 days of pumping from the abstraction boreholes in the Southern Wellfield. The CJWFM was again used for the delineation of this protection zone. Any additional groundwater abstractions within this zone would result in a water level lower than the defined limit and can therefore not be allowed. The delineated outer protection zone is shown in Figure 78.

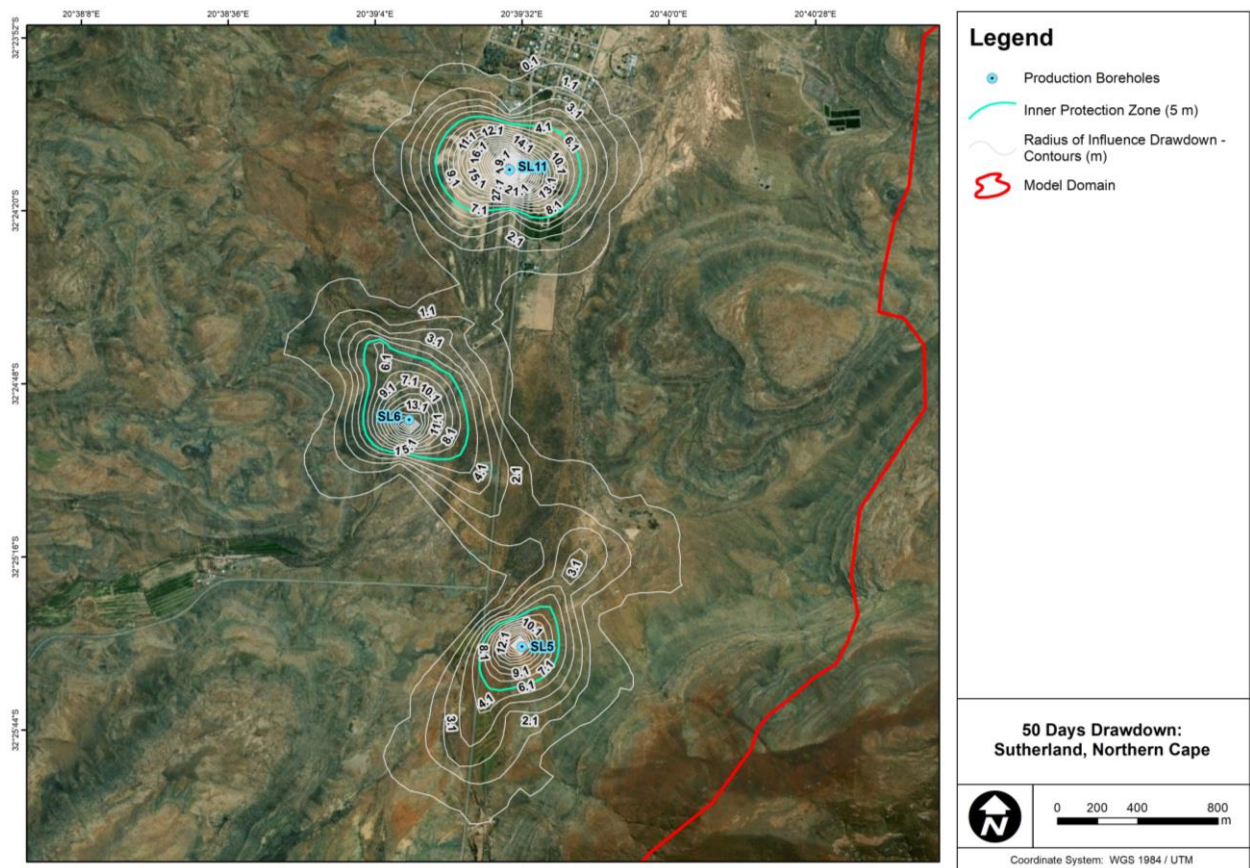


Figure 77: Delineation of the inner protection zone around the boreholes of the Southern Wellfield

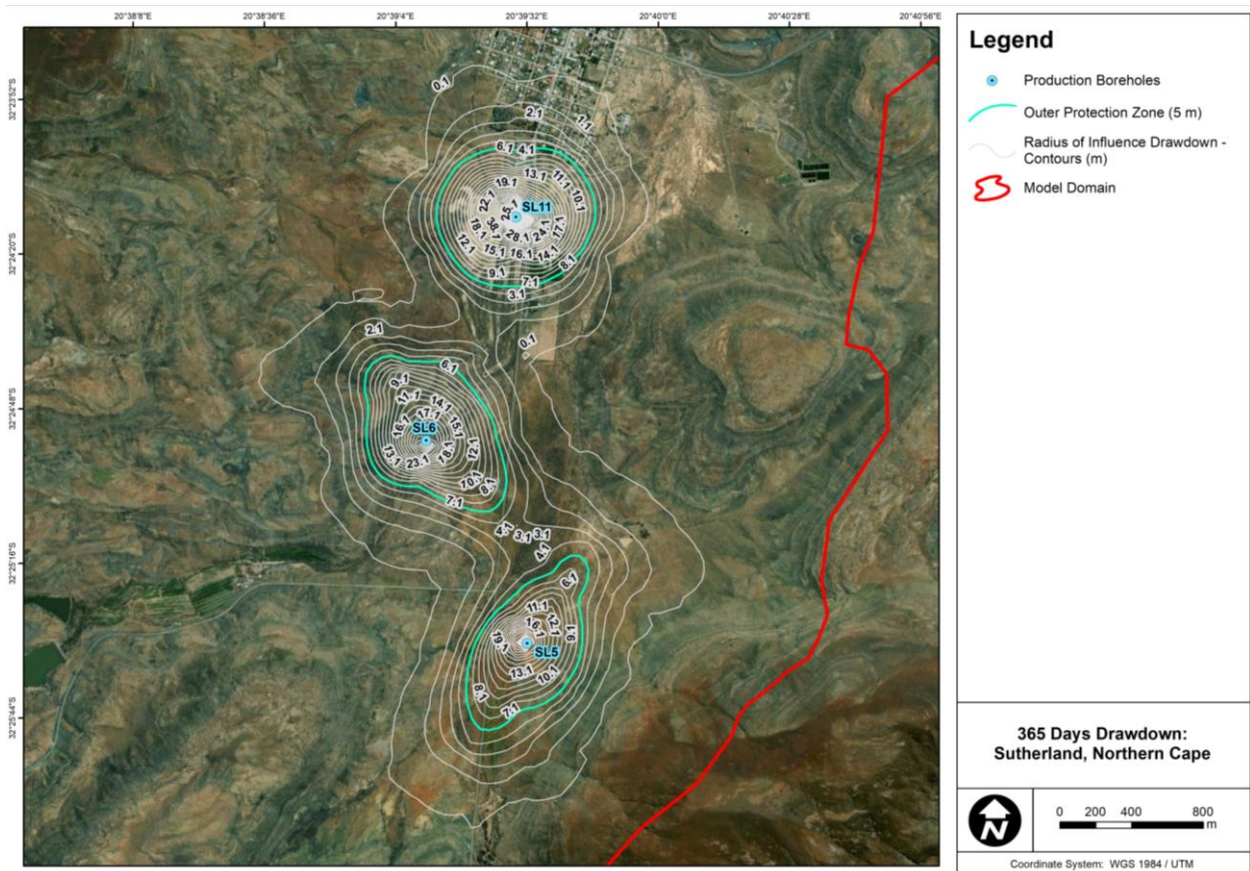


Figure 78: Delineation of the outer protection zone around the boreholes of the Southern Wellfield

5.12.3 Source catchment protection zone

Over-abstraction of groundwater from the aquifer in the Sutherland area has resulted in a lowering of the water table over time. In an existing borehole (BH4_Vlei) over-abstraction has even resulted in borehole collapse. Thus, long-term damage to the aquifer has occurred due to over-abstraction. In the current study, the boundaries of the GRU defined in Section 5.11.1 are also considered to be the limits of the source catchment protection zone. Care must be taken that activities within this zone do not negatively affect the aquifer system in terms of groundwater quantity and quality. The source catchment protection zone is shown along with the inner, outer and wellhead protection zones in Figure 79. These protection zones are also shown in Figure 80 relative to the infrastructure and different land uses in and around the town of Sutherland.

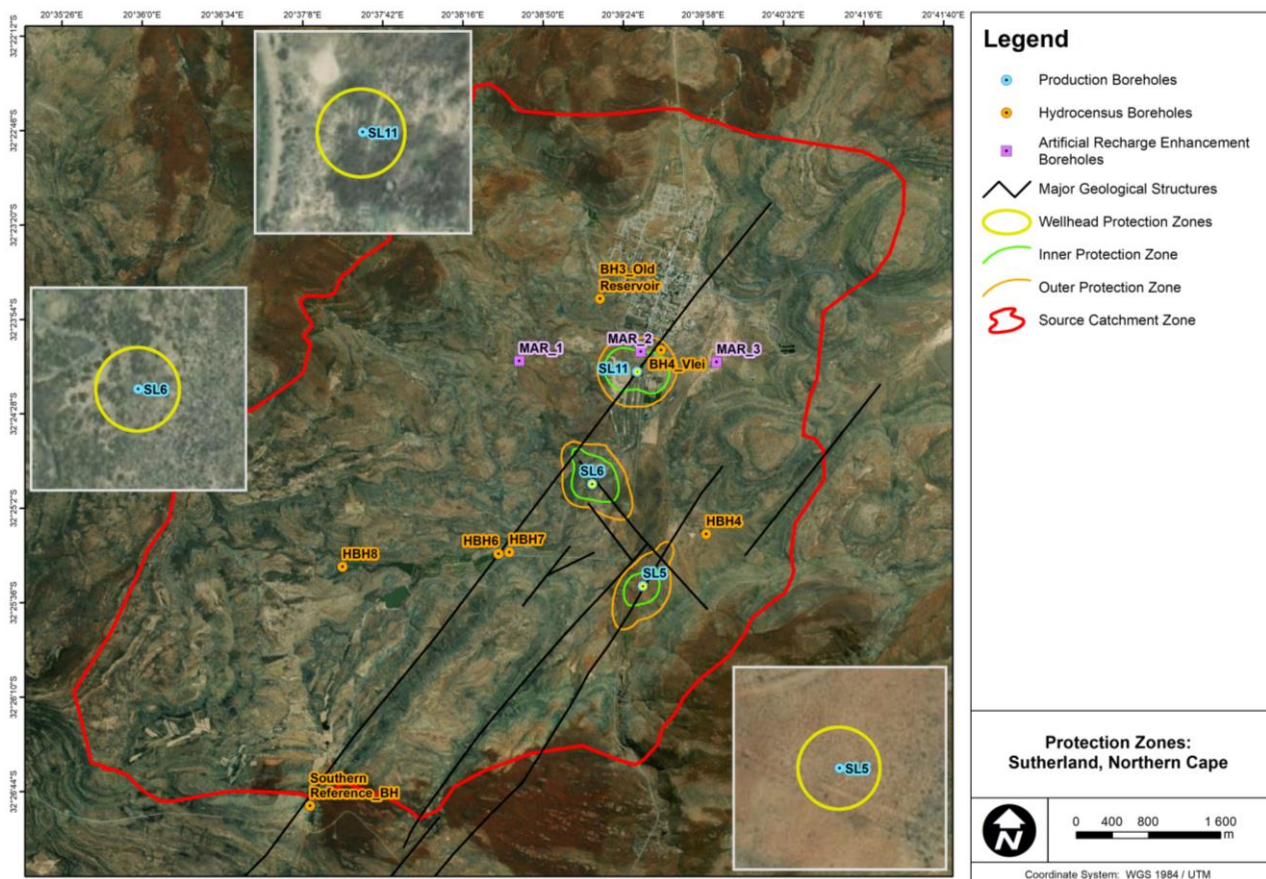


Figure 79: Delineated protection zones for the Southern Wellfield

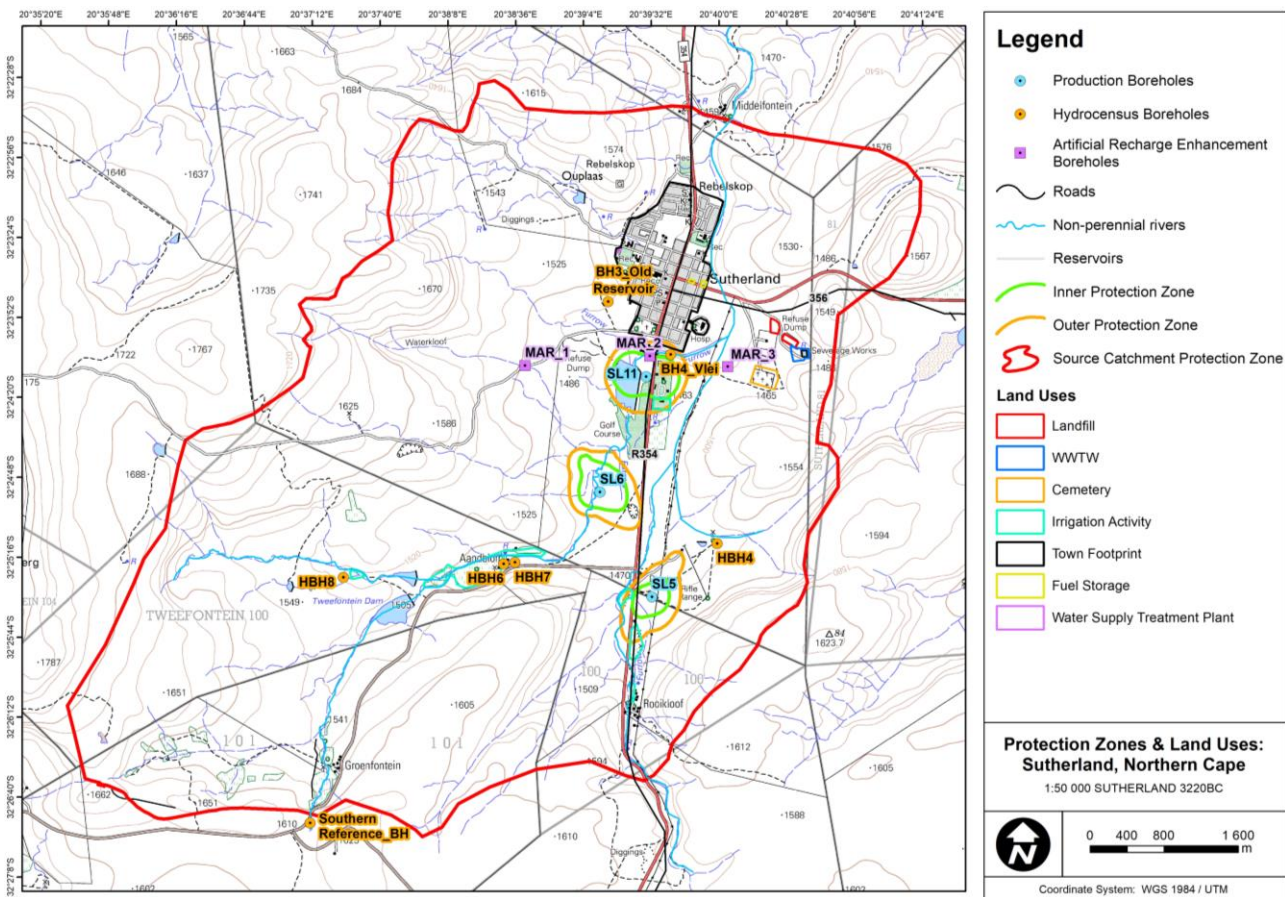


Figure 80: Delineated protection zones relative to land use in and around the town of Sutherland

5.13 RISK ASSESSMENT FOR PROTECTION ZONES

The greater Sutherland area is largely undeveloped with a small anticipated growth factor in terms of population and development in the foreseeable future. The production boreholes within the Southern Wellfield are located in conduit zones where groundwater flow is controlled by the presence of non-continuous open joints and fractures, while storage is associated with the large rock mass matrix recharging the conduit zones. The commissioning of the Southern Wellfield comprises abstraction activities planned for the short and medium term, with proposed expansion in the long term. There are minimal to no development plans in terms of buildings, cemetery development or erecting of fuel storage facilities.

The evaluation of the potential risk through the potential source-pathways-receptors approach, as well as the risk for aquifer yield and quality deterioration due to abstraction, is outlined below. The potential for contamination due to anthropogenic factors is low and such potential sources are located far from the Southern Wellfield. The potential impact for aquifer deterioration in terms of quantity and quality was assessed by considering sources of contamination and abstraction from the aquifer. The potential contaminant sources are summarised and rated in Table 22.

Table 22: Impact table for potential pollution of the aquifer underlying the Southern Wellfield

Potential impact on groundwater quality deterioration due to contamination through point source								
Activity	Description	Type of impact	Assessment of impact				Rating total	Confidence rating
			P	I	D	E		
Pit latrines	Two homesteads with no municipal sewerage connection towards the south and southwest	Direct	1	1	3	1	6	3
Irrigation agricultural activities	Three small scale irrigation farming activities (pesticide and fertilizer application)	Direct	2	2	3	2	9	2
Road	R354 access road towards town	Direct	1	1	0	2	4	3
WWTW	Located towards the far northeast of the Southern Wellfield	Indirect	0	1	4	0	5	3
Waste Disposal Yard	Located towards the far northeast of the Southern Wellfield	Indirect	0	2	4	0	6	3
Cemetery	Located towards the far northeast of the Southern Wellfield	Indirect	0	1	4	0	5	3
Potential impact on groundwater quality deterioration through over abstraction								
Municipal supply abstraction	Abstraction for the municipal supply is based on conservative volumes considering a net zero recharge to the aquifer over 10 years.	Direct	2	1	2	3	8	3
Municipal + private abstraction	Volume abstraction from private groundwater users unknown.	Direct	2	3	3	3	11	1
Potential impact on groundwater quantity deterioration through over abstraction								
Municipal supply abstraction	Abstraction for the municipal supply is based on conservative volumes considering a net zero recharge to the aquifer over 10 years.	Direct	1	1	1	1	4	3
Municipal + private abstraction	Volume abstraction from private groundwater users unknown.	Direct	4	2	3	3	12	2

P: probability; I: intensity; D: duration; E: extent

The outcome of the risk assessment shows high confidence in a medium risk for point source contamination. There are minimal existing potential point source contaminant sources within the inner and outer protection zone. An indirect contaminant is the most likely to occur within the local to regional setting and can be mitigated through the implementation of the groundwater management

plan. Municipal groundwater abstraction with the addition of private groundwater abstraction is considered to pose the highest risk of directly negatively impacting the aquifer in terms of quality and quantity. The municipal supply on its own could directly impact the aquifer; however, this is less probable should a comprehensive groundwater management plan be implemented.

CHAPTER 6: PROPOSED GROUNDWATER MANAGEMENT AND MONITORING PLAN

6.1 INTRODUCTION

The purpose of source protection within the predefined protection zones is to ensure long-term operation and sustainability of the newly developed Southern Wellfield for the town of Sutherland. The goal is to ensure that the water resource is protected from over-abstraction and contamination, keeping in mind the potential for expansion of the existing groundwater supply network within the source catchment zone.

6.2 PROPOSED REGULATIONS FOR GROUNDWATER PROTECTION ZONES AROUND THE SOUTHERN WELLFIELD

The protection zones are to be enforced by adopting a standard operating procedure to mitigate aquifer deterioration in terms of yield and quality. Restrictions were chosen specifically for the site, based on activities that may negatively impact the source. Proposed regulations for activities within the boundaries of the groundwater response unit are discussed below for each protection zone and are summarised in Table 23.

6.2.1 Inner protection zone (zone 1)

Proposed regulations of activities within the inner protection zone are as follows:

- No point source contamination activities are permitted. Pesticide and fertiliser application should be restricted and monitored; no feedlots allowed or any other high-risk activity.
- Pit latrines systems should be replaced by sealed pit latrines or conservation tanks. Regular maintenance of the system is a requirement.
- Access roads are allowed; however, with maintenance, no storage yards are permitted within this zone.
- No fuel storage facilities are permitted within this zone.
- No new groundwater development and use are permitted within this zone unless it is an existing groundwater use for small-scale garden irrigation or domestic use.

Table 23: Proposed regulations for activities within the different protection zones

Activity	Wellhead	Inner zone	Outer zone	Source catchment zone
Pit latrines (discharge)	Not permitted	Not permitted	Permitted, but discharge must be regulated	Permitted
Agricultural activities (inorganic farming)	Not permitted	No new activities permitted	Existing activities permitted, no new large scale activities	Permitted
Road	Not permitted	Permitted, due to short term impact of potential contamination	Permitted, due to short term impact of potential contamination	Permitted
WWTW	Not permitted	Not permitted	Not permitted	Permitted, subject to proper planning and design considering environmental factors. Lined design preventing seepage into the vadose zone. Developed in low aquifer vulnerability area. Mitigations measures are in place for potential spillage or leakage.
Waste Disposal Yard	Not permitted	Not permitted	Not permitted	Permitted, where existing and new installations conforms to acts and regulations for the disposal of hazardous and non-hazardous waste
Cemetery	Not permitted	Not permitted, unless existing sites are evident	Not permitted, unless existing sites are evident	Permitted

6.2.2 Outer protection zone (zone 2)

The proposed regulations of activities within the outer protection zone are:

- Similar to zone 1, having point source contaminants within zone 2 is to be avoided. However, considering the extent of existing farming and town activities, it is not possible to completely prohibit such contaminant sources. Thus, existing activities must be monitored and regulated. For example, pit latrines could be replaced by sealed pit latrines or conservation tanks or connections can be made to the existing municipal sewer system. Organic farming as point source pollution should establish a monitoring network upgradient and downgradient of the activity which should include groundwater level and quality monitoring.
- To prevent hydrocarbons from entering the aquifer no fuel storage facilities are permitted within zone 2.
- The establishment of facilities for waste disposal, storage of hazardous chemicals, wastewater treatment works and disposal of water treatment disposal is prohibited.

- Groundwater use within zone 2 is permitted; however, this is subject to a technical review of the planned abstraction and potential impact on the municipal supply.

6.2.3 Source catchment protection zone (zone 3)

The extent of the source catchment zone and the existing established activities within this zone make the prohibition of certain activities difficult. Hence, restrictions are more relaxed and should be managed through mitigation and monitoring practices. Caution should be taken with waste disposal, storage of hazardous chemicals, wastewater treatment works, and the disposal of residual water treatment products. Monitoring of groundwater abstraction volumes, levels and quality should be done. The spacing between abstraction points within the catchment should be taken into account.

Detailed hydrogeological studies must be completed with the introduction of any potentially polluting activities, especially along major groundwater flow-controlling geological structures. Depending on the nature of the activity and the associated risks to the groundwater system, the development of a numerical model (flow or transport, depending on the activity) should be considered.

No commercial groundwater use is to be permitted in the source catchment zone with the exemption of existing farming activities, based on the condition that groundwater monitoring is done.

6.3 IMPLEMENTATION OF PROTECTION ZONES

The implementation of protection zones requires the involvement of all stakeholders within the source catchment zone. A groundwater management committee needs to be established, comprising members of the local government and community, with oversight of a qualified hydrogeologist from an NGO or the DWS. The committee will be responsible for day-to-day resource management and for educating the community on the importance of resource protection. The committee should also be the appropriate channel of communication for reporting violations of regulations within the protection zones. The implementation should be a continuous and recurring process comprising of:

- Establishment of the groundwater management area, i.e., defining the protection zones, associated risks and mitigation measures.
- Management of groundwater use within the source catchment zone. From the assessment, it is clear that the source catchment zone is already stressed in terms of abstraction as a result of an increase in the number of private groundwater users within the town area. Therefore, groundwater use must be regulated within the different zones. Any proposed groundwater use within the source protection zones requires a pumping test according to the National

Standard (SANS 10299-4:2003, Part 4 – Test pumping of water boreholes) which has stipulated guidelines for the testing of water boreholes.

- Protection against contamination through mitigation. This entails ensuring that all boreholes within the area are properly constructed and monitored to ensure that contaminants do not enter the aquifer through artificial pathways. Casings must be intact and sanitary seals must be established around newly drilled and existing boreholes.
- Establishment of a detailed groundwater monitoring and management plan to ensure that the regulations relevant to the different groundwater protection zone regulations are adhered to.

6.4 GROUNDWATER MANAGEMENT PLAN

The source protection zones should be implemented through the establishment of a groundwater management plan. The groundwater management plan has clear objectives, incorporated into the monitoring plans and standard operating procedures. Furthermore, the management plan should include fixed revision timelines to assess whether the objectives have been achieved. Flexibility should be built into the plan to accommodate any deviation from the original scope. The following objectives have been set out for the management plan:

- To stabilise and potentially reverse, the long-term decline in groundwater levels within the aquifer.
- To sustain baseline groundwater quality. This is based on one set of test results; therefore, seasonal changes may occur in the chemistry of groundwater from the boreholes that have not been accounted for.
- To establish environmental and compliance monitoring within delineated protection zones.
- To incorporate a mitigation plan and standard operating procedure for point source contamination and aquifer deterioration.

An annual revision of the management plan is recommended, based on data collected throughout the year of monitoring. The parameters monitored within the groundwater management area should be well understood. As described by the WRC guidelines for monitoring and management of groundwater resources in rural supply schemes (Meyer, 2002), parameters should include production groundwater levels, monitoring borehole water levels, groundwater quality, volumes abstracted from boreholes, borehole pumping regimes and the town demand.

6.4.1 Wellhead protection zone (production boreholes)

All of the production boreholes need to be equipped with water level and flow monitoring equipment. This includes the installation of an observation pipe and an automated water level logger that allows for continuous water level monitoring during production. A flow meter must be installed that can monitor the total volume abstracted and the flow rate during production. It is highly recommended that this is connected to a telemetry system for remote access to the data. The safe yields and crucial water levels were obtained from the hydraulic testing data discussed in Section 5.7. Table 24 provides a summary of the recommended abstraction rates, pumping durations and critical management water levels for the three new production boreholes in the Southern Wellfield.

Table 24: Production borehole abstraction rates and management water levels

BH ID	Recommended abstraction rate (L/s)	Abstraction duration (hrs)	Recovery duration (hrs)	Pump installation depth (m)	Rest water level (mbgl)	Dynamic water level (mbgl)	Critical water level (mbgl)
SL5	4.5	24	0	55	18	30	50
SL6	5.2	24	0	72	25	35	65
SL11	5.2	24	0	75	21	30	70

Groundwater level trend analysis of the monitoring data must inform abstraction rate adjustments and optimisations. The water level in the production boreholes may not drop below the critical water level (Table 24). If the water level drops below the critical water level, the abstraction rate must immediately be reduced by 20%. After a week (7 days) the monitored groundwater levels should be assessed; should this still be below the critical water level, abstraction must be reduced by a further 20%. This process must be repeated until the problem of low water levels in the abstraction borehole is solved. Should the abstraction borehole show sufficient recovery, the abstraction rate can be increased by between 5% and 10% and groundwater levels assessed weekly until this is close to or above the predefined dynamic water levels. Alternatively, where one of the backup boreholes can be used to abstract groundwater at a low rate, the pump in the production borehole should be switched off and recovery should be allowed for a period of 2 months.

Baseline chemistry values were obtained during the initial hydrochemical assessment. Considering the heterogeneous characteristics and sometimes unpredictable nature of the natural system, a percentage deviation needs to be allowed in terms of chemical parameter analysis and results. Should the chemical parameter results deviate more than 10% during a particular monitoring and sampling run, further investigation will be required. If this trend continues at a single production borehole or within all boreholes within the wellfield, the wellfield abstraction should be re-assessed during the annual management plan evaluation. Groundwater from the boreholes has been classified as the

sodium-bicarbonate type; therefore, careful monitoring of the following chemical parameters should be done: sodium, total carbon, total alkalinity and total hardness.

6.4.2 Inner protection zone, outer and source catchment protection zone

Boreholes located within these zones will form part of the monitoring network. If boreholes are equipped and in use, flow rates and water levels must be monitored. Those that are unequipped should be closed with a lockable cap that can be monitored. Abstraction and flow monitoring within these zones will provide valuable information on water level responses within the aquifer. Furthermore, key boreholes (up and down gradient) can be identified where groundwater sampling should take place with the aim to monitor any deviation from the baseline chemistry that may be associated with aquifer quality deterioration due to over-abstraction. The MAR boreholes within the source catchment zone form part of the water balance management as prevention of aquifer yield and quality deterioration, as discussed in Section 6.4.2.3.

6.4.2.1 Inner protection zone

Boreholes located in the inner protection zone that are not the production boreholes should be decommissioned and solely used for monitoring purposes or utilised as MAR boreholes. All boreholes should be closed with a lockable cap and clearly marked.

6.4.2.2 Outer and source catchment protection zones

Groundwater abstraction outside of the production boreholes is permitted in this zone; however, such abstractions must comply with the regulations outlined in Section 6.2.2. All boreholes must be equipped with a flow meter, a sampling tap and an observation pipe similar to the infrastructure required at the production boreholes. This allows for more accurate flow rates and water level responses in the aquifer to be measured.

6.4.2.3 Managed aquifer recharge (MAR) within the source catchment zone

Considering the current water demand of the town of Sutherland, the projected increase in demand and erratic precipitation, natural recharge is the limiting factor of the groundwater balance. Recharge can, however, be enhanced through the process of intentionally injecting source water (precipitation or surface runoff) into the aquifer. There is a wide variety of reasons for doing this, as well as a range of methods and technologies that can be used to achieve the desired outcome. In general, groundwater recharge in the Sutherland area occurs episodically, rather than seasonally, due to the limited number of rainfall events above the threshold value where groundwater recharge occurs. The benefits of

implementing artificial recharge in Sutherland are that at these locations recharge would not only be higher during “normal” episodic recharge events but the artificial recharge areas would additionally allow for recharge to occur during rainfall events that would otherwise be lower than the threshold.

The conceptual idea for implementing MAR in the Sutherland area is to locally increase recharge in areas of municipal groundwater production. This is to be done locally at areas of abstraction, that is, within proximity of abstraction boreholes. MAR into porous aquifers can be done by infiltration ponds or injection boreholes.

Infiltration ponds require a greater surface area and are subject to decreasing efficiency over time due to sediment build-up and blockage at the bottom of the ponds. This can be mitigated with management plans and pre-treatment; however, the extent of management required will be dependent on the designs of the ponds. The high evaporation rates should also be considered, which may cause infiltration losses. For this reason, it is recommended that while infiltration tests can be done in the feasibility study, the focus should be on injection rate determinations. Authorisation to manage the recharge of the aquifer will be required from the Department of Water and Sanitation (DWS). In areas where there are high biodiversity concerns (such as drainage channel reeds), it may be required to also discuss authorisation with the Department of Environmental Affairs (DEA). These departments will be responsible for allowing the managed aquifer recharge, as well as for specifying licence conditions.

The benefit of these boreholes is shown conceptually in Figure 81 where pumping water levels are kept above critical fractured water strikes in production boreholes by facilitating a local rise in the piezometric level of the aquifer.

6.5 GROUNDWATER MONITORING PLAN

The groundwater monitoring plan will provide valuable data for the groundwater database that can be referred to in decision-making. The information recorded will include details on the production boreholes and the overall status of the source catchment zone. The monitoring plan aims to:

1. Monitor the crucial operation water levels and abstraction rates at the production boreholes, thereby preventing water levels from dropping below major water strikes during abstraction.
2. Monitor the water levels in the borehole network to prevent a drop in water levels that could result in aquifer deterioration in terms of yield and quality.
3. Evaluate the chemistry data obtained from a sampling event at predefined monitoring points.
4. Build a database from which seasonal trends can be deduced.

Through long-term monitoring, inconsistencies might be picked up, where deviation from the baseline data occurs. However, considering the complexity of the natural system, such deviations are to be expected and can be used to update the conceptual model of the hydrogeological setting. To achieve the aims of the monitoring plan, certain input parameters need to be monitored according to a standard operating procedure, as described below.

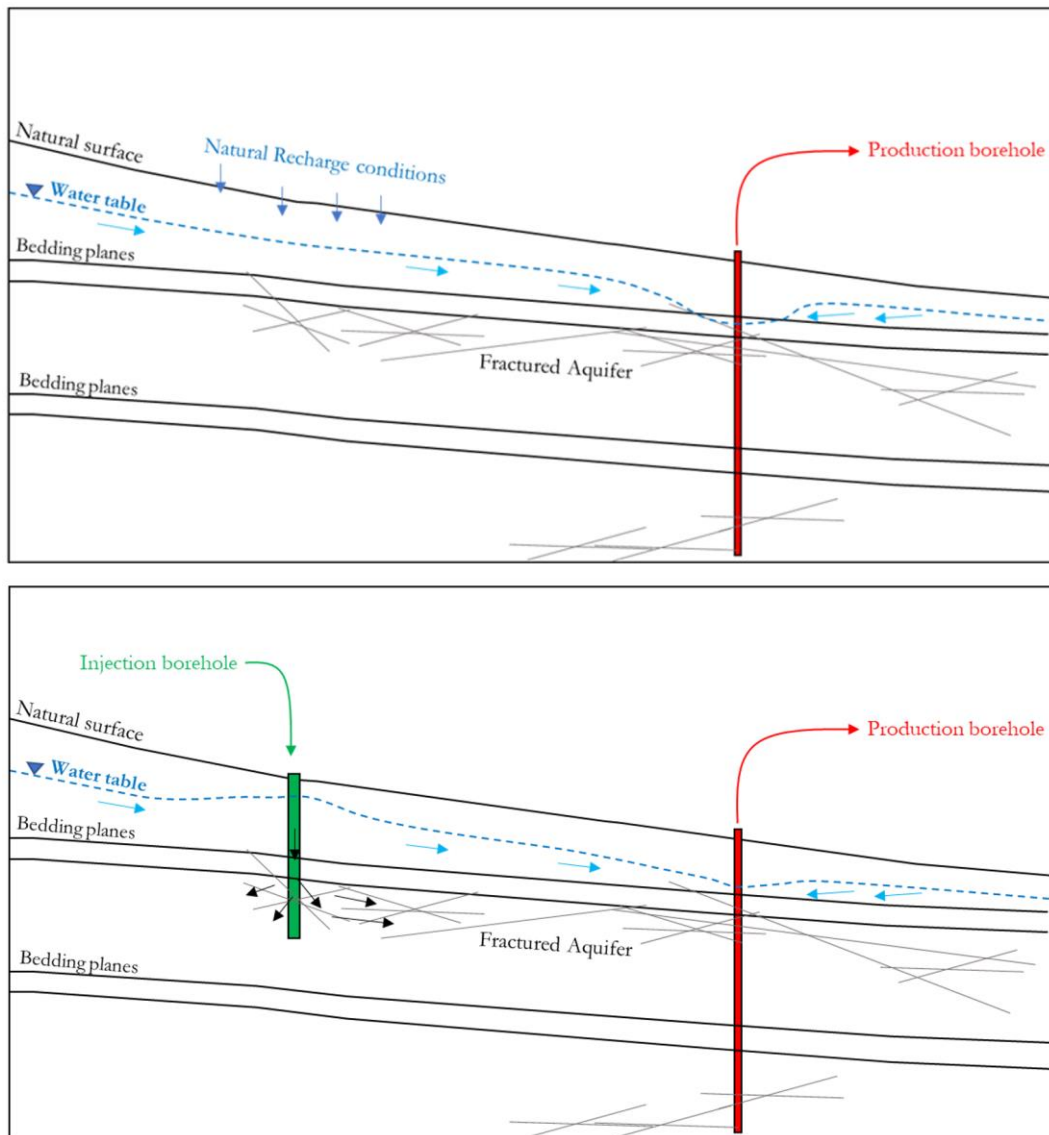


Figure 81: The expected effects of implementing injection MAR schemes in the study area. Normal production conditions (top) and MAR facilitated injection (bottom).

6.5.1 Standard operating procedure (SOP) for the monitoring plan

A standard operating procedure (SOP) has been developed to clarify what activities would be required during the groundwater resource monitoring for the source catchment of the study area. The monitoring network comprises 17 boreholes, including the three newly established production boreholes (Table 25). The monitoring network can be expanded should additional sites be identified

during the revision period of all of the obtained data compared to the baseline data. At this stage, no surface water monitoring points have yet been incorporated into the monitoring plan due to the non-perennial nature of the rivers within the catchment.

Table 25: Groundwater monitoring network with background values

Site ID	BH Type	Elevation (mamsl)	Latitude (WGS 84)	Longitude (WGS 84)	Depth (mbgl)	RWL (mbgl)	WL (mamsl)
BH3_Old Reservoir	Hydrocensus	1476	-32.39647	20.65387	120	72.00	1404.00
BH4_Vlei		1469	-32.40162	20.66102	44	21.63	1447.37
HBH4		1477	-32.42004	20.66628	-	12.20	1464.80
HBH6		1486	-32.42195	20.64179	150	22.50	1463.50
HBH7		1484	-32.42181	20.64308	150	23.00	1461.00
HBH8		1517	-32.42321	20.62340	150	18.00	1499.00
Southern Reference_BH		1595	-32.44710	20.61946	-	12.00	1583.00
SL1	Investigative/ Explorative	1485	-32.40117	20.64714	151	68.00	1417.00
SL3		1461	-32.40171	20.66632	150	23.25	1437.75
SL4		1474	-32.42004	20.66260	146.6	12.27	1461.73
SL9		1476	-32.42231	20.65247	100	29.56	1446.44
MAR_1	Managed artificial recharge	1493	-32.40266	20.64431	50	25.00	1468.00
MAR_2		1462	-32.40177	20.65863	50	20.60	1441.40
MAR_3		1595	-32.40229	20.66646	90	18.00	1577.00
SL5	Production	1482	-32.42522	20.65880	121	18.00	1464.00
SL6		1472	-32.41500	20.65286	121	25.00	1447.00
SL11		1464	-32.40378	20.65822	121	21.00	1443.00

All the boreholes should be accessible for groundwater sampling and water level measurements. Boreholes that are not in production must be constructed with a lockable cap to allow access to only authorised personnel tasked with completing the monitoring runs. Should telemetry systems not be in place, data must be collected by hand. However, in-person site visits should be completed regularly to assess the general status of the boreholes and surrounding areas. The monitoring frequency will depend on the role of the specified site within the monitoring network. Boreholes used for production purposes should be monitored daily for flow rates and water levels, whereas observation boreholes could be monitored monthly, quarterly or annually.

6.5.1.1 Abstraction rates, groundwater levels and chemistry

The monitoring of groundwater levels and abstraction rates requires high accuracy. Where it is recommended that production boreholes are equipped with advanced technology telemetry systems, connected to water level loggers and flow meters. The monitoring frequency depends on the type and the location of the borehole. Less frequent monitoring is required at boreholes towards the outer

protection zones. Table 26 provides an example summary of groundwater level and flow monitoring frequencies.

Table 26: Groundwater level and abstraction monitoring within different protection zones

Borehole category	Water level measurement frequency	Flow rate measurement frequency
Production boreholes (SL5, SL6 and SL11)	Every 5 minutes using telemetry system connected to logger. Manual water level measurement once a month.	Every 5 minutes using telemetry system connected to logger. Total volumes abstracted must be measured manually from flow meter readings once a week.
Observation borehole within the inner protection zone	Hand measurements weekly.	N/A
Observation borehole within the outer protection zone	Hand measurements monthly.	N/A
Observation borehole within the source catchment zone	Hand measurements monthly.	N/A

6.5.1.1.1 Water levels

Manual water level measurements need to be read with a dip meter. This should be measured from the datum level (the top of the borehole casing or observation pipe) to the groundwater level. Water levels should be recorded as meters below the datum level (mbdl) along with the datum level and converted to meters below ground level (mbgl), by subtracting the datum from the measured value.

6.5.1.1.2 Flow rate

The flow condition should be noted at production boreholes during each monitoring run, i.e., whether the pump is running or switched off. This is crucial to understand the water levels measured. The total volume of groundwater abstracted should be recorded during each monitoring trip and recorded in m³. The flow rate should be measured by timing the duration of one rotation of the 0.01 m³ (100 L) dial on the flow meter. A stopwatch should be used to time the dial. The flow rate in L/s is determined by dividing 100 by the rotation duration in seconds. For example, if the 0.01 m³ dial takes 40 secs for 10 rotations, the flow rate will be:

$$0.01 \text{ m}^3 \times 10 \text{ (revolutions)} \times 1000 \text{ L/m}^3 / 40 \text{ s}$$

$$= 2.5 \text{ L/s}$$

6.5.1.1.3 Chemistry

Groundwater quality monitoring includes basic field chemistry measurements, bulk sampling and individual sampling at monitoring sites. All samples should be submitted to an accredited laboratory

for analysis. Table 27 provides a list of the parameters for analysis during each groundwater sampling run. For the production boreholes and the inner protection zone, it is recommended that field chemistry measurements be taken monthly and samples submitted to a laboratory for analysis quarterly. Field chemistry can be taken quarterly in the outer protection zone, and annually within the source catchment during the annual bulk sampling run. The resulting data should be reviewed after each sampling run, and the sampling frequency should be assessed annually. All the data should be reviewed by a geohydrologist to make informed decisions on the abstraction rates and to detect any trends that could be associated with source contamination.

Table 27: Proposed groundwater sample chemical analysis parameters

Parameter	Frequency	
	Production boreholes (wellhead zone) and inner protection zone	Outer protection and source catchment zone
pH (at 25 °C)	Monthly (field chemistry)	Quarterly (field chemistry)
Conductivity (mS/m) (at 25 °C)	Monthly (field chemistry)	Quarterly (field chemistry)
Total Dissolved Solids (mg/L)	Monthly (field chemistry)	Quarterly (field chemistry)
Turbidity (NTU)	Quarterly	Annually
Colour (mg/L as Pt)	Quarterly	Annually
Sodium (mg/L as Na)	Quarterly	Annually
Potassium (mg/L as K)	Quarterly	Annually
Magnesium (mg/L as Mg)	Quarterly	Annually
Calcium (mg/L as Ca)	Quarterly	Annually
Chloride (mg/L as Cl)	Quarterly	Annually
Sulphate (mg/L as SO ₄)	Quarterly	Annually
Nitrate & Nitrite Nitrogen (mg/L as N)	Quarterly	Annually
Nitrate Nitrogen (mg/L as N)	Quarterly	Annually
Nitrite Nitrogen (mg/L as N)	Quarterly	Annually
Ammonia Nitrogen (mg/L as N)	Quarterly	Annually
Total Alkalinity (mg/L as CaCO ₃)	Quarterly	Annually
Total Hardness (mg/L as CaCO ₃)	Quarterly	Annually
Fluoride (mg/L as F)	Quarterly	Annually
Aluminium (mg/L as Al)	Quarterly	Annually
Manganese (mg/L as Mn)	Quarterly	Annually
Iron (mg/L as Fe)	Quarterly	Annually
Arsenic (mg/L as As)	Quarterly	Annually
Total Organic Carbon (mg/L as C)	Quarterly	Annually
E.coli (count per 100 ml)	Quarterly	Annually
Total Coliform Bacteria (count per 100 ml)	Quarterly	Annually
Heterotrophic Plate Count (count per ml)	Quarterly	Annually

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Informed groundwater management is essential for the longevity of the Sutherland town water supply scheme. This requires a good understanding of the geohydrological setting of the aquifer underlying the study area from which abstraction is taking place. Furthermore, an objective-driven management plan is required to prevent aquifer deterioration in terms of quality and quantity. This was deduced from the geohydrological investigations conducted at Sutherland for the Karoo Hoogland Municipality as part of an emergency water supply appraisal for drought relief.

7.1.1 Conceptualisation

A good conceptual understanding of the geological setting was valuable in saving time and costs during the investigation. Satellite imagery and literature showed a clear preference for the orientation of major fractured zones. The fracture zone characteristics made it easy to identify where these zones cut through the bedrock outcrop. This simplified the geophysical investigations in the lower-lying areas which are overlain by surficial cover and alluvial material. Furthermore, knowledge of the positions and orientations of the fracture zones, the locations of existing production boreholes, and the presence of potential contaminant sources allowed new boreholes to be drilled at positions across the study area removed from existing groundwater users and potential contamination risks.

Boreholes drilled into or close to the major fractured zones generally had higher yields in comparison to those drilled into the bedrock matrix only intersecting bedding plane fractures. Fractured zone boreholes intersected numerous fractures, while matrix boreholes generally only intersected one or two fractures associated with a transition from mudstone to sandstone within the Abrahamskraal Formation. Down-the-hole camera logging of the boreholes confirmed the fractured nature of the fracture zone boreholes. Displacement of the geological units was evident in some of the boreholes, indicating that the fracture zones are associated with fault structures.

The bedrock associated with the Abrahamskraal Formation is considered the sole aquifer within the regional setting. Where major fractured zones are evident, these are classified as conduit zones for groundwater flow, while the bedrock matrix forms the storage within the aquifer. The fractured zones are the most favourable targets for groundwater development, but are also susceptible to contamination due to the preferential flow that occurs along them.

7.1.2 Aquifer flow characteristics and parameters

The Abrahamskraal Formation owes its aquifer characteristics to folding, faulting and large intrusive events. The formation is associated with a well-developed fractured network with a high degree of connectivity between boreholes, even between boreholes that are almost 900 m apart. The 72-hour pumping tests completed in boreholes located in several major structures provided sufficient data from which assumptions could be made on the aquifer flow characteristics. Conduit zones are associated with high transmissivities and a relatively low storativity. Boreholes drilled into the bedrock matrix show the inverse, i.e., low transmissivities and higher storativity values. Groundwater flow within the aquifer is expected to be dominated by flow within the fracture zones with storage release from the matrix to the fracture zones. Both linear and bi-linear flow is expected to occur.

7.1.3 Risk for aquifer quality and quantity deterioration

In the process of developing the conceptual model, the aquifer characteristics, historical groundwater use and challenges were identified. It was important to understand existing groundwater use and potential activities that could negatively impact the aquifer. The Sutherland area has limited commercial groundwater use with only small-scale organic farming operations. The baseline data obtained during the testing phase showed generally good quality groundwater across the site. However, some boreholes were considered poor, especially in areas where there is a high density of boreholes and where over-abstraction has been taking place over the years.

Only a few potential contaminant sources were identified within the larger Sutherland area, and very limited contaminant sources in the study area. Should any contaminants be introduced into the area, contamination is likely to be episodic or of short duration. The non-perennial rivers within the source catchment could act as transport mechanisms for contaminants. The only existing contaminant source that could affect the groundwater quality in the Southern Wellfield is low-dose application of fertilizer, pesticide or herbicide up-gradient from the wellfield.

7.1.4 Protection zones and groundwater management plan

Considering the prominent difference between the matrix bedrock and the major conduit zones in which the production boreholes were drilled, the low risk for contamination in the newly developed wellfield, and the low potential for expansion of the wellfield, an analytical approach based on the Cooper-Jacob method was used to delineate the inner and outer protection zones around the boreholes in the wellfield. These protection zones were modelled by assuming zero recharge to provide a conservative approach. On the other hand, the source catchment protection zone was delineated by

considering several aspects of the water balance within the groundwater response unit defined for the study area. The delineated wellhead protection zones around the production boreholes were not based on aquifer characteristics, but consisted of an area of specified radius around the borehole in which protection occurs as a form of policing, preventing direct impacts on the production boreholes.

The inner protection zone provides insight into the radius of influence from the cumulative abstraction from all production boreholes from where contaminant sources can be drawn from the surface or the bedrock matrix, should such contaminants have progressed this far towards the conduit zones. Furthermore, a simulation of the water level response in the aquifer for 50 days of continuous pumping during production can be referred to as a baseline level as part of the groundwater management plan.

The delineated outer protection zone shows that over one year of continuous abstraction, the groundwater contribution towards the production boreholes will approach the town area where there are existing groundwater users and potential contaminant sources. Furthermore, the modelled water levels may be used as critical water levels in the aquifer to be used in the management plan.

The source catchment zone is considered a zone in which the water balance needs to be monitored and managed to ensure the sustainability of the aquifer. Regulations for the outer protection zone could potentially be implemented and relieved or relaxed, depending on the overall status of the source catchment zone. However, the wellhead and inner protection zones should be kept permanently in place to prevent aquifer deterioration. The proposed management plan developed as part of this study provides a guideline for the permitted or prohibited actions within each protection zone.

7.2 RECOMMENDATIONS

The town of Sutherland relies solely on groundwater for its drinking water supply. Careful management of the groundwater system is therefore crucial to ensure that the resource is utilised sustainably. In this regard, the following recommendations are made:

- The inner protection zones of the Southern Wellfield should be declared as protected areas with notices indicating the activities not allowed within the boundaries thereof.
- Mitigation measures should be established for those activities with the potential for contamination of the aquifer within the study area. Pit latrines should be sealed, replaced or connected to the municipal system.

- No groundwater abstraction for municipal supply can take place without adhering to the standard operating procedure specified in the groundwater management plan.
- Any commercial groundwater use should be prohibited within the source catchment zone. Existing boreholes within the inner and outer protection zones should form part of the monitoring network for the measurement of water levels. These boreholes should also be sampled during the annual sampling runs. The results of all monitoring events should be submitted to the groundwater management committee.
- With future studies, surface water monitoring should be done within the source catchment zone to improve the understanding of the processes that may affect the groundwater environment. This is of particular importance if managed aquifer recharge schemes are going to be put into place.
- The conceptual model should be updated with monitoring data from the borehole network. If additional boreholes are found within the study area, information from these boreholes should be incorporated to improve the conceptual understanding of the groundwater system. The conceptual hydrogeological model could then be used to construct a numerical groundwater flow model to further investigate the protection zones around the boreholes in the Southern Wellfield.

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ABSTRACT

This dissertation investigates the delineation of groundwater source protection zones for the newly developed Southern Wellfield for Sutherland in the Northern Cape, South Africa. This was achieved through a combination of a literature study, an investigation completed during an emergency bulk water supply study for the town, and by applying an analytical approach to delineate the different protection zones. The investigation included: 1) a desktop study, 2) detailed structural and geological mapping, 3) a geophysical survey, 4) investigative drilling, 5) pumping tests on six boreholes and a modified injection test on an artificial recharge borehole to estimate aquifer parameters and sustainable yields of each borehole, and 6) geochemical investigation of several groundwater samples to characterize the groundwater associated with the hydrogeological setting.

The information obtained during the investigations was collated in a database from which a conceptual hydrogeological framework (conceptual model) was developed. This framework considered the desktop phase, field studies, land use, climate data and hydrogeological impacts to characterize the physical environment with the end goal to compile a sustainable groundwater management plan. The delineation of protection zones for the newly established production boreholes included information from the conceptual model which considers the groundwater resource as part of the hydrological cycle and locally part of the source catchment area.

From the data obtained during the investigation, an analytical modelling approach was found to be ideal to meet the objectives of the study. The wellhead protection zones were based on a fixed radius, thus a demarcated area surrounding the borehole required for basic protection. For the inner and outer protection zones, major fractured zones were found to be key components in the process, as these conduit zones control local groundwater flow within the aquifer. Therefore, the flow characteristics from the bedrock matrix towards the fractured zones were used in simulating the radius of influence from the boreholes themselves, as well as the radius of influence of the cone of depression formed along the conduit zones in which the boreholes have been drilled. The source catchment was also delineated as a protection zone, based on the safe yield for the total capture zone in which groundwater abstraction is taking place. This was done by means of a water balance approach taking into account the rainfall, recharge and specific yield of the study area, either from literature or data obtained during the site investigation.

A risk assessment was included in the investigation to identify existing and potential threats for aquifer deterioration in terms of quality or yield, whether due to point source contamination or over-abstraction. Risks do exist within the source catchment zone with regard to contamination; however, these are considered low. Existing activities were identified within the outer protection zone that

could negatively impact the aquifer; however, these are small scale and have a low-risk classification. The biggest concern for aquifer deterioration has been identified as the cumulative municipal and unregulated private groundwater abstraction.

Using the result obtained, a groundwater management plan was compiled with regulations and mitigation measures considering the risks to the aquifer posed by different activities. Furthermore, a standard operating procedure for implementing the management plan and land use restrictions was recommended in the different protection zones.

Recommendations were made on the process required to implement the protection zones as well as mitigation measures to ensure the longevity of the water resource. Incorporating non-perennial surface water monitoring in the conceptual model was discussed, as well as a frequent revision of the conceptual model as new data become available. Should the database be considered sufficient in terms of the data pertaining to the hydrogeological environment, a groundwater flow and transport numerical model can be developed to improve the understanding of the aquifer and its processes.

APPENDIX A – BOREHOLE LOGS

Log of Borehole No.:		SL1		
Location:	Sutherland	Latitude:	-32.401172	
Date:	12/10/2021	Longitude:	20.647139	
D. Mulder Masters		Ground Elevation:	1483 mamsl	
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike	
Brown highly weathered bedrock	0		254 mm air percussion drilling (0 - 5 m) 219 mm OD/214 mm ID solid steel casing (0 - 5 m) Water strike @ 8 & 13 m. Yield ~3000 L/h, EC = 58 mS/m	
Greyish-brown moderately weathered siltstone	10		Fractured zone @ 32m	
Greyish-green moderately weathered and fractured siltstone	20		RWL ~68 mbgl	
Greyish-red moderately weathered siltstone	30		165 mm drilling (5 - 151)	
Light-grey siltstone, moderately to highly weathered	40		Water strike @ 97 & 101 m. Yield ~5000 L/h, EC 185 mS/m	
Light-grey moderately weathered siltstone	50		Water strike @ 110 m. Yield ~7100 L/h, EC 168 mS/m	
Grey competent siltstone bedrock with signs of fracturing	60		Water strike @ 122 m. Yield ~14400 L/h, EC 178 mS/m	
	70		Gas at fracture @ 140 m	
	80		EOH @ 151 m	
Grey moderately weathered and fractured siltstone	110			
Alternating light-grey to dark-grey slightly weathered siltstone	120			
Reddish-grey siltstone	140			
	150			
Drilled By:	Steyns Drilling		Remarks:	Total Airlift yield: 20 120L/h EC: 178 mS/m pH: 7.3
Drill Method:	Air percussion			
Logged By:	D. Mulder			

Log of Borehole No.:		SL3	
Location:	Sutherland	Latitude:	-32.401714
Date:	15/10/2021	Longitude:	20.66632
D.Mulder Masters		Ground Elevation:	1461 mamsl
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike
Brown soil	0	<p>254 mm air percussion drilling (0 - 5 m) 219 mm OD/214 mm ID solid steel casing (0 - 6 m) 140 mm OD solid uPVC casing (0 - 30 m) RWL = 21.66 mbgl</p> <p>Water strike @ 85 & 89 m. Yield ~9000 L/h, EC = 92mS/m</p> <p>140 mm OD screened uPVC casing (72 - 145 m)</p> <p>140 mm OD/125 mm ID uPVC casing (0 - 151 m)</p> <p>Water strike @ 132 m. EC = 92 mS/m. Airlift yield ~14 000 L/h</p> <p>EOH @ 151 m</p>	
Grey moderately weathered sandstone			
Reddish grey mudstone			
Light grey moderately weathered sandstone	20		
Grey moderately weathered and highly fractured siltstone	40		
Light grey moderately weathered sandstone with signs of fracturing	60		
Reddish grey mudstone with little to no weathering	100		
Light grey sandstone with signs of fracturing	140		
Drilled By:	Steyns Drilling	Remarks:	Total Airlift yield: ~14 000 L/h EC: 95 mS/m
Drill Method:	Air percussion		
Logged By:	D.Mulder		

Log of Borehole No.:		SL4	
Location:	Sutherland	Latitude:	-32.420039
Date:	19/10/2021	Longitude:	20.662603
Masters D. Mulder		Ground Elevation:	1474 mamsl
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike
Brown soil	0	<p>254 mm air percussion drilling (0 - 6 m) 219 mm OD/214 mm ID solid steel casing (0 - 6.0 m) 140 mm OD solid uPVC casing (0 - 30 m) RWL = 12.27 mbgl Water strike @ 24 m. Yield ~3000 L/h, EC = 75 mS/m Water strike @ 47 m. Yield ~24 000 L/h, EC = 75 mS/m 140 mm OD/125 mm ID uPVC casing (0 - 151 m) 140 mm OD screened uPVC casing (30 - 145 m) Water strike @ 122 m. EC 75 mS/m EOH @ 151 m</p>	
Grey moderately weathered sandstone			
Reddish grey mudstone			
Light grey moderately weathered sandstone	20		
Grey moderately weathered and highly fractured siltstone	40		
Light grey moderately weathered sandstone with signs of fracturing	60		
Reddish grey mudstone with little to no weathering	80		
Light grey sandstone with signs of fracturing	140		
Reddish Grey siltstone with no signs of weathering			
Drilled By:	Steyns Drilling		Remarks:
Drill Method:	Air percussion		
Logged By:	D. Mulder		

Log of Borehole No.:		SL5	
Location:	Sutherland	Latitude:	-32.425216
Date:	20/10/2021	Longitude:	20.658795
Masters D. Mulder		Ground Elevation:	1482 mamsl
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike
Brown soils	0		254 mm air percussion drilling (0 - 9 m)
Grey moderately weathered siltstone	10		219 mm OD/214 mm ID solid steel casing (0 - 9 m)
Reddish grey moderately weathered siltstone	20		Water strike @ 15 m. Signs of wetness
Greenish grey siltstone	30		RWL = 18 mbgl
Light grey siltstone with signs of fracturing	40		Water strike @ 21 m. Signs of wetness
Grey siltstone, moderately weathered	50		Water strike @ 33 m. Signs of wetness
Light grey sandstone, highly fractured	60		Water strikes at 56, 57, 58, 59, 61 and 71 meters. Airlift 30 000 L/h. EC = 59 mS/m
Reddish grey siltstone and mudstone layers	70		Water strike @ 82 m, airlift 43 000 L/h, EC = 59 mS/m
Reddish grey siltstone with little to no weathering.	80		EOH @ 121 m
	90		
	100		
	110		
	120		
Drilled By:	Steyns Drilling	Remarks:	Total Airlift yield: 43 000 L/h EC: 59 mS/m
Drill Method:	Air percussion		
Logged By:	D. Mulder		

Log of Borehole No.:		SL6		
Location:	Sutherland	Latitude:	-32.414999	
Date:	20/10/2021	Longitude:	20.652862	
Masters D. Mulder		Ground Elevation:	1482 mamsl	
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike	
Brown soils	0		254 mm air percussion drilling (0 - 6 m)	
Reddish brown highly weathered siltstone	10		177 mm OD/168 mm ID solid steel casing (0 - 6 m)	Water strike @ 8 m and 17 m. Signs of wetness
Light grey siltstone	20		RWL = 21 mbgl	Water strike @ 21 m. Signs of wetness
Reddish brown mudstone	30			Water strike @ 34 m and 40m. Airlift Yield ~ 16 000 L/h
Light grey fractured sandstone	40			140 mm OD solid uPVC (0 - 65 m)
Grey siltstone with clear signs of fracturing	50			Water strike @ 55, 57, 65, 68 and 71 m. Airlift Yield ~ 24 000 L/h. EC = 75 mS/m
Dark grey siltstone with signs of fracturing	70			140 mm OD perforated uPVC casing (65 - 109 m)
Dark grey to reddish grey alternating layers of mudstone and siltstone	80			Water strike @ 96 m. Airlift Yield 53 000 L/h
	90			Water strike @ 107 m. Airlift Yield ~ 62 000 L/h
	110			
	120			EOH @ 121 m
Drilled By:	Steyns Drilling		Remarks:	Total Airlift Yield : 62 000 L/h
Drill Method:	Air percussion		EC: 75 mS/m	
Logged By:	D. Mulder			

Log of Borehole No.:		SL11	
Location:	Sutherland	Latitude:	-32.403784
Date:	04/11/2021	Longitude:	20.65821
Masters D. Mulder		Ground Elevation:	1464 mamsl
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike
Brown overburden	0		216 mm air percussion drilling (0-6 m)
	10		177 mm OD/168mm ID solid steel casing (0-6 m)
Light grey siltstone with signs of fracturing	20		Water strike @ 13 meters, airlift yield ~ 1 600 L/h
	30		165 mm air percussion drilling (6-103 m)
	40		RWL = 21 mbgl
Blueish grey sandstone with clear signs of fracturing	50		Water strike @ 35 meters, airlift yield ~ 4 800 L/h
	60		Water strike @ 57 m. Yield ~22 400 L/h, EC =74 mS/m
Reddish grey siltstone with signs of fracturing	70		
	80	Water strike @ 80 m. Yield ~43 000 L/h, EC =74 mS/m	
Light grey sandstone with signs of fracturing	90		
	100	Water strike @ 100m. Yield ~43 000 L/h	
Grey siltstone with angular and fractured drill chips	110	EOH @ 100 m	
Drilled By:	Steyns Drilling	Remarks:	Total Airlift yield:
Drill Method:	Air percussion		43 000 L/h
Logged By:	D. Mulder		EC: 74 mS/m

Log of Borehole No.:		SL9	
Location:	Sutherland	Latitude:	-32.42231
Date:	09/11/2021	Longitude:	20.652471
Masters D. Mulder		Ground Elevation:	1477 mamsl
Lithological Description	Lithology Symbol & Depth (m)	Borehole Construction	Description & water strike
Brown highly weathered siltstone	0		216 mm air percussion drilling (0 - 6 m)
Light grey competent siltstone	10		177 mm OD/168mm ID solid steel casing (0 - 6 m)
Reddish - grey mudstone	20		RWL = 29.56 mbgl
Light grey sandstone with signs of fracturing	30		165 mm air percussion drilling (6 - 100 m)
Reddish grey siltstone with signs of fracturing	40		Water strike @ 69 m. Yield ~12 279 L/h, EC = 67 mS/m
	50		Water strike @ 85 m. Yield ~21 060 L/h, EC = 67 mS/m
	60		EOH @ 100 m
	70		
	80		
	90		
	100		
Drilled By:	Steyns Drilling	Remarks:	Total Airlift yield: 24 800 L/h EC: 69 mS/m
Drill Method:	Air percussion		
Logged By:	D. Mulder		

APPENDIX B – YIELD TESTING DATA

BOREHOLE TEST CONTROL SHEET							
Groundwater Solutions t/a AB PUMPS							
Borehole number:	SL1	Old / Alternative number:					
Contractor:	ATS	Supervisor:	ABEL				
Operator:	KOLEN	Rig number & Type rig:	#26				
EXISTING EQUIPMENT							
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Condition	Remarks
TESTING EQUIPMENT							
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)				
WA50-2	120.83	14/11/2021 07H30	14/11/2021 14H00				
MULTI-RATE OR STEPTEST DETAILS							
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)		
1	60		0.82	l/s	1.54		
2	60		2.53	l/s	8.04		
3	40		5.00	l/s	51.12		
4	60		3.54	l/s	19.13		
5				l/s			
6				l/s			
7				l/s			
8				l/s			
Calibration:				l/s			
TOTAL:	220	150		l/s			
COMMENT:							
CONSTANT RATE DISCHARGE TEST							
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)				
WA50-2	120.83	15/11/2021 08H00	20/11/2021 08H00				
Yield l/s	Drawdown (m)	Duration (min)	Recovery (min)				
3.02	38.26	4320	2880				
Total: (Multi-rate and Constant Discharge rate)		4540	3030				
COMMENT:							
MAINTENANCE							
Work time:	hour	Transport existing equipm.	Km	Travelling (To fix);	Km		
List of parts replaced or repaired:							
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)		
Observation Hole 1	01-Mar	4320	0	HAND	323		
Observation Hole 2					0		
Observation Hole 3					0		
Observation Hole 4							
Observation Hole 5							
GENERAL							
ESTABLISHMENT	From: SUTHERLAND		To: SUTHERLAND				
Site Move	From project#	2581	To #:	P2581	Travelling km: 5KM		
	Village	Borehole no	Village	Borehole no			
	SUTHERLAND	SL4	SUTHERLAND	SL1			
Maintenance:	Work time hr		Parts repaired/replaced		Travelling km		
After test measurements	Water level	76.98	Borehole depth	150.12	Casing depth m 3.25		
Water level before installing test pump: (mbch)		69.08					
Depth before installing test pump:		150.12					
Testpump Installed	Once / Twice / More		Reason:				
Installed Testpump	<10 l/s / >10l/s		Reason:				
Was existing equipment re-installed:	Yes:	No:	If not where was it left:		NEW BOREHOLE		
GPS Unit number:	#151						
EC Unit number:	#151						
Remarks:							
Signed Contractor:			Signed Consultant:				

FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : P2581	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: SL1	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
BOREHOLE DEPTH (m) 150.12	DATUM LEVEL ABOVE CASING (m): 0.50	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 69.71	CASING HEIGHT: (magl): 0.24	CONTRACTOR: ATS
DEPTH OF PUMP (m): 120.83	DIAM PUMP INLET (mm): 210.00	PUMP TYPE: WA50-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					DISCHARGE RATE 2					DISCHARGE RATE 3				
RPM 263					RPM 387					RPM 627				
DATE: 14/11/2021		TIME: 07H30			DATE: 14/11/2021		TIME: 08H30			DATE: 14/11/2021		TIME: 09H30		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.31		1		1	1.89		1		1	9.37		1	44.64
2	0.36		2		2	2.36	2.35	2		2	10.81	3.86	2	36.40
3	0.38		3		3	2.84	2.53	3		3	12.36	4.88	3	20.57
5	0.66		5		5	4.77		5		5	15.23	5.01	5	15.20
7	0.70	0.50	7		7	5.36	2.51	7		7	18.09		7	12.98
10	0.90	0.76	10		10	5.90		10		10	21.02	5.03	10	11.10
15	1.00	0.81	15		15	6.38	2.54	15		15	27.06		15	8.39
20	1.19		20		20	6.71		20		20	32.67	5.02	20	5.46
30	1.39	0.83	30		30	7.19	2.52	30		30	39.60	5.00	30	3.04
40	1.41		40		40	7.49		40		40	51.12		40	2.47
50	1.48	0.82	50		50	7.87	2.53	50		50	51.12	3.91	50	2.33
60	1.54		60		60	8.04		60		60	51.12	3.56	60	2.15
70			70		70			70		70	51.12	3.24	70	2.07
80			80		80			80		80			80	1.95
90			90		90			90		90			90	1.89
100			100		100			100		100			100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	21.00	°C	180		TEMP	20.60	°C	180		TEMP		°C	180	
EC	1	µS/cm	210		EC	2	µS/cm	210		EC		µS/cm	210	
DISCHARGE RATE 4					DISCHARGE RATE 5					DISCHARGE RATE 6				
RPM 483					RPM					RPM				
DATE: 14/11/2021		TIME: 12H00			DATE:		TIME:			DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	1.22		1	10.50	1			1		1			1	
2	2.06		2	7.91	2			2		2			2	
3	2.19	2.65	3	5.34	3			3		3			3	
5	3.61	3.25	5	4.17	5			5		5			5	
7	8.97	3.51	7	3.70	7			7		7			7	
10	9.69		10	2.39	10			10		10			10	
15	10.89	3.52	15	1.69	15			15		15			15	
20	13.66		20	1.22	20			20		20			20	
30	16.30	3.53	30	1.03	30			30		30			30	
40	17.70		40	0.90	40			40		40			40	
50	18.73	3.54	50	0.79	50			50		50			50	
60	19.13		60	0.67	60			60		60			60	
70			70		70			70		70			70	
80			80		80			80		80			80	
90			90		90			90		90			90	
100			100		100			100		100			100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	21.10	°C	180		TEMP		°C	180		TEMP		°C	180	
EC	2	µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
			240					240					240	
			300					300					300	
			360					360					360	

S/W/L:(mbch) 69.08
STEP 4 WATER LEVEL: 71.53M MAR1 WL: 5.86M

FORM 5 F CONSTANT DISCHARGE TEST & RECOVERY												
BOREHOLE TEST RECORD SHEET												
PROJ NO : P2581			MAP REFERENCE: S32.23279			PROVINCE: NORTHERN CAPE			DISTRICT: KAROO HOOGLAND			
BOREHOLE NO: SL1			E 020.64719			DISTRICT: KAROO HOOGLAND			SITE NAME: SUTHERLAND			
ALT BH NO: 0												
ALT BH NO: 0												
BOREHOLE DEPTH: 150.12			DATUM LEVEL ABOVE CASING (m): 0.50			EXISTING PUMP: NEW BOREHOLE						
WATER LEVEL (mbdl): 70.59			CASING HEIGHT: (magl): 0.24			CONTRACTOR: ATS						
DEPTH OF PUMP (m): 120.83			DIAM PUMP INLET(mm): 210			PUMP TYPE: WA50-2						
CONSTANT DISCHARGE TEST & RECOVERY												
TEST STARTED						TEST COMPLETED						
DATE:	15/11/2021	TIME:	08h00	DATE:	18/11/2021	TIME:	08/00	TYPE OF PUMP:	WA50-2			
						OBSERVATION HOLE 1		OBSERVATION HOLE 2		OBSERVATION HOLE 3		
						NR: Mar-01		NR:		NR:		
DISCHARGE BOREHOLE						Distance(m): 323		Distance(m):		Distance(m):		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)
1	1.31		1	25.67	1			1			1	
2	1.48		2	24.02	2			2			2	
3	1.68		3	22.24	3			3			3	
5	2.48	2.44	5	20.46	5			5			5	
7	5.81	2.76	7	19.33	7			7			7	
10	7.44	3.08	10	18.76	10			10			10	
15	9.09		15	17.94	15			15			15	
20	9.72	3.07	20	16.79	20			20			20	
30	10.75		30	15.25	30			30			30	
40	11.48	3.09	40	14.42	40			40			40	
60	12.51		60	13.71	60			60			60	
90	14.38	3.00	90	13.30	90			90			90	
120	17.42		120	12.96	120			120			120	
150	18.18	3.05	150	12.75	150			150			150	
180	19.11		180	12.53	180			180			180	
210	20.00	3.07	210	12.32	210			210			210	
240	20.92		240	12.10	240			240			240	
300	22.05	3.09	300	11.84	300			300			300	
360	22.83		360	11.54	360	0.00		360			360	
420	23.63	3.06	420	11.29	420			420			420	
480	24.18		480	11.05	480			480			480	
540	24.76	3.04	540	10.85	540			540			540	
600	25.25		600	10.65	600			600			600	
720	26.16	3.03	720	10.32	720			720			720	
840	26.73		840	10.00	840			840			840	
960	27.15	3.05	960	9.79	960			960			960	
1080	27.70		1080	9.41	1080			1080			1080	
1200	28.05	3.09	1200	9.16	1200			1200			1200	
1320	28.44		1320	8.91	1320			1320			1320	
1440	28.65	3.07	1440	8.72	1440	0.00		1440			1440	
1560	28.71		1560	8.53	1560			1560			1560	
1680	29.00	3.02	1680	8.34	1680			1680			1680	
1800	29.17		1800	8.15	1800			1800			1800	
1920	29.32	3.06	1920	7.98	1920	0.00		1920			1920	
2040	29.10		2040	7.84	2040			2040			2040	
2160	29.22	3.08	2160	7.71	2160			2160			2160	
2280	29.47		2280	7.59	2280			2280			2280	
2400	29.65	3.05	2400	7.38	2400			2400			2400	
2520	29.94		2520	7.26	2520			2520			2520	
2640	30.30	3.09	2640	7.14	2640			2640			2640	
2760	30.53		2760	7.05	2760			2760			2760	
2880	31.00	3.04	2880	6.94	2880	0.00		2880			2880	
3000	31.14		3000		3000			3000			3000	
3120	31.57	3.06	3120		3120			3120			3120	
3240	32.12		3240		3240			3240			3240	
3360	32.93	3.03	3360		3360			3360			3360	
3480	33.61		3480		3480			3480			3480	
3600	34.66	3.07	3600		3600			3600			3600	
3720	35.16		3720		3720			3720			3720	
3840	35.71	3.08	3840		3840			3840			3840	
3960	36.46		3960		3960			3960			3960	
4080	36.94	3.05	4080		4080			4080			4080	
4200	37.92		4200		4200			4200			4200	
4320	38.26	3.02	4320		4320	0.00		4320			4320	
Total time pumped(min):				4320		W/L	5.92		W/L		W/L	
Average yield (l/s):				3.02								

BOREHOLE TEST CONTROL SHEET							
Groundwater Solutions t/a AB PUMPS							
Borehole number:	BH-SL3	Old / Alternative number:					
Contractor:	ATS	Supervisor:	ABEL				
Operator:	KOLEN	Rig number & Type rig:	#26 DEUTZ				
EXISTING EQUIPMENT							
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Condition	Remarks
TESTING EQUIPMENT							
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)				
W30-2	60.73	31/10/2021 09H30	01/11/2021 14H00				
MULTI-RATE OR STEPTTEST DETAILS							
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)		
1	60		3.07	l/s	21.54		
2	30	90.00	4.11	l/s	38.61		
3				l/s			
4				l/s			
5				l/s			
6				l/s			
7				l/s			
8				l/s			
Calibration:				l/s			
TOTAL:	130	90		l/s			
COMMENT:							
CONSTANT RATE DISCHARGE TEST							
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)				
Yield l/s	Drawdown (m)	Duration (min)	Recovery (min)				
Total: (Multi-rate and Constant Discharge rate)							
COMMENT:							
MAINTENANCE							
Work time:	hour	Transport existing equipm.	Km	Travelling (To fix);	Km		
List of parts replaced or repaired:							
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)		
Observation Hole 1					0		
Observation Hole 2					0		
Observation Hole 3					0		
Observation Hole 4							
Observation Hole 5							
GENERAL							
ESTABLISHMENT	From: GLOSAM MINE		To: SUTHERLAND				
Site Move	From project# 2571		To #: #REF!		Travelling km:		
	Village	Borehole no	Village	Borehole no			
	GLOSAM	BH1	SUTHERLAND	BH-SL3			
Maintenance:	Work time hr		Parts repaired/ replaced		Travelling km		
After test measurements	Water level	22.65	Borehole depth	149.90	Casing depth m	PVC	
Water level before installing test pump: (mbch)			22.30M				
Depth before installing test pump:			149.90M				
Testpump Installed	Once /Twice /More		Reason:	PIPES WERE ADDED AFTER STEPS REACHED PUMP INLET			
Installed Testpump	<10 l/s / >10l/s		Reason:				
Was existing equipment re-installed:				If not where was it left:	NEW BOREHOLE		
GPS Unit number:			NO NUMBER				
EC Unit number:			#151				
Remarks:							
Signed Contractor:				Signed Consultant:			

**FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY**

BOREHOLE TEST RECORD SHEET

PROJ NO : 0	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: BH-SL3	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
ALT BH NO: 0		
BOREHOLE DEPTH (m) 149.90M	DATUM LEVEL ABOVE CASING (m): 0.46	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 22.12	CASING HEIGHT: (magl): 0.21	CONTRACTOR: ATS
DEPTH OF PUMP (m): 60.73	DIAM PUMP INLET (mm): 125.00	PUMP TYPE: W30-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					DISCHARGE RATE 2					DISCHARGE RATE 3				
RPM 600					RPM 786					RPM				
DATE:		TIME:			DATE:		TIME:			DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	1.48		1		1	22.36		1	26.20	1			1	
2	2.21	1.48	2		2	23.15	3.91	2	18.90	2			2	
3	2.66	2.76	3		3	24.40	4.16	3	14.17	3			3	
5	3.60	3.09	5		5	27.85		5	12.18	5			5	
7	6.30		7		7	31.56	4.09	7	11.11	7			7	
10	11.17	3.07	10		10	34.89		10	9.86	10			10	
15	14.17		15		15	35.67	4.11	15	8.45	15			15	
20	15.52	3.05	20		20	37.40	4.08	20	7.57	20			20	
30	17.74		30		30	38.61		30	6.44	30			30	
40	19.38	3.08	40			38.61	2.65	40	5.53	40			40	
50	20.55		50			38.61	2.71	50	5.05	50			50	
60	21.54	3.04	60			38.61	2.89	60	4.60	60			60	
70			70					70	4.25	70			70	
80			80					80	3.94	80			80	
90			90					90	3.71	90			90	
100			100					100		100			100	
110			110					110		110			110	
120			120					120		120			120	
pH			150		pH			150		pH			150	
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
DISCHARGE RATE 4					DISCHARGE RATE 5					DISCHARGE RATE 6				
RPM					RPM					RPM				
DATE:		TIME:			DATE:		TIME:			DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1			1		1			1		1			1	
2			2		2			2		2			2	
3			3		3			3		3			3	
5			5		5			5		5			5	
7			7		7			7		7			7	
			10		10			10		10			10	
			15		15			15		15			15	
			20		20			20		20			20	
			30		30			30		30			30	
			40		40			40		40			40	
			50		50			50		50			50	
			60		60			60		60			60	
			70		70			70		70			70	
			80		80			80		80			80	
			90		90			90		90			90	
			100		100			100		100			100	
			110		110			110		110			110	
			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
			240					240					240	
			300					300					300	
			360					360					360	

S/W/L:(mbch) 22.3

FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	#REF!	MAP REFERENCE:	PROVINCE:	NORTHERN CAPE	
BOREHOLE NO:	BH-SL3	LATITUDE: S 32.23279	DISTRICT:	KAROO HOOGLAND	
ALT BH NO:	0	LONGITUDE: E 27.89804	SITE NAME:	SUTHERLAND	
ALT BH NO:	0				
BOREHOLE DEPTH (m)	149.90M	DATUM LEVEL ABOVE CASING (m):	0.46	EXISTING PUMP:	NEW BOREHOLE
WATER LEVEL (mbdl):	22.41	CASING HEIGHT: (magl):	0.21	CONTRACTOR:	ATS
DEPTH OF PUMP (m):	96.73	DIAM PUMP INLET (mm):	125.00	PUMP TYPE:	W30-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					RPM	DISCHARGE RATE 2					RPM	DISCHARGE RATE 3					RPM
DATE:		TIME:				DATE:		TIME:				DATE:		TIME:			
TIME	DRAW	YIELD	TIME	RECOVERY		TIME	DRAW	YIELD	TIME	RECOVERY		TIME	DRAW	YIELD	TIME	RECOVERY	
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)		(MIN)	DOWN (M)	(L/S)	(MIN)	(M)		(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	
1	2.70		1	41.40		1			1			1			1		
2	3.89		2	35.60		2			2			2			2		
3	5.07	4.73	3	29.14		3			3			3			3		
5	14.34	5.09	5	19.35		5			5			5			5		
7	21.08		7	14.40		7			7			7			7		
10	32.45	5.07	10	9.88		10			10			10			10		
15	47.18		15	7.47		15			15			15			15		
20	60.22	5.04	20	6.23		20			20			20			20		
30	71.20	5.00	30	5.00		30			30			30			30		
40	74.32		40	4.23		40			40			40			40		
	74.32	3.97	50	3.85		50			50			50			50		
	74.32	5.69	60	3.39		60			60			60			60		
	74.32	2.58	70	2.59		70			70			70			70		
			80	2.39		80			80			80			80		
			90	2.27		90			90			90			90		
			100	2.16		100			100			100			100		
			110	2.06		110			110			110			110		
			120	1.97		120			120			120			120		
pH			150			pH			150			pH			150		
TEMP		°C	180			TEMP		°C	180			TEMP		°C	180		
EC		µS/cm	210			EC		µS/cm	210			EC		µS/cm	210		
DISCHARGE RATE 4					RPM	DISCHARGE RATE 5					RPM	DISCHARGE RATE 6					RPM
DATE:		TIME:				DATE:		TIME:				DATE:		TIME:			
TIME	DRAW	YIELD	TIME	RECOVERY		TIME	DRAW	YIELD	TIME	RECOVERY		TIME	DRAW	YIELD	TIME	RECOVERY	
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)		(MIN)	DOWN (M)	(L/S)	(MIN)	(M)		(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	
1			1			1			1			1			1		
2			2			2			2			2			2		
3			3			3			3			3			3		
5			5			5			5			5			5		
7			7			7			7			7			7		
			10			10			10			10			10		
			15			15			15			15			15		
			20			20			20			20			20		
			30			30			30			30			30		
			40			40			40			40			40		
			50			50			50			50			50		
			60			60			60			60			60		
			70			70			70			70			70		
			80			80			80			80			80		
			90			90			90			90			90		
			100			100			100			100			100		
			110			110			110			110			110		
			120			120			120			120			120		
pH			150			pH			150			pH			150		
TEMP		°C	180			TEMP		°C	180			TEMP		°C	180		
EC		µS/cm	210			EC		µS/cm	210			EC		µS/cm	210		
			240						240						240		
			300						300						300		
			360						360						360		

S/W/L:(mbch) 23.3

FORM 5 F												
CONSTANT DISCHARGE TEST & RECOVERY												
BOREHOLE TEST RECORD SHEET												
PROJ NO :	#REF!	MAP REFERENCE: S32.23279				PROVINCE: NORTHERN CAPE		DISTRICT: KAROO HOOGLAND				
BOREHOLE NO:	BH-SL3	E 020.66630				SITE NAME: SUTHERLAND						
ALT BH NO:	0					EXISTING PUMP: NEW BOREHOLE						
ALT BH NO:	0					CONTRACTOR: ATS						
BOREHOLE DEPTH:	149.90M	DATUM LEVEL ABOVE CASING (m):		0.46	EXISTING PUMP:		NEW BOREHOLE					
WATER LEVEL (mbdl):	23.82	CASING HEIGHT: (magl):		0.21	CONTRACTOR:		ATS					
DEPTH OF PUMP (m):	96.73	DIAM PUMP INLET (mm):		125	PUMP TYPE:		W30-2					
CONSTANT DISCHARGE TEST & RECOVERY												
TEST STARTED						TEST COMPLETED						
DATE:	01/11/2021	TIME:	16H00	DATE:	01/11/2021	TIME:	18H00	TYPE OF PUMP:		WA30-2		
				OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3		
				NR:			NR:			NR:		
DISCHARGE BOREHOLE				Distance(m):			Distance(m):			Distance(m):		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)
1	2.00		1	36.84	1			1			1	
2	3.95		2	28.82	2			2			2	
3	5.75	2.96	3	24.64	3			3			3	
5	7.96	3.21	5	18.70	5			5			5	
7	9.90	3.51	7	14.91	7			7			7	
10	13.84		10	11.14	10			10			10	
15	19.96	3.52	15	10.36	15			15			15	
20	25.50		20	9.26	20			20			20	
30	34.90	3.50	30	8.61	30			30			30	
40	39.48		40	7.63	40			40			40	
60	42.81	3.51	60	6.19	60			60			60	
90	49.93		90		90			90			90	
120	52.97	3.52	120		120			120			120	
150			150		150			150			150	
180			180		180			180			180	
210			210		210			210			210	
240			240		240			240			240	
300			300		300			300			300	
360			360		360			360			360	
420			420		420			420			420	
480			480		480			480			480	
540			540		540			540			540	
600			600		600			600			600	
720			720		720			720			720	
840			840		840			840			840	
960			960		960			960			960	
1080			1080		1080			1080			1080	
1200			1200		1200			1200			1200	
1320			1320		1320			1320			1320	
1380			1440		1440			1440			1440	
1560			1560		1560			1560			1560	
1680			1680		1680			1680			1680	
1800			1800		1800			1800			1800	
			1920		1920			1920			1920	
			2040		2040			2040			2040	
			2160		2160			2160			2160	
			2280		2280			2280			2280	
			2400		2400			2400			2400	
			2520		2520			2520			2520	
			2640		2640			2640			2640	
			2760		2760			2760			2760	
			2880		2880			2880			2880	
			3000		3000			3000			3000	
			3120		3120			3120			3120	
			3240		3240			3240			3240	
			3360		3360			3360			3360	
			3480		3480			3480			3480	
			3600		3600			3600			3600	
			3720		3720			3720			3720	
			3840		3840			3840			3840	
			3960		3960			3960			3960	
			4080		4080			4080			4080	
			4200		4200			4200			4200	
			4320		4320			4320			4320	
Total time pumped(min):				120	W/L			W/L			W/L	
Average yield (l/s):				3.52								

FORM 5 F												
CONSTANT DISCHARGE TEST & RECOVERY												
BOREHOLE TEST RECORD SHEET												
PROJ NO :	2581			MAP REFERENCE:	S32.23279			PROVINCE:	NORTHERN CAPE			
BOREHOLE NO:	BH-SL3				E 020.66630			DISTRICT:	KAROO HOOGLAND			
ALT BH NO:	0							SITE NAME:	SUTHERLAND			
ALT BH NO:	0							EXISTING PUMP:	NEW BOREHOLE			
BOREHOLE DEPTH:	149.90M			DATUM LEVEL ABOVE CASING (m):	0.46			CONTRACTOR:	ATS			
WATER LEVEL (mbdl):	23.71			CASING HEIGHT: (magl):	0.21			PUMP TYPE:	0			
DEPTH OF PUMP (m):	96.73			DIAM PUMP INLET (mm):	125							
CONSTANT DISCHARGE TEST & RECOVERY												
TEST STARTED						TEST COMPLETED						
DATE:	02/11/2021		TIME:	08H20		DATE:	01/11/2021		TIME:	18H00		
										TYPE OF PUMP:		
										WA30-2		
						OBSERVATION HOLE 1		OBSERVATION HOLE 2		OBSERVATION HOLE 3		
						NR:		NR:		NR:		
						Distance(m);		Distance(m);		Distance(m);		
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	Drawdown	Recovery	TIME	Drawdown	Recovery	TIME	Drawdown
(MIN)	DOWN (M)	(L/S)	MIN	(M)	(min)	m	(m)	(min)	(m)		(min)	(m)
1	2.67		1	27.39	1			1			1	
2	3.47		2	22.12	2			2			2	
3	4.67	1.67	3	19.45	3			3			3	
5	8.77	1.89	5	18.34	5			5			5	
7	9.99	2.08	7	17.82	7			7			7	
10	11.72		10	17.08	10			10			10	
15	13.80	2.06	15	16.07	15			15			15	
20	14.71		20	15.34	20			20			20	
30	16.69	2.04	30	14.31	30			30			30	
40	18.12		40	13.47	40			40			40	
60	19.72	2.01	60	12.28	60			60			60	
90	21.75		90	10.98	90			90			90	
120	23.22	2.02	120	10.01	120			120			120	
150	24.38		150	9.31	150			150			150	
180	25.24	2.03	180	8.48	180			180			180	
210	25.95		210	7.84	210			210			210	
240	26.64	2.04	240	7.08	240			240			240	
300	27.80		300	6.26	300			300			300	
360	29.26	2.06	360	5.73	360			360			360	
420	30.06		420	4.87	420			420			420	
480	31.08	2.01	480	4.30	480			480			480	
540	31.72		540	3.80	540			540			540	
600	32.22	2.03	600	3.34	600			600			600	
720	32.86		720	2.35	720			720			720	
840	33.67	2.05	840	1.93	840			840			840	
960	33.96		960	1.43	960			960			960	
1080	34.28	2.04	1080	1.09	1080			1080			1080	
1200	34.94		1200	0.74	1200			1200			1200	
1320	35.16	2.02	1320	0.38	1320			1320			1320	
1380	35.34		1440	0.13	1440			1440			1440	
1560	35.57	2.08	1560	0.00	1560			1560			1560	
1680	35.75		1680	0.18	1680			1680			1680	
1800	35.89	2.07	1800	0.34	1800			1800			1800	
1920	35.97		1920		1920			1920			1920	
2040	36.17	2.08	2040		2040			2040			2040	
2160	36.32		2160		2160			2160			2160	
2280	36.49	2.06	2280		2280			2280			2280	
2400	36.57		2400		2400			2400			2400	
2520	36.63	2.07	2520		2520			2520			2520	
2640	36.70		2640		2640			2640			2640	
2760	36.78	2.08	2760		2760			2760			2760	
2880	36.86		2880		2880			2880			2880	
3000	36.94	2.06	3000		3000			3000			3000	
3120	37.10		3120		3120			3120			3120	
3240	37.22	2.07	3240		3240			3240			3240	
3360	37.37		3360		3360			3360			3360	
3480	37.46	2.08	3480		3480			3480			3480	
3600	37.68		3600		3600			3600			3600	
3720	37.70	2.05	3720		3720			3720			3720	
3840	37.71		3840		3840			3840			3840	
3960	37.73	2.06	3960		3960			3960			3960	
4080	37.75		4080		4080			4080			4080	
4200	37.77	2.08	4200		4200			4200			4200	
4320	37.78		4320		4320			4320			4320	
Total time pumped(min):				4320		W/L			W/L			W/L
Average yield (l/s):				2.05								

BOREHOLE TEST CONTROL SHEET						
Groundwater Solutions t/a AB PUMPS						
Borehole number:	SL4	Old / Alternative number:				
Contractor:	ATS	Supervisor:	ABEL			
Operator:	PHILLIP	Rig number & Type rig:	#26 DEUTZ			
EXISTING EQUIPMENT						
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Remarks
TESTING EQUIPMENT						
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)			
WA30-2	72.70	07/11/2021 09H50	07/11/2021 46H50			
MULTI-RATE OR STEPEST DETAILS						
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)	
1	60		3.10	I/s	1.26	
2	60		5.10	I/s	2.43	
3	120	180	6.22	I/s	3.54	
4				I/s		
5				I/s		
6				I/s		
7				I/s		
8				I/s		
Calibration:				I/s		
TOTAL:	240	180		I/s		
COMMENT:						
CONSTANT RATE DISCHARGE TEST						
Pump type	Depth installed (m)	Date & time (started)		Date & time (completed)		
WA30-2	72.70	08/11/2021	07H00	13/11/2021	07H00	
Yield l/s	Drawdown (m)	Duration (min)		Recovery (min)		
6.04	5.73	4320		2880		
Total: (Multi-rate and Constant Discharge rate)		4560		3060		
COMMENT:						
MAINTENANCE						
Work time:	hour	Transport existing equipm.	Km	Travelling (To fix);	Km	
List of parts replaced or repaired:						
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)	
Observation Hole 1	SL5	4320	3.52	HAND	1.41km	
Observation Hole 2					0	
Observation Hole 3					0	
Observation Hole 4						
Observation Hole 5						
GENERAL						
ESTABLISHMENT	From: SUTHERLAND		To: SUTHERLAND			
Site Move	From project#	2581	To #:	2581	Travelling km:	4KM
	Village	Borehole no	Village	Borehole no		
	SUTHERLAN D	SL3	SUTHERLAN D	SL4		
Maintenance:	Work time hr		Parts repaired/ replaced		Travelling km	
After test measurements	Water level	12.56	Borehole depth	146.40	Casing depth m	PVC
Water level before installing test pump: (mbch)			12.48			
Depth before installing test pump:			146.40			
Testpump Installed	Once /Twice /More		Reason:			
Installed Testpump	<10 l/s / >10l/s		Reason:			
Was existing equipment re-installed:		Yes:	No:	If not where was it left:		
GPS Unit number:			GARMIN			
EC Unit number:			#115 NEW			
Remarks:						
Signed Contractor:				Signed Consultant:		

FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : 2581	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: SL4	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
BOREHOLE DEPTH (m) 146.40	DATUM LEVEL ABOVE CASING (m): 0.57	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 12.99	CASING HEIGHT: (magl): 0.15	CONTRACTOR: ATS
DEPTH OF PUMP (m): 72.70	DIAM PUMP INLET (mm): 125mm	PUMP TYPE: WA30-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					RPM	DISCHARGE RATE 2					RPM 911	DISCHARGE RATE 3					RPM 1111
DATE:	TIME:					DATE:	TIME:					DATE:	TIME:				
07/11/2021	09h50					07/11/2021	10h50					07/11/2021	11h50				
TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)		TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)		TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	
1	0.50		1			1	1.52		1			1	2.60		1	1.85	
2	0.68		2			2	1.64		2			2	2.63		2	1.52	
3	0.71	2.97	3			3	1.82	4.60	3			3	2.72	5.89	3	1.31	
5	0.87	3.10	5			5	2.07	5.10	5			5	2.78	6.22	5	1.12	
7	0.91		7			7	2.09		7			7	2.82		7	1.07	
10	0.97	3.09	10			10	2.16	5.08	10			10	2.87	6.21	10	0.93	
15	1.07		15			15	2.23		15			15	2.90		15	0.76	
20	1.11	3.10	20			20	2.26	2.10	20			20	3.02	6.22	20	0.66	
30	1.17		30			30	2.32		30			30	3.14		30	0.56	
40	1.20	3.09	40			40	2.36	5.09	40			40	3.21	6.20	40	0.51	
50	1.23		50			50	2.41		50			50	3.25		50	0.47	
60	1.26	3.10	60			60	2.43	5.10	60			60	3.31	6.21	60	0.42	
70			70			70			70			70	3.35		70	0.40	
80			80			80			80			80	3.37	6.20	80	0.39	
90			90			90			90			90	3.40		90	0.37	
100			100			100			100			100	3.44	6.21	100	0.35	
110			110			110			110			110	3.49		110	0.33	
120			120			120			120			120	3.54	6.22	120	0.31	
pH			150			pH			150			pH			150	0.27	
TEMP		°C	180			TEMP	17.90	°C	180			TEMP	17.20	°C	180	0.23	
EC		µS/cm	210			EC	0.84	µS/cm	210			EC	0.81	µS/cm	210		
DISCHARGE RATE 4					RPM	DISCHARGE RATE 5					RPM	DISCHARGE RATE 6					RPM
DATE:	TIME:					DATE:	TIME:					DATE:	TIME:				
TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)		TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)		TIME (MIN)	DRAW (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	
1			1			1			1			1			1		
2			2			2			2			2			2		
3			3			3			3			3			3		
5			5			5			5			5			5		
7			7			7			7			7			7		
			10			10			10			10			10		
			15			15			15			15			15		
			20			20			20			20			20		
			30			30			30			30			30		
			40			40			40			40			40		
			50			50			50			50			50		
			60			60			60			60			60		
			70			70			70			70			70		
			80			80			80			80			80		
			90			90			90			90			90		
			100			100			100			100			100		
			110			110			110			110			110		
			120			120			120			120			120		
pH			150			pH			150			pH			150		
TEMP		°C	180			TEMP		°C	180			TEMP		°C	180		
EC		µS/cm	210			EC		µS/cm	210			EC		µS/cm	210		
			240						240						240		
			300						300						300		
			360						360						360		

S/W/L:(mbch) 12.48

FORM 5 F CONSTANT DISCHARGE TEST & RECOVERY													
BOREHOLE TEST RECORD SHEET													
PROJ NO :	2581		MAP REFERENCE:	S32.23279 E 020.66254				PROVINCE:	NORTHERN CAPE				
BOREHOLE NO:	SL4						DISTRICT:	KAROO HOOGLAND					
ALT BH NO:	0						SITE NAME:	SUTHERLAND					
BOREHOLE DEPTH:	146.40		DATUM LEVEL ABOVE CASING (m):	0.57		EXISTING PUMP:	NEW BOREHOLE						
WATER LEVEL (mbdl):	12.99		CASING HEIGHT: (magl):	0.15		CONTRACTOR:	ATS						
DEPTH OF PUMP (m):	72.70		DIAM PUMP INLET (mm):	125mm		PUMP TYPE:	WA30-2						
CONSTANT DISCHARGE TEST & RECOVERY													
TEST STARTED						TEST COMPLETED							
DATE:	08/11/2021		TIME:	07h00		DATE:	11/11/2021		TIME:	07h00		TYPE OF PUMP:	WA30-2
						OBSERVATION HOLE 1		OBSERVATION HOLE 2		OBSERVATION HOLE 3			
						NR: SL5		NR:		NR:			
DISCHARGE BOREHOLE						Distance(m):		1.41		Distance(m):		Distance(m):	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery (m)
1	1.10		1	3.85	1			1			1		
2	1.41	5.98	2	3.69	2			2			2		
3	1.53	6.04	3	3.57	3			3			3		
5	1.64		5	3.41	5			5			5		
7	1.83	6.03	7	3.27	7			7			7		
10	1.91		10	3.13	10			10			10		
15	2.25	6.02	15	3.03	15			15			15		
20	2.32		20	2.95	20			20			20		
30	2.49	6.03	30	2.84	30		3.16	30			30		
40	2.59		40	2.75	40			40			40		
60	2.71	6.01	60	2.67	60	0.42	2.98	60			60		
90	2.87		90	2.51	90		2.96	90			90		
120	2.98	6.05	120	2.53	120	0.62	2.93	120			120		
150	3.05		150	2.47	150		2.87	150			150		
180	3.14	6.04	180	2.43	180	0.72	2.80	180			180		
210	3.25		210	2.39	210		2.76	210			210		
240	3.32	6.03	240	2.36	240	0.81	2.73	240			240		
300	3.38		300	2.29	300	1.06	2.67	300			300		
360	3.49	60.20	360	2.23	360		2.60	360			360		
420	3.58		420	2.18	420			420			420		
480	3.65	6.04	480	2.13	480			480			480		
540	3.77		540	2.08	540	1.46		540			540		
600	3.83	6.01	600	2.03	600			600			600		
720	3.96		720	1.95	720	1.62		720			720		
840	4.10	6.05	840	1.85	840			840			840		
960	4.19		960	1.79	960	1.88		960			960		
1080	4.30	6.03	1080	1.70	1080			1080			1080		
1200	4.40		1200	1.65	1200	2.04		1200			1200		
1320	4.48	6.04	1320	1.55	1320			1320			1320		
1380	4.58		1440	1.46	1440	2.31		1440			1440		
1560	4.61	6.02	1560	1.38	1560			1560			1560		
1680	4.62		1680	1.31	1680			1680			1680		
1800	4.65	6.00	1800	1.23	1800	2.49	1.51	1800			1800		
1920	4.69		1920	1.16	1920			1920			1920		
2040	4.81	6.03	2040	1.09	2040	2.62		2040			2040		
2160	4.87		2160	1.03	2160			2160			2160		
2280	4.93	6.04	2280	0.98	2280	2.71		2280			2280		
2400	4.98		2400	0.91	2400			2400			2400		
2520	5.02	6.02	2520	0.85	2520	2.83		2520			2520		
2640	5.11		2640	0.79	2640			2640			2640		
2760	5.20	6.01	2760	0.72	2760	2.98		2760			2760		
2880	5.27		2880	0.67	2880			2880			2880		
3000	5.31	6.05	3000		3000	3.09		3000			3000		
3120	5.34		3120		3120			3120			3120		
3240	5.38	6.02	3240		3240	3.20		3240			3240		
3360	5.41		3360		3360			3360			3360		
3480	5.45	6.04	3480		3480	3.28		3480			3480		
3600	5.51		3600		3600			3600			3600		
3720	5.56	6.02	3720		3720	3.33		3720			3720		
3840	5.59		3840		3840			3840			3840		
3960	5.63	6.05	3960		3960	3.41		3960			3960		
4080	5.67		4080		4080			4080			4080		
4200	5.69	6.04	4200		4200	3.52		4200			4200		
4320	5.73		4320		4320			4320			4320		
Total time pumped(min):				4320		W/L	21.08		W/L			W/L	
Average yield (l/s):				6.04									

BOREHOLE TEST CONTROL SHEET						
Groundwater Solutions t/a AB PUMPS						
Borehole number:		BH-SL5		Old / Alternative number:		
Contractor:		ATS		Supervisor:		ABEL
Operator:		THABANG		Rig number & Type rig:		#29
EXISTING EQUIPMENT						
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Remarks
TESTING EQUIPMENT						
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)			
WA110-2	82.26	31/10/21 09H00	06/11/2021 14H00			
MULTI-RATE OR STEPTEST DETAILS						
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)	
1	60		4.63	I/s	0.91	
2	60		9.22	I/s	2.34	
3	60		13.80	I/s	4.46	
4	60	240	15.21	I/s	5.61	
5				I/s		
6				I/s		
7				I/s		
8				I/s		
Calibration:				I/s		
TOTAL:		240	240	I/s		
COMMENT:						
CONSTANT RATE DISCHARGE TEST						
Pump type	Depth installed (m)	Date & time (started)		Date & time (completed)		
WA110-2	82.26	01/11/2021	08H30	06/11/2021	14H00	
Yield l/s	Drawdown (m)	Duration (min)	Recovery (min)			
14.01	10.58	3690	3840			
Total: (Multi-rate and Constant Discharge rate)		3930	4080			
COMMENT: RIG #29 HAD A BREAKDOWN AT 3690 MINUTES (BH-SL5)						
MAINTENANCE						
Work time:		hour	Transport existing equipm.	Km	Travelling (To fix):	Km
List of parts replaced or repaired:						
LOGGERS/HANDREADINGS ON SURROUNDING BOREHOLES						
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)	
Observation Hole 1	BH-SL4	3480	6.07	HAND	1.41KM	
Observation Hole 2					0	
Observation Hole 3					0	
Observation Hole 4						
Observation Hole 5						
GENERAL						
ESTABLISHMENT	From: ROOIFONTEIN		To: SUTHERLAND		Distance: 557km	
Site Move	From project# 2568		To #: 2581		Travelling km:	
	Village	Borehole no	Village	Borehole no		
	ROOIFONTEIN	HBH2	SUTHERLAND	BH-SL5		
Maintenance:	Work time hr		Parts repaired/replaced		Travelling km	
After test measurements	Water level	21.63	Borehole depth	120.00	Casing depth m	7.20M
Water level before installing test pump: (mbch)			18.25			
Depth before installing test pump:			120.00M			
Testpump Installed	Once /Twice /More		Reason:			
Installed Testpump	<10 l/s / >10l/s/s		Reason:		HIGH YIELD	
Was existing equipment re-installed:	Yes:	No:	If not where was it left:		NEW BOREHOLE	
GPS Unit number:			#15			
EC Unit number:			#77			
Remarks:						
Signed Contractor:				Signed Consultant:		

FORM 5 F CONSTANT DISCHARGE TEST & RECOVERY															
BOREHOLE TEST RECORD SHEET															
PROJ NO :		2581		MAP REFERENCE:				S32.23279 E 020.65878		PROVINCE:		NORTHERN CAPE			
BOREHOLE NO:		BH-SL5								DISTRICT:		KAROO HOOGLAND			
ALT BH NO:		0								SITE NAME:		SUTHERLAND			
ALT BH NO:		0													
BOREHOLE DEPTH:				120.00M				DATUM LEVEL ABOVE CASING (m):		0.42M		EXISTING PUMP:		NEW BOREHOLE	
WATER LEVEL (mbdl):				19.16M				CASING HEIGHT: (magl):		0.32M		CONTRACTOR:		ATS	
DEPTH OF PUMP (m):				82.26				DIAM PUMP INLET(mm):		170MM		PUMP TYPE:		WA110-2	
CONSTANT DISCHARGE TEST & RECOVERY															
TEST STARTED							TEST COMPLETED								
DATE:	01/11/2021			TIME:	08H30			DATE:	01/11/2021			TIME:	10H00		
							OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3		
							NR: BH-SL4			NR:			NR:		
							Distance(m); 1.41KM			Distance(m);			Distance(m);		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery	TIME (min)	Drawdown (m)			
1	0.32		1	10.04	1			1			1				
2	0.58		2	9.82	2			2			2				
3	0.72	11.12	3	9.67	3			3			3				
5	0.94	11.57	5	9.40	5			5			5				
7	1.14	14.05	7	9.18	7			7			7				
10	1.45		10	9.11	10			10			10				
15	1.67	14.07	15	9.05	15			15			15				
20	1.92		20	8.98	20			20			20				
30	2.30	14.03	30	8.85	30	0.00	5.67	30			30				
40	2.78		40	8.71	40	0.00	5.58	40			40				
60	3.03	14.05	60	8.59	60	0.00	5.32	60			60				
90	3.62		90	8.37	90	0.00	5.07	90			90				
120	4.20	14.02	120	8.19	120	0.00	4.81	120			120				
150	4.67		150	8.08	150		4.68	150			150				
180	5.20	14.03	180	7.94	180		4.52	180			180				
210	5.37		210	7.82	210		4.31	210			210				
240	5.50	14.01	240	7.74	240		4.19	240			240				
300	5.97		300	7.58	300		4.04	300			300				
360	6.33	14.03	360	7.32	360	0.00	3.92	360			360				
420	6.57		420	7.13	420		3.81	420			420				
480	6.98	14.01	480	6.96	480		3.75	480			480				
540	7.10		540	6.84	540		3.68	540			540				
600	7.33	14.02	600	6.71	600	3.92	3.45	600			600				
720	7.65		720	6.51	720		3.29	720			720				
840	7.91	14.04	840	6.33	840	4.11		840			840				
960	8.13		960	6.20	960			960			960				
1080	8.35	14.02	1080	6.11	1080	4.20		1080			1080				
1200	8.50		1200	5.87	1200			1200			1200				
1320	8.74	14.05	1320	5.68	1320	4.32		1320			1320				
1380	8.87		1440	5.47	1440			1440			1440				
1560	9.01	14.03	1560	5.31	1560	4.65		1560			1560				
1680	9.13		1680	5.24	1680			1680			1680				
1800	9.24	14.01	1800	5.18	1800	4.89		1800			1800				
1920	9.34		1920	5.10	1920			1920			1920				
2040	9.46	14.00	2040	5.00	2040	5.10		2040			2040				
2160	9.53		2160	4.93	2160			2160			2160				
2280	9.61	14.02	2280	4.80	2280	5.24		2280			2280				
2400	9.68		2400	4.67	2400			2400			2400				
2520	9.75	14.05	2520	4.58	2520	5.45		2520			2520				
2640	9.84		2640	4.34	2640			2640			2640				
2760	9.97	14.03	2760	4.23	2760	5.67		2760			2760				
2880	10.08		2880	4.14	2880			2880			2880				
3000	10.15	14.01	3000	4.02	3000	5.82		3000			3000				
3120	10.23		3120	3.94	3120			3120			3120				
3240	10.34	14.02	3240	3.87	3240	5.98		3240			3240				
3360	10.41		3360	3.84	3360			3360			3360				
3480	10.46	14.00	3480	3.73	3480	6.07		3480			3480				
3600	10.52		3600	3.62	3600			3600			3600				
3690	10.58	14.01	3720	3.54	3720			3720			3720				
			3840	3.45	3840			3840			3840				
			3960		3960			3960			3960				
			4080		4080			4080			4080				
			4200		4200			4200			4200				
			4320		4320			4320			4320				
Total time pumped(min):				3690		W/L	12.8		W/L			W/L			
Average yield (l/s):				14.01											

FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : 2581	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: BH-SL5	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
ALT BH NO: 0		
BOREHOLE DEPTH (m) 120.00M	DATUM LEVEL ABOVE CASING (m): 0.42M	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 18.65M	CASING HEIGHT: (magl): 0.32M	CONTRACTOR: ATS
DEPTH OF PUMP (m): 82.26	DIAM PUMP INLET (mm): 170MM	PUMP TYPE: WA110-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					DISCHARGE RATE 2					DISCHARGE RATE 3				
RPM 183					RPM 286					RPM 397				
DATE: 31/10/2021		TIME: 09H00			DATE: 31/10/2021		TIME: 10H00			DATE: 31/10/2021		TIME: 11H00		
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1	0.08		1		1	1.15		1		1	2.45		1	
2	0.11		2		2	1.25	8.51	2		2	2.73	10.09	2	
3	0.16	2.41	3		3	1.27	9.01	3		3	2.77	13.01	3	
5	0.29	4.25	5		5	1.39	9.21	5		5	2.89	13.79	5	
7	0.34	4.62	7		7	1.46		7		7	3.02	13.80	7	
10	0.44		10		10	1.49	9.24	10		10	3.21		10	
15	0.48	4.60	15		15	1.59		15		15	3.34	13.81	15	
20	0.50		20		20	1.70	9.21	20		20	3.39		20	
30	0.57	4.62	30		30	1.86		30		30	3.63	13.82	30	
40	0.73		40		40	2.06	9.20	40		40	3.87		40	
50	0.82	4.63	50		50	2.17		50		50	4.35	13.80	50	
60	0.91		60		60	2.34	9.22	60		60	4.46		60	
70			70		70			70		70			70	
80			80		80			80		80			80	
90			90		90			90		90			90	
100			100		100			100		100			100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	22.40	°C	180		TEMP	23.80	°C	180		TEMP	25.60	°C	180	
EC	387	µS/cm	210		EC	762	µS/cm	210		EC	730	µS/cm	210	
DISCHARGE RATE 4					DISCHARGE RATE 5					DISCHARGE RATE 6				
RPM 680					RPM					RPM				
DATE: 31/10/2021		TIME: 12H00			DATE:		TIME:			DATE:		TIME:		
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1	4.48		1	4.45	1			1		1			1	
2	4.50	14.80	2	4.34	2			2		2			2	
3	4.52	15.25	3	4.24	3			3		3			3	
5	4.54		5	4.15	5			5		5			5	
7	4.60	15.21	7	4.06	7			7		7			7	
10	4.66		10	3.97	10			10		10			10	
15	4.77	15.25	15	3.88	15			15		15			15	
20	4.84		20	3.84	20			20		20			20	
30	5.04	15.20	30	3.61	30			30		30			30	
40	5.26		40	3.53	40			40		40			40	
50	5.37	15.21	50	3.47	50			50		50			50	
60	5.61		60	3.33	60			60		60			60	
70			70	3.20	70			70		70			70	
80			80	3.15	80			80		80			80	
90			90	3.09	90			90		90			90	
100			100	3.04	100			100		100			100	
110			110	3.00	110			110		110			110	
120			120	2.97	120			120		120			120	
pH			150	2.83	pH			150		pH			150	
TEMP	23.10	°C	180	2.71	TEMP		°C	180		TEMP		°C	180	
EC	717	µS/cm	210	2.60	EC		µS/cm	210		EC		µS/cm	210	
			240	2.46				240					240	
			300					300					300	
			360					360					360	

S/W/L:(mbch) 18.25M

SL6

BOREHOLE TEST CONTROL SHEET						
Groundwater Solutions t/a AB PUMPS						
Borehole number:	SL6		Old / Alternative number:			
Contractor:	ATS		Supervisor:	ABEL		
Operator:	PHILLIP		Rig number & Type rig:	#26		
EXISTING EQUIPMENT						
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Remarks
TESTING EQUIPMENT						
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)			
WA30-2	90.83	21/11/2021 08H00	21/11/2021 14H00			
MULTI-RATE OR STEPEST TEST DETAILS						
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)	
1	120		3.03	l/s	1.46	
2	60		4.02	l/s	2.04	
3	60	120	5.50	l/s	2.83	
4				l/s		
5				l/s		
6				l/s		
7				l/s		
8				l/s		
Calibration:				l/s		
TOTAL:	240	120		l/s		
COMMENT:						
CONSTANT RATE DISCHARGE TEST						
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)			
WA30-2	90.83	21/11/2021 15H10	26/11/2021	11H10		
Yield l/s	Drawdown (m)	Duration (min)	Recovery (min)			
5.06	3.96	4320	2640			
Total: (Multi-rate and Constant Discharge rate)		4560	2760			
COMMENT:						
MAINTENANCE						
Work time:	hour	Transport existing equipm.	Km	Travelling (To fix):	Km	
List of parts replaced or repaired:						
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)	
Observation Hole 1	SL9	4320	0.57	Hand	813	
Observation Hole 2					0	
Observation Hole 3					0	
Observation Hole 4						
Observation Hole 5						
GENERAL						
ESTABLISHMENT	From: SUTHERLAND		To: SUTHERLAND			
Site Move	From project#	2581	To #:	P2581	Travelling km:	5.500KM
	Village	Borehole no	Village	Borehole no		
	SUTHERLAND	SL1	SUTHERLAND	SL6		
Maintenance:	Work time hr		Parts repaired/replaced		Travelling km	
After test measurements	Water level	25.16	Borehole depth	116.83	Casing depth m	PVC
Water level before installing test pump: (mbch)		24.76				
Depth before installing test pump:		116.83				
Testpump Installed	Once /Twice /More		Reason:			
Installed Testpump	<10 l/s / >10l/s		Reason:			
Was existing equipment re-installed:	Yes:	No:	If not where was it left:		NEW BOREHOLE	
GPS Unit number:			GARMIN			
EC Unit number:			#151 NEW			
Remarks:						
Signed Contractor:			Signed Consultant:			

FORM 5 E

STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : P2581	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: SL6	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
ALT BH NO: 0		
BOREHOLE DEPTH (m) 116.83	DATUM LEVEL ABOVE CASING (m): 0.56	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 25.41	CASING HEIGHT: (magl): 0.19	CONTRACTOR: ATS
DEPTH OF PUMP (m): 90.83	DIAM PUMP INLET (mm): 125MM	PUMP TYPE: WA30-2

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1					DISCHARGE RATE 2					DISCHARGE RATE 3				
RPM 610					RPM 796					RPM 1034				
DATE:	TIME:		TIME:		DATE:	TIME:		TIME:		DATE:	TIME:		TIME:	
21/11/2021	08H00				21/11/2021	10H00				21/11/2021	11H00			
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1	0.36		1		1	1.52		1		1	2.17		1	1.67
2	0.42	2.30	2		2	1.60	4.04	2		2	2.31		2	1.19
3	0.48		3		3	1.68		3		3	2.45	4.80	3	0.98
5	0.71	3.03	5		5	1.83	4.03	5		5	2.55	5.20	5	0.80
7	0.94		7		7	1.88		7		7	2.61		7	0.73
10	1.09	3.02	10		10	1.91	4.02	10		10	2.66	5.50	10	0.61
15	1.19		15		15	1.94		15		15	2.71		15	0.51
20	1.24	3.01	20		20	1.98	4.04	20		20	2.73	5.50	20	0.43
30	1.29		30		30	2.01		30		30	2.75		30	0.35
40	1.34	3.03	40		40	2.02	4.01	40		40	2.78	5.51	40	0.30
50	1.37		50		50	2.03		50		50	2.80		50	0.27
60	1.38	3.02	60		60	2.04	4.02	60		60	2.83	5.50	60	0.26
70	1.39		70		70			70		70			70	0.24
80	1.40	3.03	80		80			80		80			80	0.22
90	1.41		90		90			90		90			90	0.21
100	1.43	3.01	100		100			100		100			100	0.20
110	1.44		110		110			110		110			110	0.19
120	1.46	3.03	120		120			120		120			120	0.18
pH			150		pH			150		pH			150	
TEMP	21.10	°C	180		TEMP	21.10	°C	180		TEMP	20.20	°C	180	
EC	1	µS/cm	210		EC	1	µS/cm	210		EC	1	µS/cm	210	
DISCHARGE RATE 4					DISCHARGE RATE 5					DISCHARGE RATE 6				
RPM					RPM					RPM				
DATE:	TIME:		TIME:		DATE:	TIME:		TIME:		DATE:	TIME:		TIME:	
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1			1		1			1		1			1	
2			2		2			2		2			2	
3			3		3			3		3			3	
5			5		5			5		5			5	
7			7		7			7		7			7	
			10		10			10		10			10	
			15		15			15		15			15	
			20		20			20		20			20	
			30		30			30		30			30	
			40		40			40		40			40	
			50		50			50		50			50	
			60		60			60		60			60	
			70		70			70		70			70	
			80		80			80		80			80	
			90		90			90		90			90	
			100		100			100		100			100	
			110		110			110		110			110	
			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
			240					240					240	
			300					300					300	
			360					360					360	

S/WL:(mbch) 24.76

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : P2581	MAP REFERENCE: S32.23279	PROVINCE: NORTHERN CAPE
BOREHOLE NO: SL6	E 020.64723	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0		SITE NAME: SUTHERLAND
ALT BH NO: 0		
BOREHOLE DEPTH: 116.83	DATUM LEVEL ABOVE CASING (m): 0.56	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (m bdl): 25.56	CASING HEIGHT: (magl): 0.19	CONTRACTOR: ATS
DEPTH OF PUMP (m): 90.83	DIAM PUMP INLET (mm): 125MM	PUMP TYPE: WA30-2

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED					TEST COMPLETED							
DATE:	21/11/2021	TIME:	15h10		DATE:	22/11/2021	TIME:	17h10	TYPE OF PUMP:	WA30-2		
					OBSERVATION HOLE 1		OBSERVATION HOLE 2		OBSERVATION HOLE 3			
					NR: SL9		NR:		NR:			
					Distance(m): 813		Distance(m):		Distance(m):			
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)
1	0.57		1	3.24	1			1			1	
2	0.73		2	2.29	2			2			2	
3	0.90		3	2.10	3			3			3	
5	1.52	4.60	5	1.99	5			5			5	
7	1.83	5.07	7	1.91	7			7			7	
10	2.07		10	1.82	10			10			10	
15	2.28	5.06	15	1.70	15			15			15	
20	2.33		20	1.62	20			20			20	
30	2.44	5.07	30	1.55	30			30			30	
40	2.48		40	1.48	40			40			40	
60	2.55	5.06	60	1.39	60		0.45	60			60	
90	2.64		90	1.37	90			90			90	
120	2.71	5.04	120	1.31	120			120			120	
150	2.75		150	1.25	150			150			150	
180	2.82	5.07	180	1.19	180			180			180	
210	2.85		210	1.17	210			210			210	
240	2.88	5.05	240	1.15	240			240			240	
300	2.93		300	1.13	300			300			300	
360	2.99	5.03	360	1.10	360			360			360	
420	3.03		420	1.08	420			420			420	
480	3.08	5.04	480	1.05	480			480			480	
540	3.12		540	1.03	540			540			540	
600	3.15	5.06	600	0.97	600			600			600	
720	3.19		720	0.95	720			720			720	
840	3.24	5.07	840	0.91	840			840			840	
960	3.28		960	0.88	960		0.08	960			960	
1080	3.34	5.05	1080	0.85	1080			1080			1080	
1200	3.40		1200	0.83	1200			1200			1200	
1320	3.45	5.08	1320	0.82	1320			1320			1320	
1440	3.50		1440	0.80	1440			1440			1440	
1560	3.54	5.06	1560	0.79	1560	0.00		1560			1560	
1680	3.57		1680	0.78	1680			1680			1680	
1800	3.59	5.05	1800	0.77	1800			1800			1800	
1920	3.61		1920	0.76	1920			1920			1920	
2040	3.64	5.08	2040	0.75	2040			2040			2040	
2160	3.68		2160	0.75	2160			2160			2160	
2280	3.71	5.07	2280	0.74	2280			2280			2280	
2400	3.73		2400	0.74	2400	0.00		2400			2400	
2520	3.75	5.08	2520	0.73	2520			2520			2520	
2640	3.78		2640	0.73	2640			2640			2640	
2760	3.80	5.05	2760		2760			2760			2760	
2880	3.81		2880		2880	0.31		2880			2880	
3000	3.83	5.07	3000		3000			3000			3000	
3120	3.84		3120		3120			3120			3120	
3240	3.85	5.04	3240		3240			3240			3240	
3360	3.85		3360		3360			3360			3360	
3480	3.86	5.05	3480		3480			3480			3480	
3600	3.87		3600		3600			3600			3600	
3720	3.97	5.07	3720		3720			3720			3720	
3840	3.89		3840		3840	0.50		3840			3840	
3960	3.91	5.04	3960		3960			3960			3960	
4080	3.92		4080		4080			4080			4080	
4200	3.96	5.06	4200		4200			4200			4200	
4320	3.96		4320		4320	0.57		4320			4320	
Total time pumped(min):			4320			W/L	29.56		W/L			W/L
Average yield (l/s):			5.06									

FORM 5 E STEPPED DISCHARGE TEST & RECOVERY														
BOREHOLE TEST RECORD SHEET					PROVINCE: NORTHERN CAPE					DISTRICT: KAROO HOOGLAND				
PROJ NO : P2581		MAP REFERENCE:			LATITUDE: S 32.23279					SITE NAME: AERODROME				
BOREHOLE NO: BH SL8		LONGITUDE: E 27.89804			EXISTING PUMP: NEW BOREHOLE					CONTRACTOR: ATS				
ALT BH NO: 0		DIAM PUMP INLET (mm): 170.00			PUMP TYPE: WA110-2									
BOREHOLE DEPTH (m): 108.20		DATUM LEVEL ABOVE CASING (m): 0.45												
WATER LEVEL (mbdl): 5.77		CASING HEIGHT: (magl): 0.25												
DEPTH OF PUMP (m): 95.76														
STEPPED DISCHARGE TEST & RECOVERY														
DISCHARGE RATE 1					DISCHARGE RATE 2					DISCHARGE RATE 3				
RPM 168					RPM 271					RPM 456				
DATE: 17/11/2021		TIME: 08H10			DATE: 14/11/2021		TIME: 19H10			DATE: 17/11/2021		TIME: 10H10		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.23		1		1	1.98		1		1	5.04		1	
2	0.25		2		2	2.06		2		2	5.78		2	
3	0.27	2.42	3		3	2.24	7.10	3		3	6.04	14.04	3	
5	0.29	3.10	5		5	2.36		5		5	6.17		5	
7	0.31	5.13	7		7	2.51	9.14	7		7	6.26	14.01	7	
10	0.37		10		10	2.76		10		10	6.45		10	
15	0.95	5.11	15		15	2.83	9.13	15		15	6.58	14.05	15	
20	0.98		20		20	2.95		20		20	6.73		20	
30	1.07	5.14	30		30	3.14	9.16	30		30	6.94	14.02	30	
40	1.19		40		40	3.22		40		40	7.12		40	
50	1.29	5.10	50		50	3.34	9.12	50		50	7.30	14.05	50	
60	1.35		60		60	3.41		60		60	7.48		60	
70			70		70			70		70			70	
80			80		80			80		80			80	
90			90		90			90		90			90	
100			100		100			100		100			100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	19.10	°C	180		TEMP	16.10	°C	180		TEMP	18.20	°C	180	
EC	3550	µS/cm	210		EC	3736	µS/cm	210		EC	3741	µS/cm	210	
DISCHARGE RATE 4					DISCHARGE RATE 5					DISCHARGE RATE 6				
RPM					RPM 603					RPM				
DATE: 17/11/2021		TIME: 11H10			DATE: 17/11/2021		TIME: 17H00			DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	8.98		1	3.97	1			1	2.55	1			1	
2	10.02		2	2.44	2	2.53		2	2.43	2			2	
3	10.16		3	2.34	3	3.10	12.23	3	2.28	3			3	
5			5	2.28	5	4.09	14.74	5	2.15	5			5	
7			7	2.24	7	4.76	15.51	7	2.06	7			7	
10			10	2.18	10	5.34		10	1.99	10			10	
15			15	2.08	15	6.14	15.54	15	1.90	15			15	
20			20	1.91	20	6.50		20	1.81	20			20	
30			30	1.76	30	7.00	15.52	30	1.63	30			30	
40			40	1.65	40	7.31		40	1.54	40			40	
50			50	1.55	50	7.63	15.50	50	1.46	50			50	
60			60	1.46	60	7.89		60	1.34	60			60	
70			70	1.36	70			70		70			70	
80			80	1.31	80			80		80			80	
90			90	1.26	90			90		90			90	
100			100	1.20	100			100		100			100	
110			110	1.15	110			110		110			110	
120			120	1.10	120			120		120			120	
pH			150		pH			150		pH			150	
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
			240					240					240	
			300					300					300	
			360					360					360	
S/W/L:(mbch) 5.32														

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : P2581	MAP REFERENCE: S32.23279	PROVINCE: NORTHERN CAPE
BOREHOLE NO: BH SL8	E 020.69196	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0		SITE NAME: AERODROME
BOREHOLE DEPTH: 108.20	DATUM LEVEL ABOVE CASING (m): 0.45	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 6.09	CASING HEIGHT: (magl): 0.25	CONTRACTOR: ATS
DEPTH OF PUMP (m): 95.76	DIAM PUMP INLET (mm): 170	PUMP TYPE: WA110-2

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED				TEST COMPLETED				
DATE: 18/11/2021	TIME: 08H10	DATE: 23/11/2021	TIME: 08H10	TYPE OF PUMP:		WA110-2		
OBSERVATION HOLE 1		OBSERVATION HOLE 2		OBSERVATION HOLE 3				
NR:		NR:		NR:				
DISCHARGE BOREHOLE				Distance(m):				
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)
1	1.91		8.40	1			1	
2	2.45		8.18	2			2	
3	2.87	12.50	8.08	3			3	
5	3.77		7.98	5			5	
7	4.33	14.78	7.88	7			7	
10	5.05	15.08	7.78	10			10	
15	5.71		7.62	15			15	
20	5.94	15.04	7.46	20			20	
30	6.24		7.24	30			30	
40	6.57	15.02	7.03	40			40	
60	7.01		6.67	60			60	
90	7.53	15.07	6.24	90			90	
120	7.96		5.86	120			120	
150	8.52	15.05	5.54	150			150	
180	8.81		5.28	180			180	
210	9.19	15.00	5.07	210			210	
240	9.37		4.85	240			240	
300	9.84	15.04	4.50	300			300	
360	10.32		4.23	360			360	
420	10.64	15.06	3.98	420			420	
480	10.92		3.75	480			480	
540	11.19	15.08	3.54	540			540	
600	11.33		3.38	600			600	
720	11.64	15.04	3.23	720			720	
840	11.87		3.09	840			840	
960	12.06	15.02	2.96	960			960	
1080	12.14		2.81	1080			1080	
1200	12.23	15.00	2.69	1200			1200	
1320	12.36		2.51	1320			1320	
1440	12.43	15.04	2.40	1440			1440	
1560	12.54		2.31	1560			1560	
1680	12.59	15.06	2.23	1680			1680	
1800	12.63		2.16	1800			1800	
1920	12.65	15.02	2.10	1920			1920	
2040	12.68		2.03	2040			2040	
2160	12.72	15.05	1.96	2160			2160	
2280	12.79		1.90	2280			2280	
2400	12.84	15.03	1.86	2400			2400	
2520	12.90		1.83	2520			2520	
2640	12.96	15.04	1.80	2640			2640	
2760	13.01		1.78	2760			2760	
2880	13.05	15.01	1.74	2880			2880	
3000	13.07			3000			3000	
3120	13.09	15.03		3120			3120	
3240	13.11	15.00		3240			3240	
3360	13.15			3360			3360	
3480	13.19	15.06		3480			3480	
3600	13.24			3600			3600	
3720	13.29	15.02		3720			3720	
3840	13.35			3840			3840	
3960	13.41	15.04		3960			3960	
4080	13.48			4080			4080	
4200	13.54	15.07		4200			4200	
4320	13.59			4320			4320	
Total time pumped(min):			4320	W/L		W/L		W/L
Average yield (l/s):			15.04					

BOREHOLE TEST CONTROL SHEET						
Groundwater Solutions t/a AB PUMPS						
Borehole number:		SL11		Old / Alternative number:		
Contractor:		ATS		Supervisor:		ABEL
Operator:		CHRISTOPHER		Rig number & Type rig:		DEUTZ #157
EXISTING EQUIPMENT						
Type pump	Depth	Condition	Drive unit	Condition	Pump house	Condition
TESTING EQUIPMENT						
Pump type	Depth installed (m)	Date & time (started)	Date & time (completed)			
WA110-2	91.26	11/11/2021 08H30	11/11/2021 14H30			
MULTI-RATE OR STEPTEST DETAILS						
STEP	DURATION (MIN)	RECOVERY (MIN)	YIELD (L/S)		DRAWDOWN (m)	
1	60		3.03	l/s	0.46	
2	60		9.10	l/s	1.28	
3	60		14.13	l/s	2.16	
4	60		18.18	l/s	3.08	
5				l/s		
6				l/s		
7				l/s		
8				l/s		
Calibration:					l/s	
TOTAL:		240	120		l/s	
COMMENT:						
CONSTANT RATE DISCHARGE TEST						
Pump type	Depth installed (m)	Date & time (started)		Date & time (completed)		
WA110-2	91.26	11/11/2021	17H00	16/11/2021	11H00	
Yield l/s	Drawdown (m)	Duration (min)		Recovery (min)		
16.07	5.17	4320		2520		
Total: (Multi-rate and Constant Discharge rate)		4560		2640		
COMMENT:						
MAINTENANCE						
Work time: hour		Transport existing equipm. Km		Travelling (To fix):		Km
List of parts replaced or repaired:						
	Borehole number	Duration (min) CONSTANT	Drawdown (m)	Hand/logger	Distance (m)	
Observation Hole 1	Mar 2	4320		LOGGER	225	
Observation Hole 2					0	
Observation Hole 3					0	
Observation Hole 4						
Observation Hole 5						
GENERAL						
ESTABLISHMENT		From:		To:		
Site Move		From project#		To #: 2581		Travelling km: 3
	Village	Borehole no	Village	Borehole no		
	SUTHERLAN D	SL5	SUTHERLAN D	SL11		
Maintenance:		Work time hr	Parts repaired/ replaced	Travelling km		
After test measurements	Water level	23.06	Borehole depth	98.40	Casing depth m	2.90
Water level before installing test pump: (mbch)				21.4		
Depth before installing test pump:				98.40		
Testpump Installed		Once / Twice / More		Reason:		
Installed Testpump		<10 l/s / >10l/s		Reason:		
Was existing equipment re-installed:		Yes:	No:	If not where was it left:		
GPS Unit number:						
EC Unit number:		#77				
Remarks:						
Signed Contractor:			Signed Consultant:			

FORM 5 E
STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : 2581	MAP REFERENCE:	PROVINCE: NORTHERN CAPE
BOREHOLE NO: SL11	LATITUDE: S 32.23279	DISTRICT: KAROO HOOGLAND
ALT BH NO: 0	LONGITUDE: E 27.89804	SITE NAME: SUTHERLAND
ALT BH NO: 0		
BOREHOLE DEPTH (m) 98.40	DATUM LEVEL ABOVE CASING (m): 0.50	EXISTING PUMP: NEW BOREHOLE
WATER LEVEL (mbdl): 21.70	CASING HEIGHT: (magl): 0.20	CONTRACTOR: ATS
DEPTH OF PUMP (m): 91.26	DIAM PUMP INLET (mm): 170.00	PUMP TYPE: WA110-2


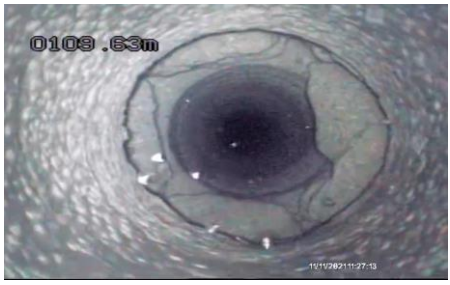


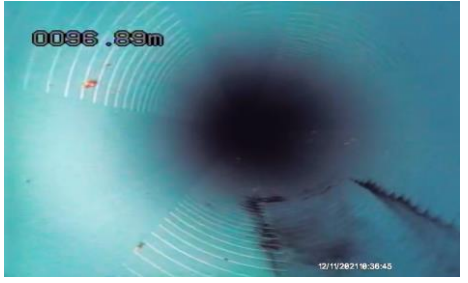



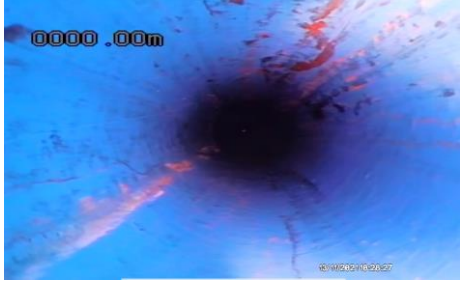



STEPPED DISCHARGE TEST & RECOVERY


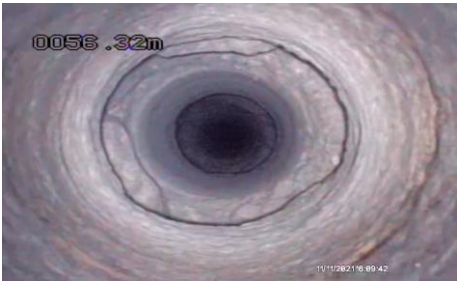



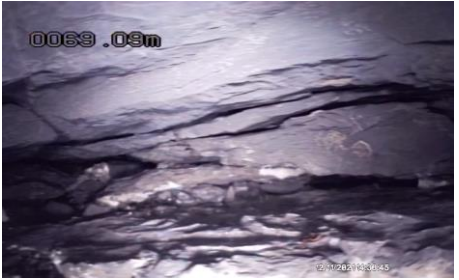

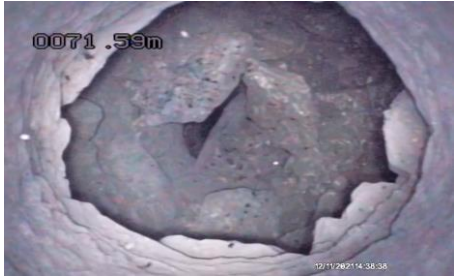



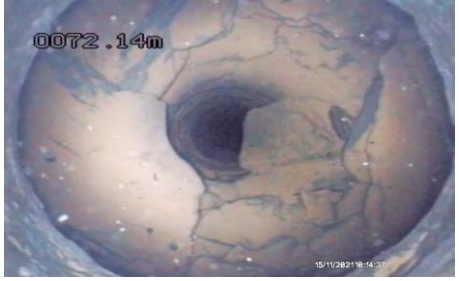
DISCHARGE RATE 1				RPM 298	DISCHARGE RATE 2				RPM 536	DISCHARGE RATE 3				RPM 728
DATE: 11/11/2021		TIME: 08H30			DATE: 11/11/2021		TIME: 09H30			DATE: 11/11/2021		TIME: 10H30		
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1	0.18		1		1	0.75		1		1	1.45		1	
2	0.19		2		2	0.81		2		2	1.64		2	
3	0.21		3		3	0.92	8.50	3		3	1.70	11.64	3	
5	0.23	3.03	5		5	0.99	9.04	5		5	1.77		5	
7	0.25		7		7	1.03		7		7	1.80	14.04	7	
10	0.27	3.02	10		10	1.09	9.10	10		10	1.82		10	
15	0.30		15		15	1.14		15		15	1.83	14.13	15	
20	0.33	3.43	20		20	1.20	9.13	20		20	1.94		20	
30	0.36		30		30	1.24		30		30	2.03	14.10	30	
40	0.40	3.43	40		40	1.26	9.11	40		40	2.09		40	
50	0.43		50		50	1.27		50		50	2.13	14.12	50	
60	0.46	3.43	60		60	1.28	9.12	60		60	2.16		60	
70			70		70			70		70			70	
80			80		80			80		80			80	
90			90		90			90		90			90	
100			100		100			100		100			100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	18.50	°C	180		TEMP	21.30	°C	180		TEMP	25.50	°C	180	
EC	609	µS/cm	210		EC	667	µS/cm	210		EC	621	µS/cm	210	
DISCHARGE RATE 4				RPM 891	DISCHARGE RATE 5				RPM	DISCHARGE RATE 6				RPM
DATE: 11/11/2021		TIME: 11H30			DATE:		TIME:			DATE:		TIME:		
TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY	TIME	DRAW	YIELD	TIME	RECOVERY
(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)	(MIN)	DOWN (M)	(L/S)	(MIN)	(M)
1	2.39		1	1.59	1			1		1			1	
2	2.48		2	1.43	2			2		2			2	
3	2.52	17.95	3	1.29	3			3		3			3	
5	2.58		5	1.10	5			5		5			5	
7	2.65	18.18	7	0.92	7			7		7			7	
10	2.72		10	0.72	10			10		10			10	
15	2.79	18.16	15	0.64	15			15		15			15	
20	2.84		20	0.53	20			20		20			20	
30	2.92	18.14	30	0.42	30			30		30			30	
40	3.01		40	0.35	40			40		40			40	
50	3.04	18.16	50	0.30	50			50		50			50	
60	3.08		60	0.26	60			60		60			60	
70			70	0.23	70			70		70			70	
80			80	0.20	80			80		80			80	
90			90	0.19	90			90		90			90	
100			100	0.18	100			100		100			100	
110			110	0.17	110			110		110			110	
120			120	0.16	120			120		120			120	
pH			150		pH			150		pH			150	
TEMP	26.30	°C	180		TEMP		°C	180		TEMP		°C	180	
EC	614	µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	
			240					240					240	
			300					300					300	
			360					360					360	




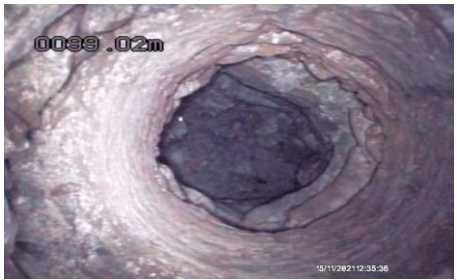
S/WL:(mbch) 21.4

FORM 5 F													
CONSTANT DISCHARGE TEST & RECOVERY													
BOREHOLE TEST RECORD SHEET													
PROJ NO :	2581		MAP REFERENCE:		S32.23279			PROVINCE:		NORTHERN CAPE			
BOREHOLE NO:	SL11				E 20.65825			DISTRICT:		KAROO HOOGLAND			
ALT BH NO:	0							SITE NAME:		SUTHERLAND			
ALT BH NO:	0												
BOREHOLE DEPTH:	98.40		DATUM LEVEL ABOVE CASING (m):		0.50			EXISTING PUMP:		NEW BOREHOLE			
WATER LEVEL (mbdl):	21.83		CASING HEIGHT: (magl):		0.20			CONTRACTOR:		ATS			
DEPTH OF PUMP (m):	91.26		DIAM PUMP INLET (mm):		170			PUMP TYPE:		WA110-2			
CONSTANT DISCHARGE TEST & RECOVERY													
TEST STARTED						TEST COMPLETED							
DATE:	11/11/2021		TIME:	17H00		DATE:			TIME:			TYPE OF PUMP:	WA110-2
						OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3	
						NR: Mar-2			NR:			NR:	
						Distance(m): 225			Distance(m):			Distance(m):	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (min)	Drawdown (m)	Recovery (m)	TIME (min)	Drawdown (m)	Recovery	TIME (min)	Drawdown (m)	
1	0.71		1	3.80	1			1			1		
2	0.92		2	3.66	2			2			2		
3	1.10		3	3.55	3			3			3		
5	1.27	14.94	5	3.34	5			5			5		
7	1.36		7	3.17	7			7			7		
10	1.43	16.01	10	3.04	10			10			10		
15	1.69		15	2.88	15			15			15		
20	1.82	16.07	20	2.80	20			20			20		
30	1.95		30	2.71	30			30			30		
40	2.10	16.05	40	2.63	40			40			40		
60	2.28		60	2.55	60			60			60		
90	2.34	16.06	90	2.48	90			90			90		
120	2.38		120	2.42	120			120			120		
150	2.43	16.05	150	2.38	150			150			150		
180	2.47		180	2.35	180			180			180		
210	2.52	16.06	210	2.32	210			210			210		
240	2.58		240	2.29	240			240			240		
300	2.61	16.05	300	2.25	300			300			300		
360	2.64		360	2.21	360			360			360		
420	2.73	16.16	420	2.18	420			420			420		
480	2.80		480	2.15	480			480			480		
540	2.86	16.05	540	2.10	540			540			540		
600	2.93		600	2.06	600			600			600		
720	2.99	16.04	720	2.02	720			720			720		
840	3.06		840	1.99	840			840			840		
960	3.29	16.07	960	1.94	960			960			960		
1080	3.30		1080	1.90	1080			1080			1080		
1200	3.33	16.09	1200	1.87	1200	1.07		1200			1200		
1320	3.39		1320	1.85	1320			1320			1320		
1440	3.44	16.05	1440	1.83	1440			1440			1440		
1560	3.56		1560	1.79	1560			1560			1560		
1680	3.64	16.07	1680	1.74	1680			1680			1680		
1800	3.72		1800	1.70	1800			1800			1800		
1920	3.80	16.05	1920	1.67	1920			1920			1920		
2040	3.89		2040	1.64	2040			2040			2040		
2160	3.98	16.06	2160	1.61	2160			2160			2160		
2280	4.08		2280	1.57	2280			2280			2280		
2400	4.09	16.07	2400	1.54	2400			2400			2400		
2520	4.17		2520	1.51	2520			2520			2520		
2640	4.22	16.05	2640		2640			2640			2640		
2760	4.28		2760		2760			2760			2760		
2880	4.36	16.06	2880		2880			2880			2880		
3000	4.42		3000		3000			3000			3000		
3120	4.49	16.05	3120		3120			3120			3120		
3240	4.54		3240		3240			3240			3240		
3360	4.60	16.07	3360		3360			3360			3360		
3480	4.68		3480		3480			3480			3480		
3600	4.76	16.08	3600		3600			3600			3600		
3720	4.85		3720		3720			3720			3720		
3840	4.94	16.06	3840		3840			3840			3840		
3960	5.01		3960		3960			3960			3960		
4080	5.07	16.07	4080		4080	1.23		4080			4080		
4200	5.11		4200		4200			4200			4200		
4320	5.17	16.05	4320		4320	1.29		4320			4320		
Total time pumped(min):				4320	W/L		20.71	W/L		W/L			
Average yield (l/s):				16.05									

APPENDIX C – SUMMARY OF CAMERA LOGS

ID	Casing	Fracture/Other	Interesting appearance	EOH/Other
SL1	 <p>0003.56m</p>	 <p>0109.63m</p>	 <p>0008.29m</p>	 <p>0151.30m</p>
SL3	 <p>0036.89m</p>	 <p>0081.38m</p>	 <p>0104.75m</p>	 <p>0149.96m</p>
SL4	 <p>0000.00m</p>	 <p>0058.46m</p>	 <p>0048.09m</p>	 <p>0144.20m</p>

ID	Casing	Fracture/Other	Interesting appearance	EOH/Other
SL5	 <p>0006 .97m</p> <p>11/11/2021 15:34:19</p>	 <p>0056 .32m</p> <p>11/11/2021 15:09:42</p>	 <p>0021 .03m</p> <p>11/11/2021 15:55:27</p>	 <p>0056 .84m</p> <p>11/11/2021 15:10:00</p>
SL6	 <p>0005 .85m</p> <p>12/11/2021 14:13:38</p>	 <p>0069 .09m</p> <p>12/11/2021 15:31:45</p>	 <p>0038 .22m</p> <p>12/11/2021 14:21:42</p>	 <p>0071 .59m</p> <p>12/11/2021 14:35:35</p>
SL9	 <p>0001 .82m</p> <p>10/11/2021 09:49:34</p>	 <p>0072 .63m</p> <p>10/11/2021 09:12:47</p>	 <p>0016 .52m</p> <p>10/11/2021 09:33:53</p>	 <p>0072 .14m</p> <p>10/11/2021 09:14:35</p>

ID	Casing	Fracture/Other	Interesting appearance	EOH/Other
SL-11				

APPENDIX D – BASELINE GROUNDWATER CHEMISTRY DATA (SANS241 – 2015).

Acute Health
Aesthetic
Chronic health
Operational
Acceptable

WATER CHEMISTRY ANALYSIS, COLOUR CODED ACCORDING TO SANS241-1:2015

Analyses	SL1	SL3	SL4	SL5	SL6	SL11	SANS 241-1:2015
pH (at 25 °C)	7.7	8.9	8.1	8.2	7.7	7.9	≥5 - ≤9.7 Operational
Conductivity (mS/m) (at 25 °C)	174.6	94.6	68.6	68.4	64.0	63.7	≤170 Aesthetic
Total Dissolved Solids (mg/L)	1183.79	641.39	465.11	463.75	433.92	431.89	≤1200 Aesthetic
Turbidity (NTU)	9.16	8.96	1.06	0.97	1.12	1.52	≤5 Aesthetic ≤1 Operational
Colour (mg/L as Pt)	<15	<15	<15	<15	<15	<15	≤15 Aesthetic
Sodium (mg/L as Na)	261	204	116	104	71	92	≤200 Aesthetic
Potassium (mg/L as K)	2	4	4	2	1	4	N/A
Magnesium (mg/L as Mg)	2	1	7	9	5	4	N/A
Calcium (mg/L as Ca)	82	3	24	30	50	38	N/A
Chloride (mg/L as Cl)	476.61	126.78	77.42	75.15	69.57	71.03	≤300 Aesthetic
Sulphate (mg/L as SO4)	6.84	8.78	<4.00	<4.00	13.36	11.34	≤250 Aesthetic ≤500 Acute Health
Nitrate & Nitrite Nitrogen (mg/L as N)	<1.05	<1.05	<1.05	<1.05	<1.05	<1.05	≤12 Acute Health
Nitrate Nitrogen (mg/L as N)	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	≤11 Acute Health
Nitrite Nitrogen (mg/L as N)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	≤0.9 Acute Health
Ammonia Nitrogen (mg/L as N)	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	≤1.5 Aesthetic
Total Alkalinity (mg/L as CaCO3)	120.5	275.4	244.6	256.2	215.7	213.6	N/A
Total Hardness (mg/L as CaCO3)	213.2	11.1	88.7	111.9	145.5	111.4	N/A
Fluoride (mg/L as F)	2.11	7.66	2.00	2.07	0.94	1.34	≤1.5 Chronic Health
Aluminium (mg/L as Al)	0.479	0.050	0.023	0.039	0.008	0.020	≤0.3 Operational
Total Chromium (mg/L as Cr)	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	≤0.05 Chronic Health
Manganese (mg/L as Mn)	0.035	<0.018	0.020	0.009	0.025	0.024	≤0.1 Aesthetic ≤0.4 Chronic Health
Iron (mg/L as Fe)	0.419	0.025	0.026	0.094	0.041	0.036	≤0.3 Aesthetic ≤2 Chronic Health
Nickel (mg/L as Ni)	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	≤0.07 Chronic Health
Copper (mg/L as Cu)	0.005	0.011	0.016	0.014	0.004	0.017	≤2 Chronic Health
Zinc (mg/L as Zn)	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	≤5 Aesthetic
Arsenic (mg/L as As)	<0.010	<0.010	<0.010	<0.010	0.013	<0.010	≤0.01 Chronic Health
Selenium (mg/L as Se)	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	≤0.04 Chronic Health
Cadmium (mg/L as Cd)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.003 Chronic Health
Antimony (mg/L as Sb)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	≤0.02 Chronic Health
Mercury (mg/L as Hg)	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.006 Chronic Health
Lead (mg/L as Pb)	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	≤0.01 Chronic Health
Uranium (mg/L as U)	<0.028	<0.028	<0.028	<0.028	<0.028	<0.028	≤0.03 Chronic Health
Cyanide (mg/L as CN-)	0.013	<0.01	<0.01	<0.01	<0.01	<0.01	≤0.2 Acute Health
Total Organic Carbon (mg/L as C)	1.08	1.58	2.04	2.27	2.48	2.15	N/A
Charge balance %	0.1	4.6	4.5	2.5	1.2	4.2	≥-5 - ≤5 Acceptable