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Developing a hydrogeological conceptual model for subterranean groundwater control areas using remote sensing techniques, Hout catchment, Limpopo, South Africa

By

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Declaration

I, Andrew Talinda Mkali, declare that project title "*Developing a hydrogeological conceptual model for subterranean groundwater control areas using remote sensing techniques, Hout catchment, Limpopo, South Africa*" is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full names: **Andrew Talinda Mkali**

Signature:

Dedication

I dedicate my work to my family and many friends. A special feeling of gratitude to my loving parents, Peter and Mary Mkali whose words of encouragement and push for tenacity ring in my ears. My sister Talumba and all my loved ones who have always believed in me and have never left my side.

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Abstract

Crystalline basement aquifers are an important source of water supply in sub-Saharan Africa for various purposes. These aquifers are characterized by fractured rock networks which form pathways for groundwater recharge, flow, and discharge in subterranean groundwater areas. The fractured rock networks in these areas form fractured rock aquifers which in some cases are protected or reserved. In South Africa, various aquifers with these characteristics have been declared as subterranean groundwater control areas. The physical characteristics of these hydrogeological settings remains crucial in sustaining ecosystems and supporting socio-economic practices such as irrigation, among others. However, the role of fracture connectivity in crystalline basement aquifers remains poorly understood despite the well-established knowledge about the hydrogeological characteristics of such areas. The current research described physical hydrogeological characteristics of crystalline basement aquifers using hydrogeological conceptual model to demonstrate the influence of connectedness of the fractured rock network system on subterranean groundwater control areas. The present study argues that comprehensive characterization of fractured rock aquifers is essential in establishing the influence of fracture connectivity on groundwater flow and discharge especially for subterranean groundwater control areas. The Hout catchment in Limpopo Province of South Africa was used as a case study. To validate that argument, the present study 1] established groundwater potential zones, 2] characterized the hydrostratigraphic system and 3] conceptualized the hydrogeological system. A records review method, remote sensing, geophysical techniques, and analytical methods were used to collect and describe geological, hydrostratigraphic, pumping test and water level data in order to characterise the fracture networks and pathways for groundwater flow path assessments. A field experimental site was set up and used for the measurement and analyses of hydrogeological parameters.

Results from thematic mapping of geology, slope, faults, lineament density, drainage density and land cover indicated that areas of high groundwater potential zones were mainly found in southern region of the Hout catchment. Indicators were presence of high borehole yields of 2.5 - 10 l/s that coincided with areas of moderate to high groundwater potential zones of 400 - 700 in the southern region. Using geophysical data, results showed that anomalies (fractured regions) occurred in range of 30m to 72m. Log profiles of four boreholes that were drilled revealed that the area was controlled by highly fractured and weathered Goudplaats granitic gneiss, younger quarzitic rocks and diabase dykes. These observations agreed with resistivity graphs that were generated. Findings of the study on drilling showed that water strikes with high blow yields of 5 - 8.4 l/s occurred in the deeper regions of the subsurface (>30m) suggesting that water-bearing fractures are present in areas near river channels. Transmissivity values from constant rate pumping tests ranged between 36.5 – 48 m^2/d. These high transmissivity values were associated with the fractured nature of weathered pegmatite lineaments and quarzitic-gneissic geology of the Limpopo mobile belt. The water levels in boreholes showed no significant responses to precipitation events which suggested that recharge and flow occur regionally.

A site-specific conceptual model of the aquifer showed the fractured rock network system in the field experimental site. Various datasets such as geophysical and hydrogeological data were used to develop the hydrogeological conceptual model for subterranean groundwater control areas. The model demonstrated the influence of connectivity in fractured rock network systems on subterranean groundwater control areas. The study showed that the use of remote sensing techniques coupled with geophysical and hydraulic parameter estimation methods for groundwater evaluation provided an improved understanding on the influence on fractures and their connectivity on crystalline basement aquifers for water resource and supply.

Key words: aquifer characterization, crystalline basement, groundwater potential, conceptual model, groundwater

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Chapter 1: Introduction

1.1 Study overview

This research is about evaluating the extent at which fractured networks influence the occurrence of groundwater in crystalline basement aquifers. The study uses the Hout river catchment as a case study to establish how hydrogeological characteristics in the area influence occurrence of groundwater in fractured regions of the underlying aquifer. Various studies have established that comprehensive knowledge of fracture connectivity at regional and local scales is necessary to delineate sustainable aquifers and manage them efficiently (Holland, 2012; Chandra *et al.*, 2019). The study argues that unless the hydrogeologic characteristics of aquifers in crystalline basement terrain are evaluated, the influence of interconnectedness of fracture networks on groundwater occurrence may not be properly established within subterranean groundwater control areas. The study would provide information to the research question: "What aspects of hydrogeological characterization can be used to describe the influence of fracture connectivity on groundwater occurrence?". Unless we determine hydrogeological characteristics that control occurrence of water in the fractured aquifer system, information to inform decision on sustainable use of groundwater will be unreliable.

1.2 Study Background

Groundwater plays a crucial role as an important part of water resources in various countries around the world. Regional and local groundwater budgets affect energy and food security, ecosystem services and drinking water availability (Gleeson *et al.*, 2016). However, due to climate change and the overexploitation of the resource for various uses, groundwater is declining steadily at a rate of approximately 545 km^3 per year in both humid and dry areas (Mussa *et al.*, 2020). Therefore, to ensure better management of groundwater resources, sustainable groundwater utilisation requires a holistic understanding of the controls that govern aquifer dynamics such as the interconnectedness of groundwater flow systems.

Throughout Sub-Saharan Africa (SSA), the development of groundwater is very important for rural water supply. Since groundwater gradually responds to changes in rainfall, the impacts of droughts are often buffered (MacDonald *et al.*, 2002). Majority of the population in SSA are highly dependent on groundwater for domestic use and socio-economic activities such as farming. Roughly three-quarters of all the groundwater pumped from boreholes or taken from springs is used for domestic purposes (Xu *et al.*, 2019). These aquifers can be composed of weathered and fractured zones whose locality and thickness are highly spatially variable (Banks *et al.*, 2011; Robins *et. al*, 2013). As a result, Crystalline Basement Aquifers' (CBA) have complex hydrogeological properties. A comprehensive understanding of these properties is an important prerequisite when applying the most sustainable methods for the development and utilization of the resource.

The occurrence and movement of groundwater in crystalline basement terrain is usually controlled by fractures, joints, geological contacts, shear zones, faults, and other discontinuities (Chandra *et al.*, 2019). The rocks in these areas have been subjected to multiple tectonic events under different stress conditions, leading to complex patterns of ductile folding and brittle fracturing, particularly in the near-surface (Foster, 2015). Apart from regional tectonic events, the intrusion of dykes, and quartzite and pegmatite veins also cause fracturing of the rock. Because fracture zones are mechanically weak and provide conditions for weathering, they can store and transmit more groundwater than intact rocks and form the main aquifers. These multifaceted interrelationships control overall aquifer dynamics and identifying the presence of structural features such as faults and fracture traces can often indicate the possible presence of groundwater in these environments (MacDonald *et al.*, 2002). One of the approaches is to assess the distribution of groundwater-bearing features, the geology and to characterize hydraulics within the area.

In South Africa, most of the groundwater is stored within sedimentary rocks. Secondary aquifers do, however, exist in the rocks beneath the country's basement. These rocks underneath include granite, gneiss, migmatites and granitoids (Foster, 2015). In hydrogeological terms, aquifers in the basement rocks are generally considered to be heterogeneous in nature. This is evidenced through the success rate of boreholes are that drilled into these aquifers as they often display yields under 1 l/s (Holland, 2011). However, these aquifers provide water to many rural communities. Constraints in developing basement aquifers for water supply include the low success rate of drilling water-yielding boreholes in basement rocks, the low storage capacity of these rocks and the low recharge rates often associated with these rocks.

A study in the Limpopo plateau was carried out based on surface and sub-surface hydrogeological features such as lithology, geological structures, geological and structural lineaments, land forms, drainage density, water bodies and weathered/fractured thickness of overburden material in order to assess how these parameters influence the transmissivities and blow yields at in the region (Holland, 2011). Findings showed that high transmissivity values are associated with areas characterised by pegmatite lineaments and dykes, topographical lows, and areas with close proximity to lineaments. The hydrogeology of the weathered zone in these regions is characterised by significantly low primary porosity and almost all groundwater movement and storage occur in fractures, faults, weathered zones, and other secondary features that enhance the aquifer potential only locally. This is due either to discontinuities or barrier boundaries within the fracture system being tapped or due to the constraints of the low permeability regolith. These features are commonly reflected in a significant borehole failure rate and a wide range of yields, with success rates that low with cases where a successful borehole has been drilled having blow yields of less than 5 l/s, and often less than 1 Litre/second despite the apparent regional uniformity of the basic controls of climate, morphology, and geology (Wright, 1997).

The Hout river catchment, despite various groundwater development projects that have been initiated in several areas, has experienced an increased water demand as a result of an increase in commercial farming. These activities threaten the availability of groundwater resources and can trigger conflicts amongst users from different sectors. A declaration in April 1994 of the Vivo-Dendron area as a Subterranean Government Water Control Area in terms of section 28 of the Water Act 1956 (Act No 54 of 1956) and the establishment of a Subterranean Water Control Board were introduced to facilitate the sustainable use of groundwater resources(Vegter, 2003). Therefore, as the study area falls within a subterranean water control area, further understanding of the subsurface is required to understand how the presence of fractures contribute to the groundwater dynamics.

1.3 Research Problem

Subterranean groundwater control areas that occur in crystalline basement settings such as the Hout catchment have been historically dependent on agricultural practices for socio-economic development, and groundwater is the only reliable source of water for many consumers. Groundwater is available and commonly used throughout the area but in varying proportions depending on the underlying aquifer's hydrogeological characteristics. Despite several significant hydrogeological studies in the 1970s and the construction of several hand-pumped boreholes for rural communities in south-east Africa, the hydrogeology of crystalline basement aquifers is not yet fully known. This is partly due to the lack of records and incorrect available data. It is also widely understood that no single unique factor will ensure high yielding boreholes, and that the significance of factors that influence borehole yields vary depending on specific conditions of the region or geological setting (Mabee, *et al.,* 1994; Wright, 2008; Mohamed *et al.,* 2015; Bour and Aquilina, 2016; Bayewu *et al.,* 2017). This suggests that information about fractured networks on groundwater is limited and therefore may lead to unreliable decisions, therefore leading to unsustainable use of groundwater resources.

1.4 Research question and thesis statement

"What aspects of hydrogeological characterization can be used to describe the influence of fracture connectivity on occurrence of groundwater?" The current study raises this question to provide a conceptual understanding on the influence of structural features on groundwater occurrence in subterranean groundwater control areas.

Unless we determine hydrogeological characteristics that control the occurrence of water in the fractured aquifer system, information to inform decision on sustainable use of groundwater will be unreliable. In other words, connectedness of fracture network needs to be established to explain the flow path or pathways for recharge, flow and discharge of groundwater. The influence of such connectedness of fractures in aquifer system on groundwater occurrences needs to be demonstrated with various methods. Such demonstration can be clearly visualised when hydrogeological conceptual model is used.

1.5 Aim and Objectives

The study aims to develop a hydrogeological conceptual model that describes the role of fracture connectivity in the occurrence of groundwater in subterranean groundwater control areas, using the Hout river catchment in Limpopo, South Africa, as a case study. Such a conceptual model will improve the understanding of the role of fractured rock networks on groundwater occurrence in crystalline basement aquifers. The improved understanding would provide an inform a basis to develop action plans for the use and management of groundwater in subterranean groundwater control areas. In this end, this thesis addresses the following objectives:

i. Identify groundwater potential zones.
ii. Determine the aquifer characteristics.
iii. Develop a hydrogeological conceptual model of the flow system.

1.6 Significance of the study

Groundwater plays a vital role in the hydrological system. However, the awareness of its limited supply has only become more prevalent in the past few decades. Recently, there has been an increase in the involvement for sustainable groundwater management. The present study is significant as the generated information will help improve an understanding of the aquifer hydrogeological properties in crystalline basement environments, which is crucial for water resource planning. Further, by producing information on groundwater flow directions and hydraulic properties which are essential for groundwater quantity and quality evaluations, the generated information will be used as case study in teaching and learning. The information in this document will be used as a source for literature review for other studies in future and by practitioners in the study area to make inferences about the general expected characteristics, which is important in groundwater resource management and development cases, planning and investigation.

1.7 Scope and Nature of the Study

The current study places focus on assessing the manner in which groundwater occurs in the study area, determining the aquifer hydraulic properties (transmissivity and storativity) and applying remote sensing, GIS and geophysics techniques to understand the extent of fracture connectivity. The collection of data required for this study includes geological maps, geophysical data, drilling logs, groundwater levels, and pumping tests in the study area and are collected to develop a hydrogeological conceptual model which is used to explain the influence of fracture connectivity on groundwater aquifers. Analytical, interpretative, and graphical methods are used to display and analyse the collected data. It is anticipated that the findings and interpretations from the study will be used to provide more detailed insight into the flow path and dynamics for sustainable utilisation of groundwater in the Hout catchment, South Africa.

The characterization of aquifers typically comprises of the comprehensive assessment of various datasets such as satellite data, geological units and, their physical and hydraulic properties (storativity, specific yield and transmissivity), faults, fractures, groundwater recharge, flow paths, aquifer thickness, water table elevations, and flow directions (Attandoh *et al.*, 2013; Vereecken *et al.*, 2005; Tooley and Erickson, 1996). A geological unit is assessed to delineate areas that are likely to have a high groundwater potential as well as establishing a basis of how groundwater occurs in the catchment. Remote sensing and Geographical Information System (GIS) are used as analysis tools in conjunction with accumulated field data in order to characterize and identify preferential groundwater flow paths in respective geologic settings. Furthermore, this study is interested in determining the potential or productivity of the secondary aquifer, of which such knowledge is critical for sound groundwater development and management planning. This requires knowledge of the aquifer hydraulic conductivity, transmissivity, borehole yields and flow directions.

1.8 Conceptualization of the current research project

This study forms part of a larger research project under the Danish funded project which being implemented by University of the Western Cape (UWC) in partnership with the Department of water and Sanitation in South Africa (DWS), International Water Management Institute (IWMI), University of Copenhagen (UCPH) in Denmark, EkoSource in South Africa. The larger project is entitled, "Enhancing sustainable groundwater utilisation in South Africa. The study covers a component of "Work-plan 1" of the project which involves the development and calibration of integrated hydrological model(s) for the Sand/Hout catchments. An objective of the workplan is to develop sustainable groundwater management in the Republic of South Africa. This is to be achieved through the use of integrated hydrological models, making innovative use of new satellite data types and state-of-the-art field investigations and monitoring to gain a better understanding of the surface and subsurface water fluxes and storages. It is from this objective on the development and calibration of integrated hydrological model(s) where this current study on evaluating the extent at which fractured networks influence the occurrence of groundwater in crystalline basement aquifers came about.

1.9 Thesis Outline

The thesis consists of seven chapters as follows: Chapter 1 introduces the study topic, background of the study, the research problem to be addressed, the aim and objectives of the study. The significance, scope, and nature of the study; the research framework and thesis outline are included in this chapter. Chapter 2 provided a description of the study area in terms of the climate, topographic, geological and hydrogeological characteristics. Chapter 3 is a review of the literature on hydrogeological conceptual modelling of Crystalline Basement Aquifers in global and local contexts to understand how they can be used to assess the role of fractured networks in different settings including crystalline basement aquifers. A review on the role of remote sensing and integrated geophysical methods in hydrogeological research studies is provided. The conceptual and theoretical frameworks guiding the current study are also included in this chapter. Chapter 4 provides the research design and methods to address the objectives of the study. The chapter includes data collection methods, data analysis methods, the reliability of the results, research integrity and limitations of the study. Chapter 5 demonstrates the use of remote sensing and integrated geophysical methods in understanding the distribution of controls on groundwater potential in the study area and how structural features influence the pathways or connectedness of fracture networks. Chapter 6 provides results on the use of aquifer characteristics in understanding aquifer parameters. Chapter 7 provides a summary of major findings and a conceptualization of the hydrostratigraphic system which is used to explain the role of fracture connectivity in crystalline basement aquifers.

Chapter 2: Study area

2.1 Introduction

Chapter 2 provides a description of the study area. The physiographic characteristics at regional and local scales are described to understand how they influence the distribution of fracture networks in the study area. The chapter focuses on describing features such as geology, surface topography and climate which influence the interaction between groundwater but also determining the extent and nature of the hydrogeology in the area.

2.2 Regional setting description

2.2.1 Location of study area

The Hout catchment is located in the Mpumalanga and Limpopo Province along the north-eastern boundary of the Republic of South Africa (RSA). It is an elongated catchment that measures at roughly 110km from north to south and an average of 32km from west to east and has an area of 2,478 km^2 (Figure 2.1). The catchment area is divided into three quaternary (fourth-order) catchments (A71E, A71F, and A71G) (Ebrahim *et al.*, 2019). This area is surrounded by small farming towns such as Mogwadi (Dendron) situated 60 km northwest of the city of Polokwane, Limpopo. The Hout river is a tributary of the Sand river, which drains into the larger Limpopo River in the north-east and is an ephemeral River that flows intermittently following large and intense precipitation events during the wet season. The Dendron aquifer, which is located in the study area, although not accurately mapped, is reported to be 1,600 km^2 (Fallon *et al.*, 2018).

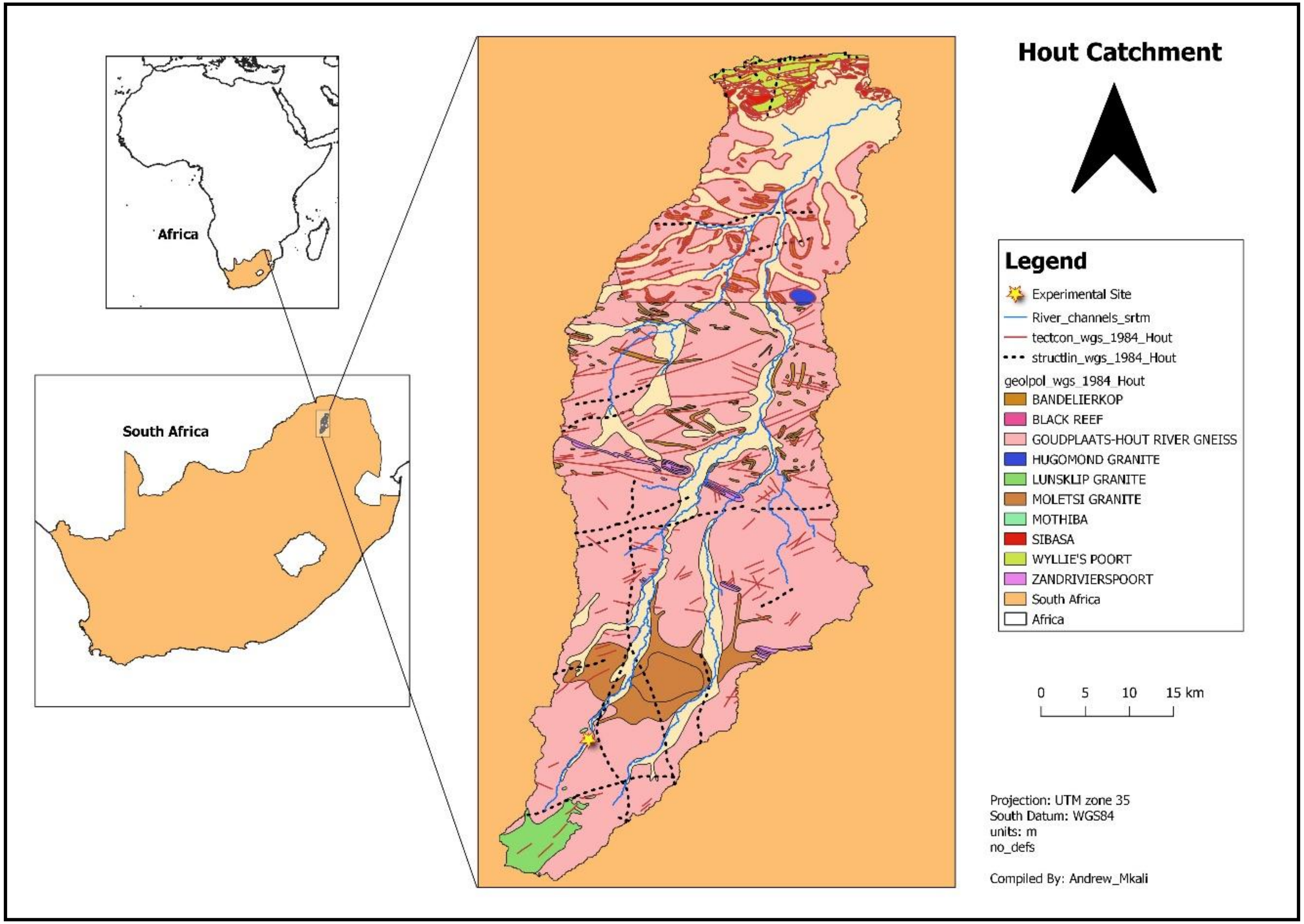


Figure 2.1 Locality of the Hout Catchment

2.2.2 Topography and landform

The topography of the Hout catchment is closely related to its geology and structural history as it is characterised by a generally flat landscape that is coupled with erosional surfaces and a few granite outcrops. The elevation in the southern region near Polokwane averages at 1400 m.a.m.s.l and decreases to 400 m.a.m.s.l in the northern region where the Hout river confluences into the Sand river (Figure 2.2). The northern region of the catchment is bound by the Soutpansberg Mountains at an elevation of around 1400 m.a.m.s.l (DWA, 2004). The headwaters of the Hout river Catchment are situated southwest of Polokwane and drain towards the northeast where it joins the Sand River. The Hout river has incised through erosional surfaces and the underlying crystalline rocks with less defined channels due to low elevations towards the northern part of the catchment. The rivers located in this region are ephemeral and normally only flow during extensive wet seasons (Vegter, 2003). As a result, it can be suggested that the relatively flat study area is more influenced by deeper-lying structural features with regards to groundwater occurrence, an aspect which was investigated in the study.

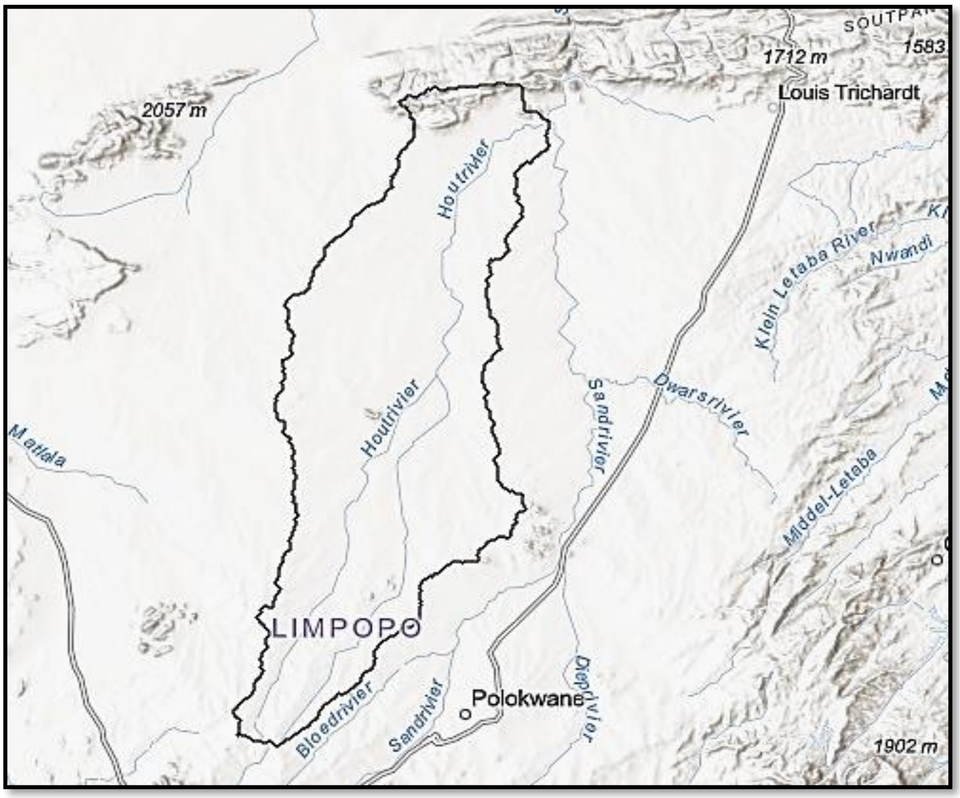


Figure 2. 2 Topography of the Hout catchment

2.2.3 Climate

The Hout catchment experiences a temperate climate and is semi-arid in the south to extremely arid in the north. The area exhibits an annual long-term mean precipitation of 407 mm/year (Dendron climate station, 1972–2015). Rainfall is seasonal with most rainfall events occurring during the summer months between November and March/April (Figure 2.3). Long-term annual recharge to the aquifer has been estimated at around 3.8% of total annual rainfall. As a result of the low rainfall over most of the study area, relatively little surface runoff is generated. The runoff is highly seasonal and variable, with intermittent flow in many of the tributaries. Only a number of major river courses are perennial and most rivers sustain flow only during the wet season or during intense rainfall events (Holland, 2011). Potential evapotranspiration in the study area is always much greater than precipitation and during average rainfall years, there is always a water deficit in the basin (Masiyandima *et al.*, 2002). Therefore, these characteristics suggest that the hydrogeology in the area is predominantly influenced by regional groundwater flows as opposed to groundwater levels that occur as a result of climatic influences. This may also have an impact on the abstraction rates of the underlying aquifer, hence the importance for its characterisation.

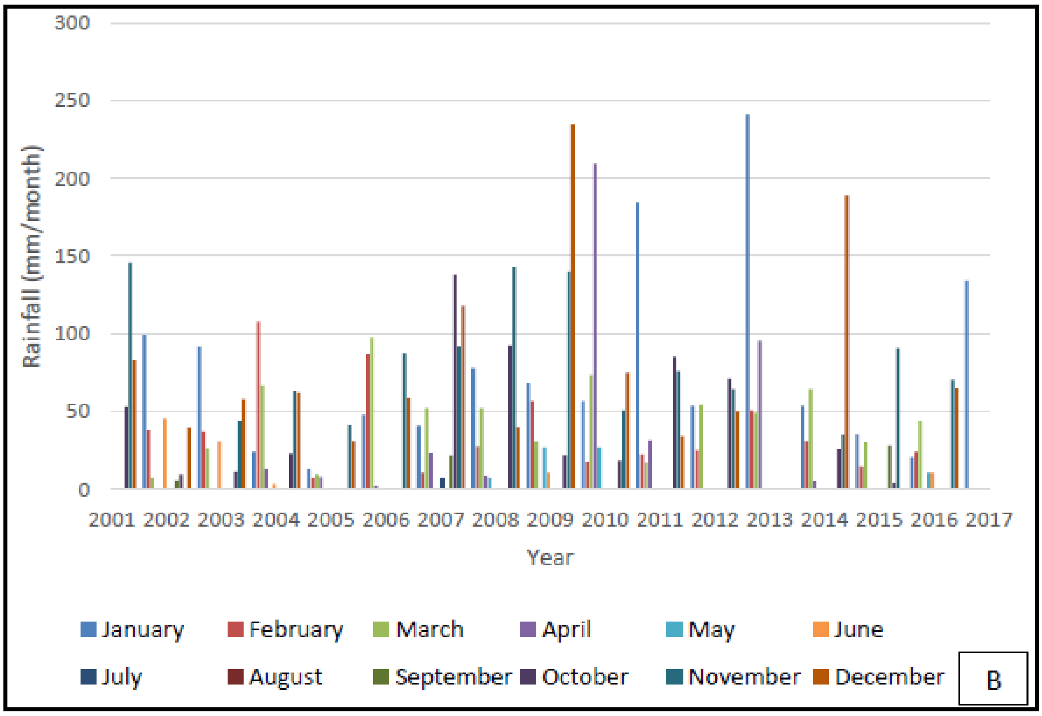


Figure 2.3 Average rainfall of the Hout catchment from 2001-2007 (Source: Tshipala, 2017)

2.2.4 Land Use

The main land use in the catchment is commercial farms which are more prevalent in the Mogwadi area and extend to the northern portion of the catchment. Livestock farming as well as sporadic subsistence farming within the surrounding villages is also a frequent occurrence. Towards the southern part of the catchment, the area is dominated by rural settlements that rely on both groundwater and Hout Dam for water supply. Livestock in rural areas are brought to parts of the river channel that form pools to drink and graze from surrounding vegetation (Figure 2.4). Groundwater is largely used for potato crop irrigation and less on maize (Masiyandima *et al.*, 2002). According to Jolly (1986), volume of groundwater that was abstracted for 3579 ha reached 20.8 x 106 m^3 and 1 x 106 m^3 for stock watering and domestic use in the year 1985/6. In 2004, about 50 farms were operational around the Mogwadi area but approximately 150 farms used groundwater for livestock watering (Mandiwana, 2004).

Figure 2.4 Livestock grazing adjacent to the Hout river channel.

2.2.5 Geology

Regional Geology

Geologically, the rock types that fall within the Limpopo Province are situated in the Southern Marginal Zone (SMZ) of the Limpopo Mobile Belt (LMB) and are described to be the high-grade metamorphic equivalents of the Northern Kaapvaal Craton (Van Reenen *et al.*, 1990). A reason behind this interpretation suggests that because there is a boundary that occurs between these two geologic Provinces that is defined by a sharp drop in metamorphic grade and concurs with a northward dipping thrust zone known as the Hout river Shear Zone (Smit *et al.,* 1992; Smit and Van Reenen, 1997). There are also abundant remnants of what is thought to have been a massive greenstone belt succession within a narrow zone adjacent to the Hout river shear zone and can be attributed to an acutely attenuated slivers that are folded within the Hout river gneiss whose extent ranges from a few metres to several kilometres (Brandl, 2010). The Limpopo region is predominantly characterized by large intrusive igneous and metamorphosed rocks. These include gneissic, basaltic and granitic rocks that occur within a shear zone, which is coupled with structures such as diabase dykes, faults and structural changes that show a NE-SW trend over a widely spread area (Figure 2.5).

Faults of various ages are also present within the region and the general orientation is in a southwest-northeast direction whose successions appear to have experienced multiple phases of metamorphism and deformation, resulting in the fracturing and general transformation of the structural features over time (Du Toit, 2001). According to Smit *et al.* (1992), an initial deformational occurred and led to the formation of crustal wedges, foliation, and isoclinal folds within the granite-greenstone rocks. This was then succeeded with the formation of major shear zones and the three LMB geological bodies which resulted in the formation of the Hour River Shar Zone (HRSZ) lineament along the southern boundary of the SMZ. A third deformational event is related to shearing within the major Limpopo Mobile Belt (LMB) terrenes, which created variable. Structural domains like the Petronella and Matok Shear zones within the SMZ. These deformational events would influence the different extent of fracturing in the basement region over time and as a result, influencing the connectivity of these conduits for the occurrence and movement of groundwater.

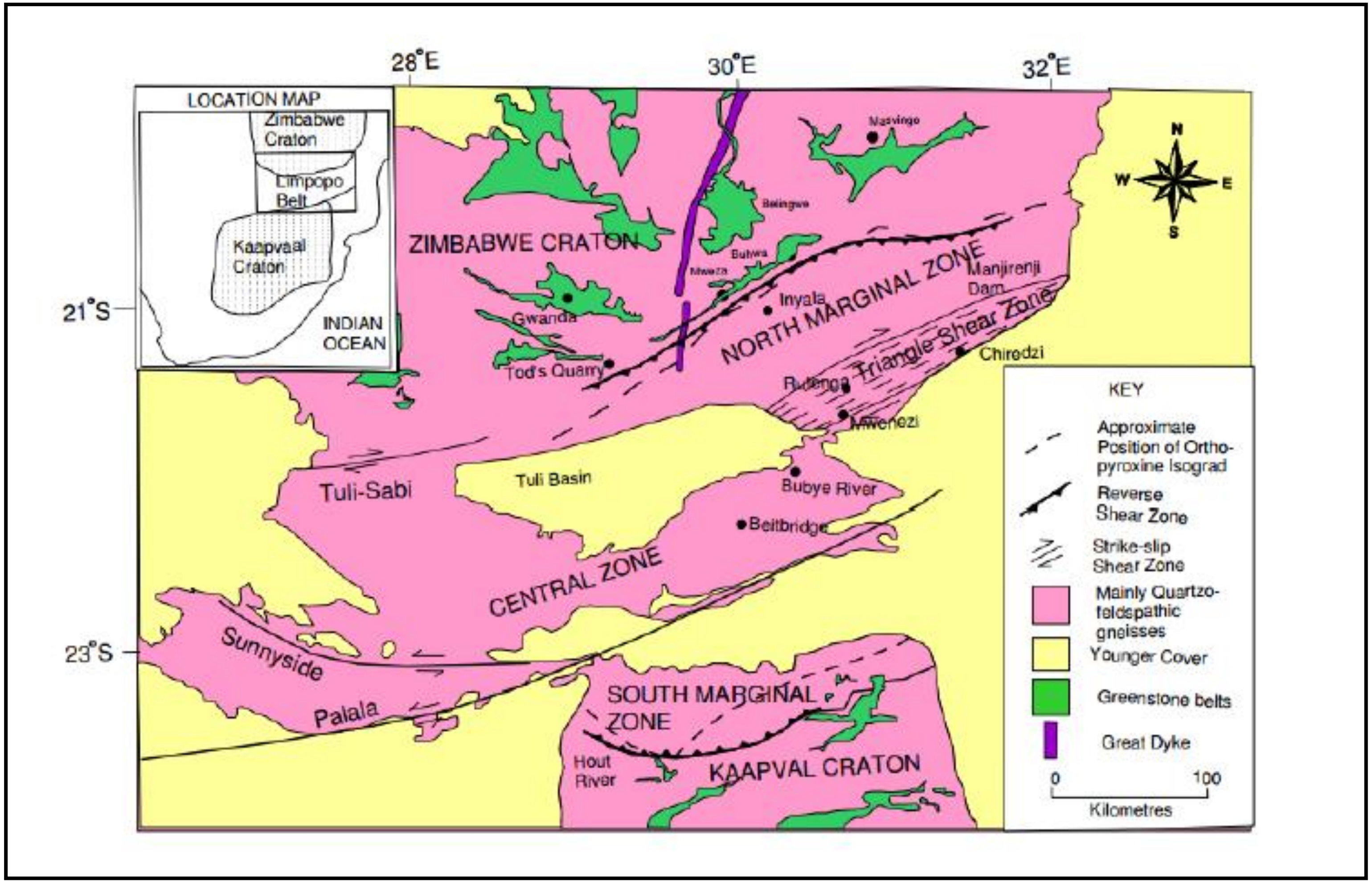


Figure 2. 5 Regional geology of Limpopo with Major faults (Source: Chinoda et al., 2009)

Local Geology

The basement rocks of the Goudplaats-Hout river Gneisses are the oldest rocks in the study area and poorly exposed due to the overlying younger successions. The Goudplaats Gneiss is assumed to be the oldest of the basement rocks that occur within the area and falls in the eastern part of the Hout river catchment, it is also assumed to be the basement rocks of the bandelierkop complex which comprises of mainly mafic, ultramafic and pelitic gneisses (Holland, 2011). This is a volumetrically dominant geology that spreads over the Southern Marginal Zone of the Limpopo belt (Wright, 1992). This geology is tectonically intermixed with the Bandelierkop Complex as well as Granitoid intrusions such as the Matok and Palmietfontein Granites. The Hout river Gneiss predominantly underlies the area and is exposed in the regions where ephemeral streams occur. Its occurrence is also prevalent in the Polokwane (Pietersburg) area and extends in the south up to the Soutpansberg.

Table 1 Stratigraphic column of the Southern Marginal Zone of the Limpopo Mobile Belt

Group	**Formation**	**Lithological description**
SOUTPANSBERG GROUP (1850 Ma) (a)	Nzhelele Formation	Volcanic rocks intercalated with argillaceous and areneous rocks
	Musekwa Formation	Basaltic rocks intercalated with minor pyroclastic and clastic sediments
	Wyllie's Formation	Reddish-pink quartzite with minor pebble washes and interbedded with volcanics
	Fundudzi Formation	Areneous and argillaceous rocks interbedded with basalts and pyroclastic
	Sibasa Formation	Tholeiitic basalts and pyroclastic lenses with clastics sediments
	Tshifhefhe Formation	Chloritised and epidotised greywacke, shale and conglomerate clasts of granitoid gneiss
HUGOMOND GRANITE (2656±2 Ma) (b)		Coarse grained, biotite bearing granite with tourmaline pegmatite veins

MOLETSI GRANITE		Pinkish-grey phases with tonalitic inclusions
MASHASHANE GRANITE	Uiltloop Granite (2687 ±2 Ma) (c)	Pinkish and medium coarse grained with biotite and hornblende
	Lunsklip Granite	Alkali-granite
	Uvtylugt Granite	Tonalitic granite
BANDELIRKOP FORMATION (2670 Ma) (d)	Pelitic Member	Purplish brown gneiss composed of biotite, quartz, garnet, cordierite and hypersthene with sporadic banded iron formation
	Mafic Member	Dark grey to black fine-crystalline rocks composed of clino and ortho-pyroxenes, plagioclase and hornblende
	Ultramafic Member	Serpentinised peridotite and pyroxenite
PIETERSBURG GROUP (2700-2800 Ma) (e)	Zandrivierspoort Formation	Mafic metalava interlayered with magnetic quartzite
	Mothiba Formation	Ultramafic rocks with minor amphibole quarzitic schist and Banded Iron Formation
BAVIANSKLOOF GNEISS (Goudplaats and Hout river Gneiss) (3500-3000 Ma) (f)		Grey, migmatised tonalitic to trondhjemitic banded gneiss consisting of plagioclase, quartz, hornblende and biotite

Reference:(a) Cheney et al. (1990), (b) Robb et al. (2006), (c) Robb et al. (2006), (d) Anhaeusser (1992), (e) de Wit et al. (1992), (f) Anhaeusser (1992).

The local geology includes leucocratic migmatite and gneiss, grey and pink hornblende-biotite gneiss, grey biotite gneiss and pegmatite rocks. The rocks belonging to the Bandelierkop Complex occur as highly deformed keels within the gneiss. The dykes in the region display a an orientation that predominantly trends in the northwest and northeast direction (Toit and Sonnekus, 2014). Evidence of dyke features cutting across some sections of the Hout river segment within the study area can be seen when along the river channel along with isolated perennial water pools adjacent to the dyke features (Figure 2.6).

Figure 2.6 Evidence of dyke features cutting across some sections of the Hout river segment within the study area. Isolated perennial water pools are also observed at the dyke features

The outcrops that occur within the region are poorly exposed and the contact between the Hout river gneiss and the Goudplaats Gneiss is randomly distributed and coupled with small remnant outcrops of fine-grained, dark grey biotite gneiss that show similarities to the Goudplaats gneiss. However, it can be noted that there is a common variety of medium to coarse grained, pinkish grey and pink leucocratic gneiss that is composed of quartz, minor plagioclase, biotite and hornblende (Figure 2.7) that can be seen in the Dendron and Blouberg areas (Wright, 1992). The Hout river Gneiss Suite range in age from 3600 to 3200 Ma and comprise a wide range of Granitoid gneisses. Younger granitic intrusions into but not forming part of the Hout river Gneiss Suite include the Duivelskloof Leucogranite, Shamriri Granite, Turfloop Granite, Matok Granite, Moletsi Granite, Matlala Granite, Utrecht Granite and Mashashane Suite (Robb *et al.*, 2006).

Figure 2.7 Photographic image of rock units showing the extent of fracturing of the weathered pink pegmatite forming part of the Hout river gneiss characterising the study area

2.2.6 Hydrogeology

Groundwater occurrence within the study area is mainly contained within the Hout river gneiss, a typical crystalline basement metamorphic formation (Jody, 1986; Holland, 2011). The Hout river Gneiss crystalline complex (Du Toit, 2001; Holland, 2011) characterises the catchments weathered material into typical pink sandy soil that covers the greater area of the catchment and the riverbed. The identified aquifer within the catchment is known as the Houdenbrak aquifer and falls within the government monitoring programme under the Water Act 1956 (Pietersen *et al.*, 2011). The aquifer is said to extend for roughly 1600 km² stretching from a few km south of the Mogwadi town towards the Vivo area along Soutpansberg Mountains (Masiyandima *et al.*, 2002). According to investigations carried out by Jolly (1986), the study area consists of two aquifers: a weathered aquifer and a high yielding fractured rock aquifer.

The weathered zone of the Houdenbrak aquifer has a variable depth within the range of 15-50 m, and is underlaid by fractured bedrock of granitic gneiss which extends much thicker reaching a depth of about 120 m around the Mogwadi area (Jolly, 1986). The two zones of the composite aquifer in the catchment experience a hydraulic connectivity such that the upper weathered unit with low permeability and high porosity acts as a reservoir that feeds the lower fractured rock with high permeability and lower porosity (Jolly, 1986). Furthermore, the composite aquifer is said to be confined and partially confined in certain locations (Pietersen et al., 2011). According to Jolly (1986) the upper and lower units of the composite aquifer are characterised by storage coefficients of 0.01 and 0.0025 respectively. These previous studies suggest that higher borehole yields are experienced when boreholes are drilled into the lower fractured zone that have a blow yields that can reach up to 40 l/s. This can be attributed to good fracture connectivity and the characteristics of the granites in the area. Transmissivity values from the Groundwater Resource Information Project (GRIP) database range between 4 m^2/d and 40 m^2/d within the catchment with consistent values occurring around the Mogwadi area (Holland, 2011). As a result, it is important to understand the extent of fracture connectivity within the area to understand the hydrogeological characteristics of the aquifer(s) in the region.

Chapter 3: Literature review

3.1 Introduction

This chapter aims to provide a review on previous literature that has been published with regards to principles and concepts that guide geological and hydrogeological conceptual modelling. Previous literature on the characterization of aquifers in crystalline basement environments has also been reviewed. In this chapter, the argument is that using integrated approaches in characterizing basement aquifers provides improved knowledge on such aquifers. As a result, this information can be used to inform sustainable and realistic utilization of groundwater from environmental and socioeconomic perspectives. The chapter ends with a review on frameworks that guide the current study such as theoretical and conceptual research frameworks for the study.

3.2 Previous studies on characterization in crystalline basement aquifers

The characterization of an aquifer is important in order to establish a conceptual understanding of the hydrogeological processes operating in any area and hydrogeological system and to define the key geological and hydraulic parameters that regulate the occurrence and flow of groundwater at a given scale (Tessema *et. al,* 2014). It has been established that the presence of fractures influences the hydrostratigraphic connection of groundwater. Groundwater flow in such media is localized in a small part of the rock volume and is assumed to be controlled by fracture connectivity (Guihéneuf *et al.*, 2014). Connectivity is dependent on the geometrical properties of the fracture network, i.e. the distribution of fracture lengths, fracture orientations as well as fracture density (Davy *et al.*, 2013). Various studies have been conducted on hydrogeological characteristics in different geological and climatic settings (Witthüser *et al.*, 2011; Davy *et al.*, 2013; Gellasch *et al.*, 2013; Tessema *et al.*, 2014). Some of these studies have placed focus on understanding the groundwater flow mechanisms, while some studies focused on providing knowledge on the connection of fracture networks to ensure effective exploration and sustainable development of groundwater resources. The current study intended to apply a combination of the two in order to understand the hydrogeological characteristics of the study area.

In order to determine the role that fractures play in the transport of near-surface contaminants such as wastewater from leaking sewers, and to protect public supply wells in a deep bedrock aquifer Gellasch *et al.* (2013) designed a conceptual model of a section of the Cambrian aquifer system in Madison, Wisconsin (USA). The aquifer was studied using a combination of geophysical, geochemical, and hydraulic testing in a borehole adjacent to a public supply well. The results from pumping test data indicated that approximately 60% of the borehole transmissivity is influenced by the presence of fractures. The bulk transmissivity of the borehole was calculated as 49.9 cm^2/s with a fracture system value of 28.8 cm^2/s and a matrix system value of 21.1 cm^2/s based on a saturated borehole thickness of 54.25 m. In comparison to values from areas that were suggested to have unfractured regions, it was then suggested that the distribution of fractures acted as conduits from the surface to the deeper sections of aquifer. The fractures, monitoring wells, and the unit well were incorporated into a 3D model in order to visualize the relationships among the accumulated data (Gellasch *et al.*, 2013). Meanwhile, Ren *et al.* (2018) assessed the hydraulic properties, groundwater storage, and flow processes based on borehole hydraulic characterization and monitoring data. In order to assess the hydrogeological characteristics of a crystalline fractured aquifer in Laramie Range, Wyoming. The present study applied a combination of geophysical and hydraulic testing in boreholes in order to infer hydrogeological characteristics.

The hydrogeological characteristics of a semi-arid crystalline basement aquifer system in the Maheshwaram catchment, state of Andhra Pradesh, India, were assessed in order to develop a 3-D conceptual model (Dewandel *et al.*, 2006). Observations of outcrops, 80 vertical electric soundings, lithology logs from 45 boreholes, flowmeter measurements and injection tests were also performed to characterize the hydraulic conductivities of the fractured zones. As a result, a generalized 3-D geological and hydrogeological conceptual model was proposed suggesting that the profile of the area is generally composed of sandy regolith from the top up to a depth of approximately 35 m, this is followed by approximately 10–15 m of laminated saprolite containing unusual, preserved fissures and a 15–20 m thick fissured layer in the bedrock. Similarly, an integrated hydrogeological study to support sustainable development and management of groundwater resources in a semi-arid catchment in Karnataka, India was performed by Chandra *et al.* (2019). Analysis from the drilling and geophysical logs of 21 wells within a 380 km^2 area was used to study the relationships of various lineaments with 'Hydrolins', particularly in respect of their groundwater potential. Aeromagnetic survey results, though calibrated and correlated with a limited number of well data, revealed a threshold groundwater horizon found to be at 80 m depth for Ankasandra watershed, beyond which a strong correlation exists between the depth of a well and its yield (Chandra *et al.*, 2019). They developed a geological and hydrogeological conceptual model in a similar setting.

A variety of characterisation and monitoring techniques find their application in fractured bedrock environments across Africa. Vassolo *et al.* (2019) carried out an integrated hydrogeological study to develop and manage groundwater resources of the Nyanzari aquifer system, in Gitega, Central Burundi. The study was based on data from soils, classification of borehole logs as well as tracer and pumping tests. Results indicated that weathering of the metamorphic basement rocks led to the development of a two-staged aquifer: a deeper fractured aquifer in the bedrock, overlaid by a shallow saprolite aquifer which is directly fed by rainfall. A conceptual hydrogeological model was then proposed, which was suggested to be representative for many other locations with a similar geological setting in Burundi. In the same way, Yidana *et al.* 2013 conceptualized the spatial distribution of a key hydraulic parameter in a crystalline aquifer in southwestern Ghana. This was to provide an initial basis for characterizing the hydrogeology of the terrain with a view to assisting in the large-scale development of groundwater resources for various uses. Results from the study suggested that aquifer heterogeneities, coupled possibly with topographical trends, have led to the development of five prominent groundwater flow paths in the area (Yidana *et al.* 2013). Though performed at a larger scale, the process of conceptualizing the hydrogeological system was similar to the current study.

A hydrogeological assessment in which physical logging methods including neutron, gamma ray and resistivity logging were carried out at Middlekop farm located south of Stella, Limpopo Province (Nel, 2001). The study was conducted to determine the potential of the aquifer to supply water to the farms and the surrounding community. Borehole camera logging was also conducted in some of the wells in order to characterize the permeability of the formations along with respective aquifer thicknesses. The results of the investigation showed that the thickness of the aquifer lies between 40 m to 45 m with a borehole yield of 25 l/s, the results also suggested that groundwater occurrence in the fractured zone occurs at depths ranging from 20 m to 45 m. Findings suggested that high blow yields around Stella are associated with dense fracture networks within the Middlekop granitic rock. In addition, the Gold Ridge Formation is an important area of focus due to cross-cutting structures allowing groundwater storage. The study also suggested that lineament length and density are important parameters for optimization of borehole yield within the hard rock terrain of the northern part of the study area (Nel, 2001). Analyses from the study were used to inform the current study as it was conducted in the region where the current study is placed.

A study in the Limpopo plateau was carried out based on surface and sub-surface hydrogeological features such as lithology, geological structures, geological and structural lineaments, landforms, drainage density, water bodies and weathered/fractured thickness of overburden material in order to assess how these parameters influence the transmissivities and blow yields within the region (Witthüser *et al.*, 2011). Findings from the report showed that high transmissivity values are associated with areas characterised by pegmatite rocks, topographical lows and areas with close proximity to lineaments. It was also noted that hydrogeology of the weathered zone in these regions is characterised by significantly low primary porosity and almost all groundwater movement and storage occur in fractures, faults, weathered zones and other secondary features that enhance the aquifer potential only locally (Witthüser *et al.*, 2011). This is due either to discontinuities or barrier boundaries within the fracture system being tapped or due to the constraints of the low-permeability regolith. These features are commonly reflected in a significant borehole failure rate and a wide range of yields, with success rates that low with cases where a successful borehole has been drilled having blow yields of less than 5 l/s, and often less than 1 l/s despite the apparent regional uniformity of the basic controls of climate, morphology and geology (Wright, 1992). This of significance to the current study as the Hout catchment is situated in the Limpopo Province and similar trends are expected to occur.

An extensive study by Holland and Witthüser (2011) was conducted on seven distinct groundwater regions within the Limpopo Province, covering about 63 500 km^2. The focus of this study was to systematically analyse regional factors that may influence borehole yields and aquifer transmissivities. The study explored different regional aspects (geology, weathered zone thickness, structural lineaments, topography, hydrology, and geomorphology) to try to understand how each parameter influence aquifer transmissivity in different areas and ultimately borehole yields. Results from over 4 000 pumping-test analyses indicated that geological setting (e.g., aureole of granitoids), proximity and orientation of dykes and lineaments and proximity of surface-water drainages may exert an influence on borehole productivity. Holland (2011) also noted that there was no distinct correlation between weathered zone thickness and the transmissivity, which provides further incentive to investigate the fractured regions with more detail. Analyses from the study were used to inform the current study as they occur in the same setting.

An integrated hydrogeological modelling approach applicable to hard-rock aquifers in semi-arid data-scarce Africa was developed by Ebrahim *et al*, (2019) using remote sensing, rainfall-runoff modelling, and a three-dimensional (3D) dynamic model. The study was applied to the Hout catchment, Limpopo Province, South Africa, where the current study is placed. The integrated dynamic 3D hydrogeological flow model, based on the One-Water Hydrologic Flow Model (MODFLOW-OWHM), helped to understand recharge and flow processes and inform water use and management. Irrigation abstraction was estimated based on irrigated crop area delineated using the Landsat Normalized Difference Vegetation Index (NDVI) and crop water requirements. Using groundwater level data, the model was calibrated (2008–2012) and validated (2013–2015). Estimated mean diffuse recharge (3.3 ± 2.5% of annual rainfall) compared well with estimates from the Precipitation Runoff Modelling System model. Recharge and groundwater storage showed significant inter-annual variability. The ephemeral river was found to be losing, with mean net flux to the aquifer (focused recharge) of approximately 1.1% of annual rainfall. The results indicate a delicate human-natural system reliant on the small but highly variable recharge, propagating through variable pumping to an even more variable storage, making the combined system vulnerable to climate and anthropogenic changes. The integrated modelling is fundamental for understanding spatio-temporal variability in key parameters required for managing the groundwater resource sustainably (Ebrahim *et al.*, 2019). The previous local studies helped in providing a basis for the hydrogeological characterization to be undertaken in the current study.

3.3 Occurrence and flow of groundwater in crystalline basement environment

3.3.1 Groundwater occurrence

Crystalline basement aquifers in sub-Saharan Africa occur in rocks that are of igneous or metamorphic origin, these include; granites, basalts, metaquartzites or gneisses and are associated with the Precambrian age (Wright, 1992). In South Africa, the occurrence of these aquifers ranges from the Archaean cratons, mobile belts to an intrusion of orogenic granite. The study area falls within the fractured granite gneiss known as the LMB Goudplaats-Hout river gneiss.

The occurrence and flow of groundwater within crystalline basement aquifers is influenced by hydraulic properties of the overlying weathered zone (regolith) and the underlying fractured zone. The rocks in these areas are characterised by low primary porosity and a low storage coefficient. The occurrence of groundwater is likely to be related to secondary porosity developed by weathering, faulting, fracturing and the influence of intrusives such as batholiths and dykes (Dewandel *et al.*, 2006; Pietersen *et al.,* 2012). The flow of groundwater in these aquifers is assumed to take place in a homogenous porous media and purely fractured media (Figure 3.1) (Cook *et al.,* 2003). The interpretation of groundwater occurrence and movement in crystalline basement aquifers where borehole yields vary significantly from one place to another, can be considered as a first step in evaluating any kind of groundwater availability, whether on catchment, basin or borehole scale, even within the same rock type (Dewandel *et al.*, 2006). Comprehensive information and good understanding of the relationship between the hard- rock aquifers and factors that determine the borehole yields within these aquifers is required for the development of sustainable water sources in hard-rock aquifer systems.

As stated in previous sections, the weathered zone in crystalline basement terrain is comprised of 3 sub-zones which vary in hydraulic properties. The soil zone is characterised by low permeability, porosity and specific yield due to a function of the weathered material which subsequently reduces the hydraulic conductivity of the aquifer. The flow of groundwater is assumed to occur in gaps between the weathered material if the aquifer is homogenous or through preferential pathways if the subsurface is heterogenous in nature (Wright, 1992; Cook, *et al.,* 2003). In addition to the groundwater flowing through gaps between grains, groundwater flow in the weathered zone also flows along decompression fractures. Decompression fracturing in southern Africa is attributed to five geomorphological cycles that resulted into intermittent erosional and weathering regimes (Dippenaar and van Rooy, 2014). These resultant fractures are suggested to provide preferential pathways for groundwater flow in addition to flow in the rock matrix.

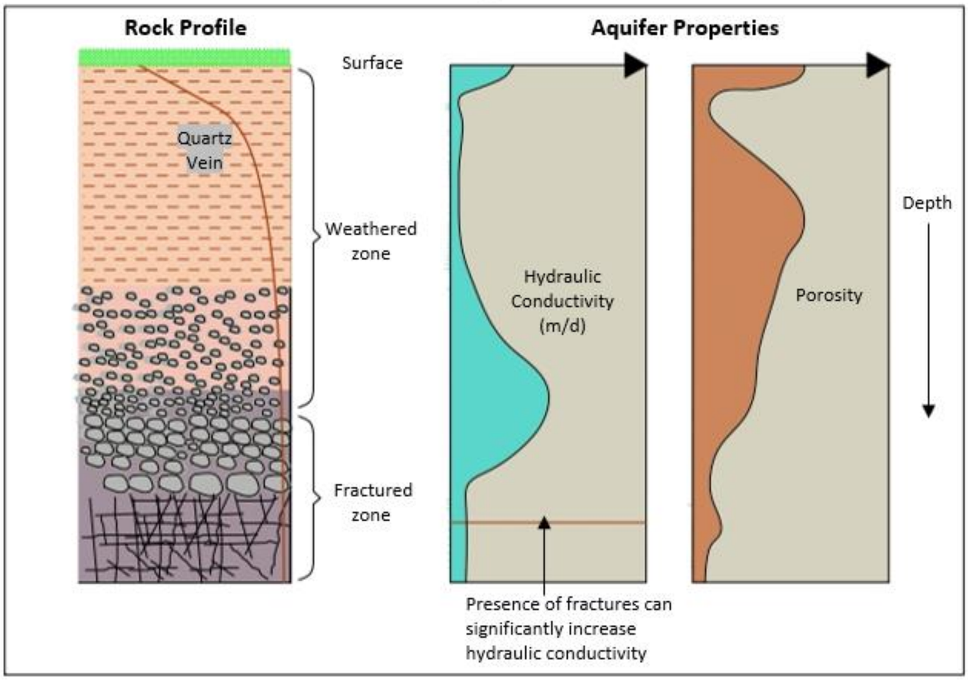


Figure 3.1 Crystalline basement aquifer profile and their aquifer properties (adapted from Chilton and Foster, 1995)

Various studies have attempted to determine the most significant factor or combination of factors influencing the high groundwater potential in the basement terrain (Wright, 1992; Alley *et al.*, 2002; Abiye *et al.*, 2011; du Toit *et al.*, 2012; Holland, 2012). The common goal of these studies was to determine the various factors that were influential in controlling the locality of high borehole yields to improve the identification of areas with high groundwater potential. Studies by du Toit *et al.* (2012) suggested factors such as neo-tectonics, surface hydrology, lithology and topography all play a significant role in the occurrence and movement of groundwater in crystalline basement rocks because they control factors such as the nature and depth of the regolith; development of fracture and fault zones; and presence of higher porosity material (or adjacent alluvium).

Several studies have suggested that the assessment of groundwater availability in crystalline basement rock poses various inconsistencies and that fractured bedrocks are extremely heterogeneous when it comes to their locality and water-bearing properties. Therefore, it is difficult to consistently predict the availability of groundwater in a crystalline basement environment. There are currently no coherent guiding principles for the location of high yielding boreholes and the common practices that assume the influence of prominent topographical and geophysically inferred fractured zones will always produce high yield values have, in some cases, been shown to be unreliable (e.g. in MacDonald, Davies and Dochartaigh, 2002; Banks *et al.*, 2011; du Toit *et al.*, 2012; Chandra *et al.*, 2019).

The presence of faults also plays an important role in the occurrence of groundwater in the Hout river catchment as the Hout river Shear Zone has been acknowledged to induce strike slip and reverse faults. The anatomy of a fault region is assumed to influence the occurrence of groundwater as the tensile force that come to play form damage zones that facilitate the occurrence of groundwater (Figure 3.2).

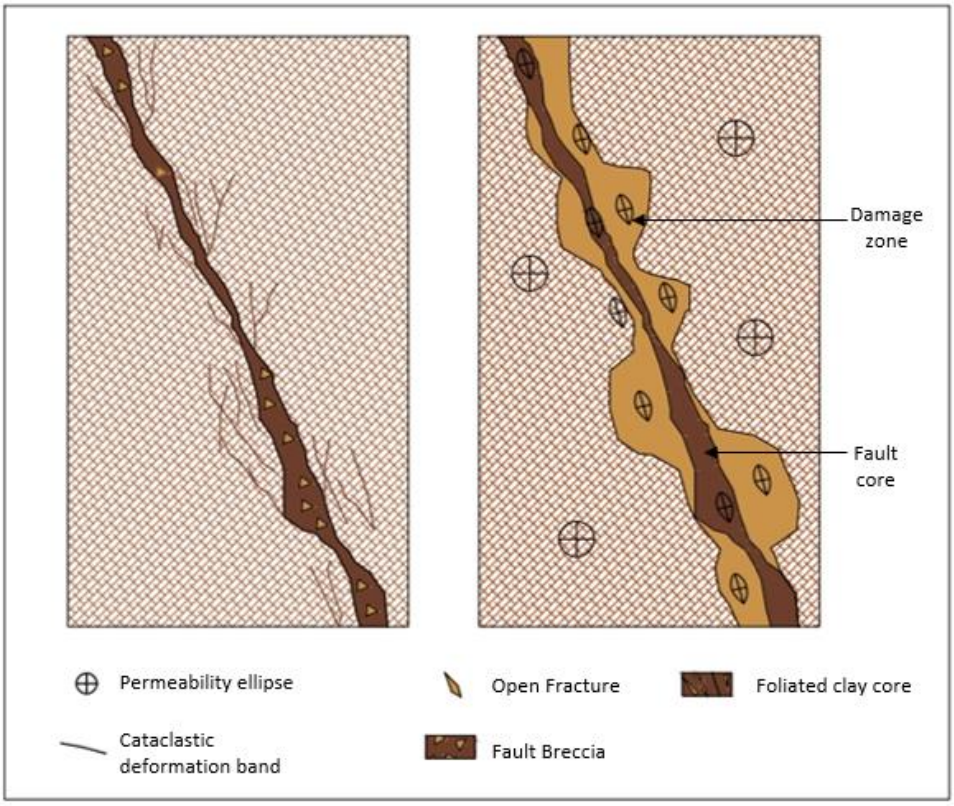


Figure 3.2 Fault anatomy (adapted from: Bense et al., 2013).

The hydrogeological characteristics of crystalline basement rock aquifers have been studied extensively in different settings (Blake *et al.*, 2010; Holland and Witthüser, 2011; Pietersen *et al.*, 2012; Amaral *et al.*, 2013; Senger *et al.*, 2015). However, relatively few studies to determine the influence of factors such as the interconnectivity of fractured networks on the occurrence and flow of groundwater in the aquifer systems in the Limpopo Province were done occurred. Therefore, it is important to present a systematic research on crystalline basement aquifers in order to improve the knowledge of factors that affect groundwater occurrence and flow in a given area.

3.3.2 Groundwater flow

Groundwater flow in the area is complex and is assumed to be governed by the hydraulic potential gradient and the hydraulic conductivities in the regolith and underlying fractured bedrock (Holland, 2011). Groundwater flow in crystalline basement aquifers is generally modelled through a purely fractured media which assumes planar and parallel fractures with no aquifer matrix (Cook, 2003). The LMB is characterized by principal horizontal stresses that are orientated in the NW-SE direction and compression stresses along the NE-SW directions (Witthüser *et al.*, 2011). It is assumed that structures perpendicular to the maximum stress (σ) have undergone expansion whereas structures parallel to the stress axes result in the closing of fractures. The former scenario induces high groundwater potential. Further studies suggest that structures that are orientated in the NE-SW direction formed during the Ventersdorp Rifting event where there was an extension in the NW-SE direction (Witthüser *et al.*, 2011; Holland, 2012). This implies that the structures in the region were re-activated by these events, resulting in extension of fracture apertures and connectivity between the fractured media.

The presence and orientation of faults also influences groundwater flow. Vertical faults are characteristic in the study area may serve as an obstruction to flow if the groundwater flow is perpendicular to the fault strike (Bense *et al.*, 2013). Conversely, the flow parallel to the fault strike would serve as a conduit and allow groundwater to flow (Figure 3.3). In general, faults that are gently dipping are normally associated with high permeability and effect of an overburden over a fault zone on groundwater and flow will be determined by the type of fault, geological and geomorphological evolution and the hydraulic properties of the overburden after faulting (Bense *et al.*, 2013).

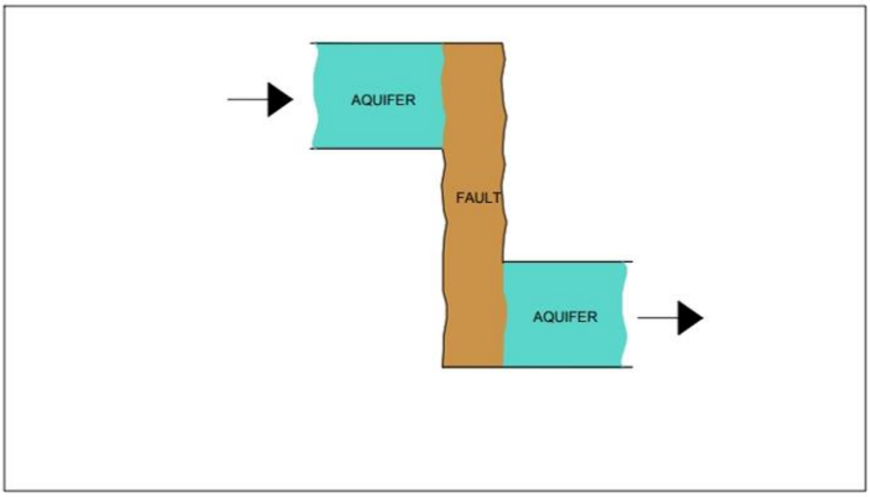


Figure 3.3 Vertical Fault (barrier fault) displacing an aquifer (Source: Bense et al., 2013).

The presence of dykes is also related to the occurrence of groundwater in crystalline basement aquifers. The thickness and orientation of dykes control whether they act as barriers or pathways for groundwater flow (Holland, 2011). Figure 3.4 shows the presence of diabase dykes within the river channel in the study area, which could act as a barrier to flow within the river channel.

Figure 3.4 Presence of a diabase dyke running across the Hout river channel.

3.4 Mapping groundwater potential zones in crystalline basement terrain

3.4.1 Remote sensing and Geographical Information Systems

Various studies have shown that the integration of the remote sensing and GIS technologies has provided a more effective method when analysing multiple data sets that contain various indications of groundwater availability (Krishnamurthy et al. 1996, Sander 1996, Kamaraju et al. 1996, Saraf and Choudhury 1998). The utilization of remote sensing, GIS and empirical findings from integrated geophysical techniques in order to characterize the hydrogeology at a catchment level in crystalline basement aquifers has been implemented in various settings. These tools provide an opportunity for better observation and more systematic and holistic analyses of various landforms due to the synoptic and multi-spectral coverage of a terrain (Das, 2017). Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become a very handy tool in exploring, evaluating, and managing vital groundwater resources (Benjmel *et al.*, 2020). The first objective of the current aims to apply a similar approach on the delineation of groundwater potential zones using valuation of the integration of Remote sensing and GIS techniques.

A study by Mogaji *et al.* (2011) demonstrated the use of LANDSAT 7 ETM+ imagery, ASTER digital elevation models (DEMs) and geological maps for mapping and analyses of lineaments in the Basement Complex region of Ondo State, Nigeria. Digital image processing techniques involving linear/edge enhancements and directional filtering were applied on the image to enhance the edges of the linear features using ENVI 4.7. The enhanced image, normalized difference vegetation index (NDVI) image and hill shaded relief image (processed ASTER DEM) were visually interpreted through GIS overlay operations for lineaments extraction through on-screen digitizing using ArcGIS 9.3. The extracted lineaments were statistically analysed to determine their lengths, densities, and intersections. The results obtained were used to generate lineament density, lineament intersection map and rose diagram. The lineament / fracture analyses indicated that the area has numerous long and short fractures whose structural trends are mainly in the north-south and east- west directions. The cross-cutting lineaments are relatively high in areas around the central, north- eastern and south-western parts of the study area, and relatively low in the other areas. The zones of high lineament intersection density are feasible zones for groundwater prospecting in the study area. The study has led to the delineation of areas where groundwater occurrences is most promising for sustainable supply and hence, further geophysical survey can be concentrated in these areas (Mogaji *et al.*, 2011). The aforementioned techniques for delineation of groundwater potential zones will be utilised in the current study along with the integration of geophysical techniques in order to provide a better understanding of the system.

Remote sensing, evaluation of digital elevation models (DEM), geographic information systems (GIS) and fieldwork techniques were combined to study the groundwater conditions in Eritrea (Solomon and Quiel, 2006). Remote sensing data were interpreted to produce lithological and lineament maps. DEM was used for lineament and geomorphologic mapping. Field studies permitted the study of structures and correlated them with lineament interpretations. Hydrogeological setting of springs and wells were investigated in the field, from well logs and pumping test data. Once all this information was collected, a database of these thematic layers was integrated and analysed in a GIS. Results show that groundwater occurrence is controlled by lithology, structures, and landforms. Highest yields occur in basaltic rocks and are due to primary and secondary porosities. High yielding wells and springs are often related to large lineaments, lineament intersections and corresponding structural features. In metamorphic and igneous intrusive rocks with rugged landforms, groundwater occurs mainly in drainage channels with valley fill deposits. Zones of high groundwater potential are characteristic for basaltic layers overlying lateralized crystalline rocks, flat topography with dense lineaments and structurally controlled drainage channels with valley fill deposits. The overall results demonstrated that the use of remote sensing and GIS provide potentially powerful tools to study groundwater resource occurrence and design a suitable exploration plan (Solomon and Quiel, 2006). A similar approach is to be adopted in the current study in order to provide an overview of the hydrogeological characteristics of the study area using available data from previous field investigations.

A study was conducted with the aim to delineate and classify possible groundwater potential zones in the West Medinipur district of West Bengal, India (Chowdhury *et al.*, 2010). This was conducted using integrated remote sensing and GIS techniques in order to produce thematic layers (lithology, landform, drainage density, recharge, soil, land slope and surface water body) using the IRS-1D imagery and secondary geological data. These layers and their individual features were then assigned weights according to their relative importance in groundwater occurrence and the corresponding normalized weights were obtained based on the Saaty's analytical hierarchy process(Chowdhury *et al.*, 2010). The thematic layers were finally integrated using ArcMap GIS software in order to produce a groundwater potential zone map of the study area. The groundwater potential zones were identified and grouped using three criteria, namely 'good', 'moderate' and 'poor'. A similar grouping is used in the current study. The region attributed to have good groundwater potential was about 15% (1400 km^2) of the total study area, followed by an area of 5400 km^2 (55%) that fall under moderate groundwater potential zone, lastly, an area of about 3000 km^2 was declared to have poor groundwater potential. The average annually exploitable groundwater reserve in the good zone was estimated to be 0.29 MCM/km^2, whereas it is 0.25 MCM/km^2 for the moderate zone and 0.13 MCM/km^2 for the poor zone. Finally, the study concluded that the integrated RS and GIS techniques are very efficient and useful for the identification of groundwater potential zones (Chowdhury *et al.*, 2010). Objective 1 of this study applies a similar approach on the delineation of groundwater potential zones using valuation of thematic layers from available data.

3.4.2 Geophysical studies

Geophysical methods are by far the most common methods for subsurface characterization in Basement rocks for rural water supply. This means that geophysical methods can be successfully applied to provide information such as the existence of any geological contacts, dykes and/or lineaments, approximate depth to groundwater table, thickness of the overlying weathered regolith, and the distribution fractured zones within the solid bedrock (Metwaly, 2012, Chuma *et.al*, 2013). Geophysical-derived sites in a weathered basement type environment can be inferred in numerous ways; these include but are not limited to electrical resistivity (a method that is commonly used on local scales), gravity methods, electromagnetic methods, and magnetic surveys. Therefore, the current study looks to adopt these methods because of their applicability in the setting.

A magnetic survey was carried out by Al-Garni (2010) to understand and delineate structures that could be of significance in the evaluation of the groundwater potential in Wadi Fatima, Saudi Arabia which is also situated in a crystalline basement environment. To achieve this, the study produced sixteen magnetic profiles with spacing intervals ranging from 10 m to 20 m. A GEM19 proton precession magnetometer was used for the survey. The results of the survey displayed presence of a highly fractured intrusive body. The study found that the basement structures in the study area control the preferential pathways for groundwater flow and that the south western part of the study area was ideal for drilling because there is intensive faulting and fracturing at that particular area (Al-Garni, 2010). A similar assumption is raised in the current study area.

A study by Muturi *et al.,* (2014) applied geophysical techniques in order to verify the groundwater potential of concealed fault zones in Kitui, Kenya. Using magnetic and geoelectrical geophysical techniques, a tera-meter was used to collect resistivity data and subsequently determine any resistivity anomalies in the subsurface layer using Wenner profiling and resistivity sounding inversion software, IP2WIN. A Proton precession magnetometer was used to measure the total magnetic field intensity of the earth and 2D Euler deconvolution software was used to model the disintegrated basement. The findings showed that there were distinct magnetic anomalies in the subsurface, signifying sudden disruption of the basement rock and presence of fracturing as a result of faulting (Muturi *et al.,* 2014). Resistivity surveys also showed low resistivity anomalies at points of significant magnetic anomaly. This suggests groundwater potential in the inferred fault. A similar approach to this previous study is to be utilised in the current study to verify the groundwater potential of the structures in the potential experimental sites.

Like the second objective of the current study where integrated geophysical methods are applied, Ahmed *et al.* (2009) used geophysical methods for groundwater exploration in the crystalline basement complex in South Sudan. An electromagnetic survey was employed along two traverse lines, which were 875 m and 475 m long respectively. The thickness of weathered and fractured basement rocks measured at approximately 77 m and was estimated to reach up to 135 m if deeper depths are considered. Drilled borehole data and geophysical interpretation results, showed that the valley in the area is an old, buried channel.

3.5 Characterization of aquifers in crystalline basement terrain

Aquifer characterization comprises of establishing geological units and their hydraulic properties such as porosity and transmissivity, faults, fractures, groundwater flow paths and the geometry of the aquifers including the type of rocks (Vereecken *et al.,* 2005). However, studies by Attandoh *et al.* (2013) state that aquifer characterization often involves the analysis of water budgets; recharge estimation and groundwater resource potential or availability assessment. Dippenaar (2008) and states that the characterization of an aquifer firstly depends on the type of aquifers being investigated. For example, in fractured rock aquifers, faults and fractures sizes are established during characterization (Dippenaar, 2008), whereas the characterization of intergranular aquifers takes primary porosities into consideration. Therefore, improved aquifer characterization can allow for a better conceptual understanding of aquifer systems. In this study aquifer characterization is used to explain subsurface lithologic variations, the distribution of the fracture networks, water levels and the aquifer hydraulic properties. This is because the storage and flow of groundwater is mainly controlled by such aquifer parameters.

3.5.1 Geological mapping

Geological mapping involves the accumulation and evaluation of geological information with the purpose of understanding the predominant conditions that may affect the availability of groundwater of an area (Amaral *et al.*, 2013). The nature and distribution of aquifers are controlled by the structure of the geologic deposit and formations, lithology and hydrostratigraphy. Lithology describes the mineral composition, grain size and grain filling of the rocks while stratigraphy describes the geometrical and age relations between various formations (Freeze and Cherry, 1979). Previous studies in the area describe the occurrence and flow of groundwater to be facilitated within the Hout river gneiss through the weathered zone, faults, fractured and other secondary features that enhance the groundwater potential locally or regionally (Jolly, 1986). In unconsolidated strata such as the current study area, the lithology and stratigraphy become the most important controls of groundwater flows. Therefore, a clear understanding of the geology of an area is essential when identifying aquifers and understanding the mechanisms of groundwater (Hiscock and Bense 2014). In this case geological maps become an important tool to understand the geologic framework that further informs the development of a hydrogeologic framework for the conceptual model.

3.4.2 Borehole drilling and lithologic logs

Characterization techniques used to develop a hydrogeological understanding of an area can be validated through the drilling of boreholes and logging of drilled material (Herrmann and Bucksch, 2014). Boreholes and wells are fundamental to aquifer characterization because they are required for most hydraulic, water chemistry, and formation testing and sampling methods (Maliva, 2016). The use of borehole drilling for aquifer characterization has been used long before the advent of geophysical methods and is still a relevant method that provides practical means for accurately establishing subsurface materials and physical properties (Price, 2013).

Borehole drilling and lithological logging normally involves construction of a vertical hole into the ground surface while collecting samples of the aquifer materials at determined intervals (normally meter intervals) to determine trends in properties such as rock type, fracturing, faulting, texture and composition within the area. Various drilling methods exist depending on the strata being penetrated. Direct-rotary method is the standard method used in the oil and gas industry and is widely used for the construction of groundwater wells in both consolidated and unconsolidated strata (Maliva, 2016). methods such as air percussion drilling uses percussion drill bit with air forced down the hole inside the drill, removing cutting from the hole. In addition, percussion drilling allows for successful drilling through hard rock formations. Mud-rotary drilling on the other hand, involves the use of mud water pressured through a drilling bit, and works well in alluvial aquifer, weathered and in sandy formations with clay material (Sundaram *et al.*, 2009). The former method is to be applied in the current study as it is situated in a hard rock environment.

However, some studies have argued that the use of borehole construction for aquifer characterization is costly and does not provide for effective characterization. Another limitation in the drilling of a borehole comes when determining whether or not the encountered strata will be lithified or sufficiently consolidated in order to avoid the collapsing of the borehole (Maliva, 2016). Stable boreholes facilitate drilling and allow for open-hole completions and testing procedures for further characterization. Where the formation is not stable, screened completions are usually required and the borehole must be drilled using either drilling muds, dual-tube methods, or other techniques in which the borehole is progressively cased off as drilling proceeds (Maliva, 2016). Another limitation is that the method only provides information at a specific point and does not provide spatial heterogeneities of the subsurface materials (Paillet and Reese, 2000; Price, 2013). A way to improve this limitation is through the drilling of multiple boreholes, an application that can be quite costly. Despite these limitations, drilling remains a useful method for establishing aquifer hydrogeological properties in area where existing boreholes are limited.

3.4.3 Aquifer hydraulic tests

The hydraulic parameters of an aquifer are used in hydrogeological conceptual modelling to provide a qualitative interpretation of an aquifer’s characteristics. These parameters are usually described using calculated transmissivity and storativity values of the water bearing formation. Aquifer hydraulic tests are performed by pumping the aquifer at a known rate or through the rapid introduction or removal of water in a well (slug tests). The resultant changes in water levels are then monitored over a period and the results are then interpreted (Hisock, 2014).

Aquifer pumping tests and slug tests differ in terms of scale as the latter are mainly used to characterize the hydraulic conductivity and storage properties of the subsurface in the near well region using simple analytic models that contain spatially homogeneous parameters (Beckie, 2002). However, in an aquifer pumping test, a larger scale, such as the experimental sites in the current study area is considered. A well is pumped and water-level responses are measured in surrounding wells. Estimation of aquifer parameters is based on the stress (pumping), drawdown and recovery (Cheremisinoff, 1997). Common practices for aquifer tests include step down tests and constant rate tests. In a step-drawdown test, the discharge rate in the pumping well is increased from an initially low constant rate through a sequence of pumping intervals (steps) of progressively higher constant rates. Each step is typically of equal duration, lasting from approximately 30 minutes to 2 hours and the resultant well efficiency and performance can be estimated (Kruseman and de Ridder 1994). Conversely, constant rate pumping tests are tests in which a well is pumped at a constant rate and the change in water-level (drawdown) is measured in a surrounding observation well(s) in order to provide information on the well performance and the characteristics of the aquifer and its boundaries (Hisock, 2014).

Due to the occurrence of crystalline basement aquifers between porous media and fracture systems, the analysis of pumping test data suffers from non-uniformity as observed responses of the groundwater in an area can fall into the criteria of more than one set of aquifer parameters, boundary and initial conditions that differ from one another (Van Tonder *et al.*, 2001). Though difficult to identify a model that best represents reality, this problem is usually solved through the application of simplified models that are based on a set of hydraulic parameters. The present study only uses the following plots to gain an understanding of the hydraulic parameters on the experimental site.

There are various analytical methods that have been developed and applied in the analysis of pumping test data in crystalline basement aquifers. The applicability of these methods is determined by the type of aquifer and its conditions (Kruseman and de Ridder 1994). These methods include the Cooper-Jacob time drawdown and distance drawdown (both confined), Theis (confined), Hantush and Jacob (leaky-confined), Nueman (unconfined), Moench (unconfined) and Moench (fracture flow) .Van Tonder *et al.* (2001) developed an Excel-programmed code that provides comprehensive tools for the detailed diagnostic and analysis of step, constant and recovery drawdown data from pumping tests for use primarily in Southern African settings based off the aforementioned methods.

Though concerns about the accuracy of the results from applying homogenous solutions to heterogeneous environments are prevalent, studies by Renard (2005b) and Butler (2008) suggest that the application of conventional pumping test analysis is still of significance as it provides practical estimations in water supply investigations. A detailed synthesis of theoretical diagnostic plots (drawdown and derivative) from which the aquifer type can be inferred from figure 3.5 below based on the drawdown behaviours in response to constant pumping rate (Renard, 2009).

Due to the heterogeneity of fracture networks in the crystalline basement aquifers, methods of determining aquifer parameters are scarce and often unsound. Sufficient data is not always readily available for numerical flow modelling, and consequently pumping test data is often used as an alternative. The results (transmissivity, hydraulic conductivity and storativity) are however dependent on the scale of the investigation due to the heterogeneity of the aquifers. The classification relating to Figure 3.5 below is: a) Theis model infinite two-dimensional confined aquifer; b) double porosity or unconfined aquifer; c) infinite linear no-flow boundary; d) infinite linear constant head boundary; e) leaky aquifer; f) well-bore storage and skin effect; g) infinite conductivity vertical fracture.; h) general radial flow—non-integer flow dimension smaller than 2; i) general radial flow model—non-integer flow dimension larger than 2; j) combined effect of well bore storage and infinite linear constant head boundary.

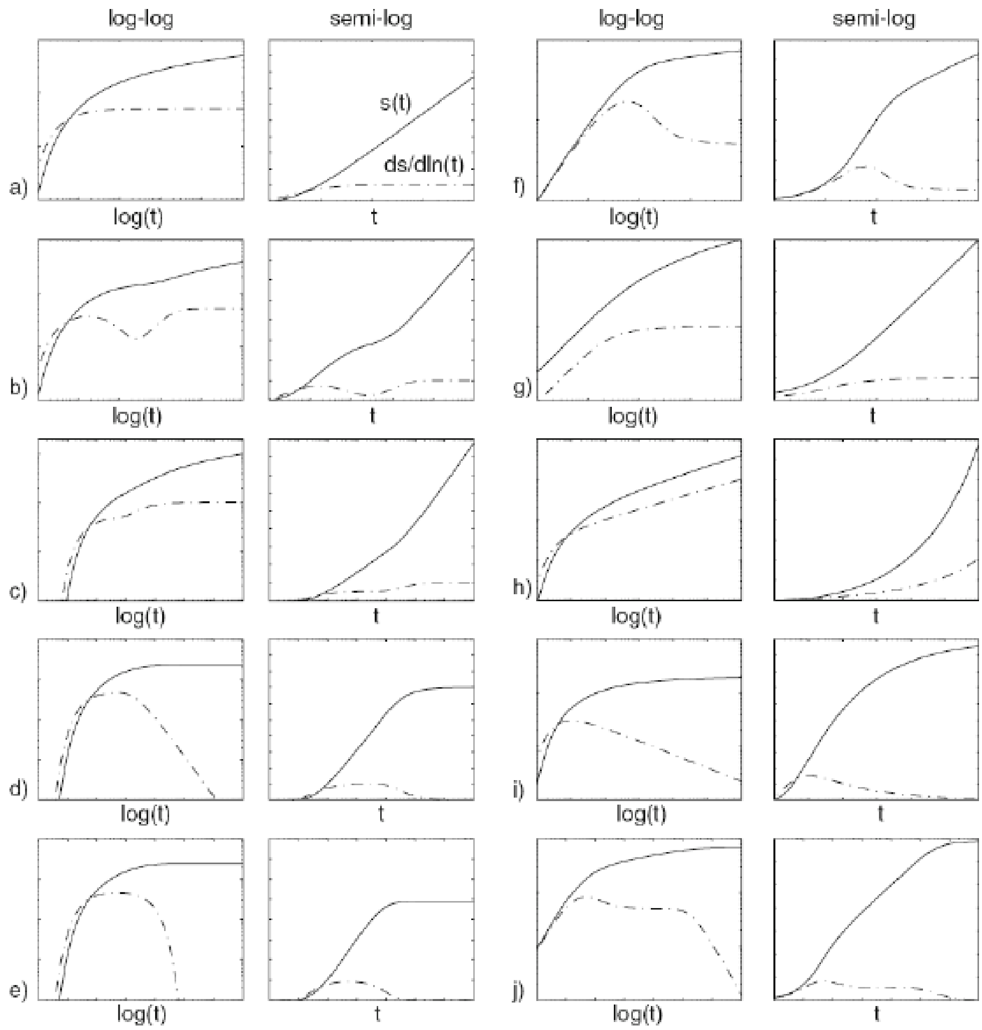


Figure 3.5 Typical diagnostic plots encountered in hydrogeology (Renard et al., 2009).

3.6 Hydrogeological conceptual modelling

Hydrogeological conceptual models are a set of simplifying assumptions that describe the groundwater system through the interpretation of all available information in order to inform the sustainable utilisation of groundwater resources. The characteristics of the real system that are summarised include topographic and surface water information, aquifer properties and boundaries, groundwater flow directions, aquifer relationships, and water balances (Brassington and Younger, 2010). Due to the complex nature of groundwater resources, conceptual modelling is used as a prerequisite before more detailed numerical hydrogeological simulations are developed as it provides an informed understanding of the system being investigated (Rivera, 2007). A conceptual model in hydrogeology is normally represented pictorial representation of the groundwater flow system, frequently in the form of a block diagram or cross section (Anderson and Woessner, 1992). This involves comprehensive integration of several datasets and assumptions to review how hydrogeological processes occur in the underlying groundwater system (Figure 3.6). As a result, hydrogeological models are used to form a basis when testing existing hypotheses as well as helping in making predictions in various real-world scenarios. The present study focused on developing a conceptual model of the study area to describe the hydrogeological properties within the catchment and a selected experimental site. The conceptual model was developed using remote sensing, geophysical techniques and field investigations.

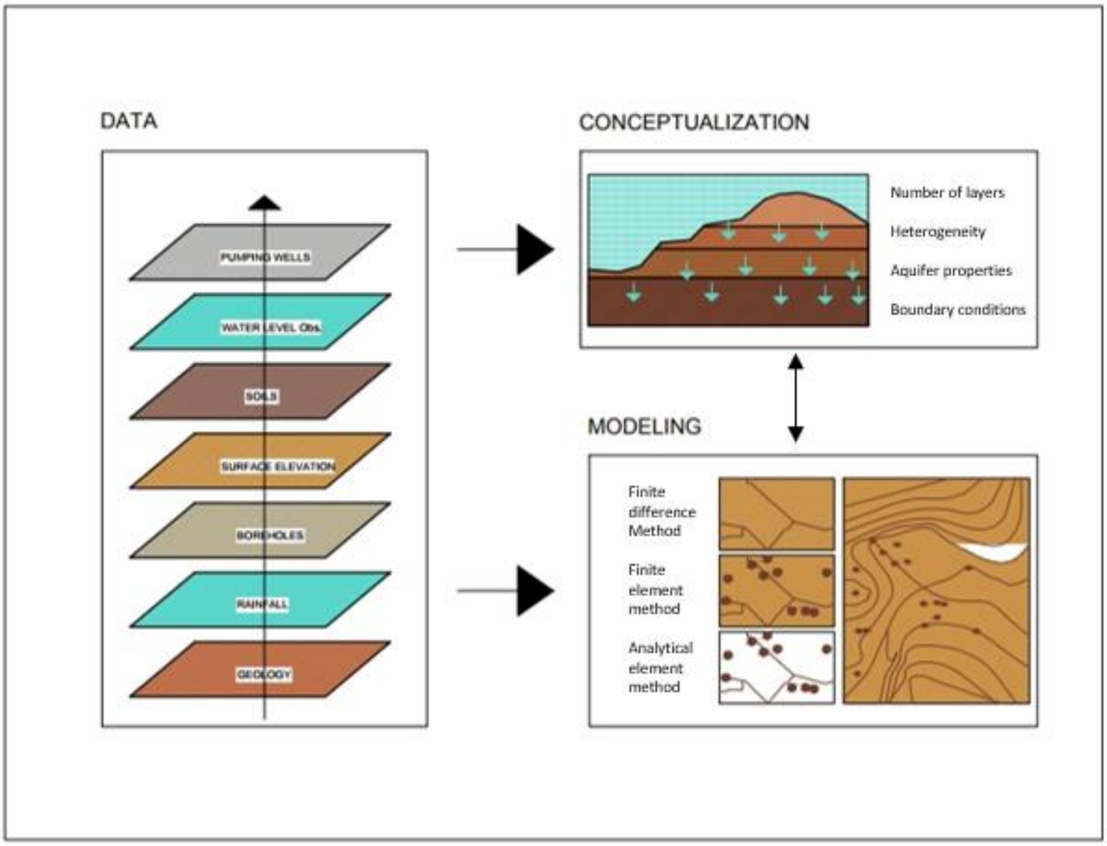


Figure 3.6 Three main components of groundwater studies (adapted from Maidment and Hopper, 2005 in Yang et al., 2010).

In order to develop a hydrogeological conceptual model, it is important to firstly define the geological framework of the region under study. The geological framework involves an understanding of the rocks, lithologies and structural relationships in an area. This information aids in defining the three-dimensional changes that affect the permeability and storage properties of an aquifer (Younger, 1993). The geological framework is then followed by the development of a hydrologic framework. This is achieved through firstly defining boundaries of the hydrologic system and hydro-stratigraphic units, preparing a water budget, and defining the flow system (Betancur *et al.,* 2012).

A hydro-stratigraphic unit is defined in order to determine number of layers controlling groundwater flow in a system (Wilson, 2005). This means that estimates of the aquifer hydraulic properties and hydrochemistry parameters are used to distinguish different hydro-stratigraphic units. The hydro-stratigraphic units are either categorised as aquifers, aquitards or aquicludes depending on their capabilities of transmitting water. Once this is applied, flows between the aquifer and its surroundings are determined. The final stage in the development of the model involves integrating all the forms of geological and hydrologic data in the study area, since the groundwater flow model is a form of mass balance (Izady *et al.,* 2014). Geological frameworks are constructed using data from borehole logs, geophysics and geological maps whereas the hydrologic framework is produced from such data as groundwater levels, aquifer hydraulic properties and hydrochemistry and isotopes.

3.7 Theoretical Framework and conceptual frameworks

The conceptual framework applied in this study is that aquifer characterisation results in knowledge and building understanding of the aquifer hydrogeological properties. In addition, this study regards aquifers occurring in the crystalline basement terrain, particularly in South Africa as poorly characterised. To provide an analysis of the aquifer hydrogeological properties, this study applies theory of aquifer characterisation as involving gaining insight or knowledge about the aquifer resource. This may involve use of various methods applicable in crystalline basement regions in order to establish the aquifer hydrogeological properties. The theory on crystalline basement aquifers which are interpreted to present unique, complex conditions and under hydrological pressure, is used to justify the crucial need for assessing aquifer properties thereof.

Darcy's law is commonly applied to explain the flow of fluid through a porous media. The theory has been widely used to calculate the flow in the unsaturated and saturated zone and has been used widely for hydrogeological investigations as it provides a basis for description of groundwater flow in all hydrogeological environments. These are homogeneous and heterogenous systems, isotropic and anisotropic media flows, fractured rock or granular media, steady state and transient flows, flow in aquifers and aquitards as well as for saturated and unsaturated flows (Freeze and Cherry, 1979). Darcy Law is valid for slow laminar flow and is guided by the principal that the amount of fluid flow between two points is directly correlated to the difference in hydraulic head between the two points, the distance between the points, and the interconnectivity of flow pathways in the rock between the points (Younger, 2007).

Darcy's Law is based off several guiding principles:

- Flow will not occur if there is no pressure gradient over a distance If there is a pressure gradient flow will occur from high pressure towards low pressure
- The greater the pressure gradient through the same material, the greater the discharge rate
- The discharge rate will be different through different formations even if the pressure gradient is the same in such differing formations.

In fractured rock aquifers, Freeze and Cherry (1979) argued that Darcy Law is valid if an assumption is made that the fracture spacing is sufficiently dense that the fractured media hydraulically acts in the same way as granular porous media. Therefore, the theory of Darcy Law has been used in this study to interpret data, understand groundwater flow system in the study area but also used as a guide to answer the research question posed in this study.

Another important theory used in this study is the theory of gravity-driven basin-scale flow of groundwater also known as regional groundwater flow theory by Tooth (2009). This theory explains the formation of groundwater flow systems in a hierarchical order, from local, subregion to regional flow in large basins. In Tooth's theory, regional flow systems of groundwater commensurate with the dimensions of the natural topographic relief, with the geology as the main actor.

Hydrogeological characterisation is employed as a conceptual framework for the current study. Hydrogeological characterisation involves evaluating various characteristics of the aquifer using different forms of data. This includes evaluating the structure (geology) and hydraulic properties. The aquifer structure is evaluated to delineate groundwater units and establish the manner in which groundwater occurs in an area. The aquifers hydraulic parameters include the hydraulic conductivity, transmissivity, storativity, specific yield and porosity. These physical properties determine the storage capacity and how much the aquifer can release water throughout the medium. This study used the concept of hydrogeological characterization to answer the research question "To what extent can hydrogeological characterization be used to explain the availability and influence of groundwater on non-perennial river systems".

3.8 Research framework

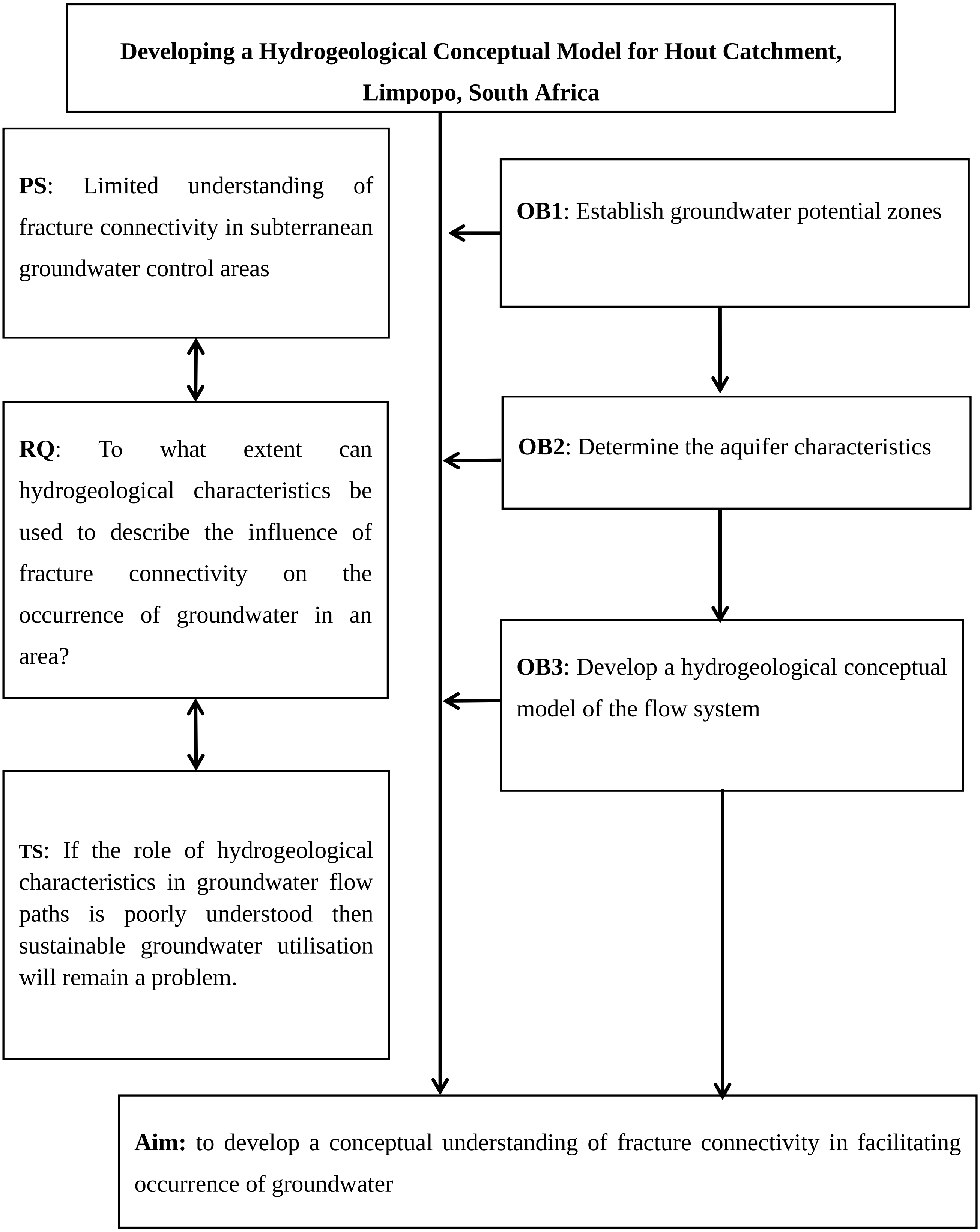


Figure 3.7 Research framework for the study indicating the key elements of the current study.

The research framework provides an overview of how the current study will be used to establish an understanding of the hydrogeological characteristics of the Hout catchment based on existing information. In the context of groundwater occurrence (potential) it is important to characterise the physical feasibility of meeting water demands through groundwater. By overlaying the different information layers such as geological and structural maps, aquifer parameter depth to groundwater and groundwater chemistry using appropriate software (i.e. GIS) this will provide an understanding of the aquifer characteristics, structural and geological influences of successful and unsuccessful boreholes an ultimately, a hydrogeological conceptual model of the basement aquifer(s) in the area.

Chapter 4: Research design and methods

4.1 Introduction

This chapter describes the research design of the study and the methods that will be used to collect, process, and analyse data to answer the research question and objectives provided in chapter 1. The research design has been developed from relevant literature and secondary data to provide an explanation for the development of the hydrogeological conceptual model. This chapter concludes with establishing quality assurance, limitations, and ethical considerations that were undertaken during this study.

4.2 Research design

4.2.1 Research design approach

The study followed a quantitative experimental design approach and case study approach informed by desktop analysis of available data and a comprehensive peer review of publications concerned with factors influencing the occurrence of groundwater in the region. This research approach allowed the study to understand trends in fracture connectivity and describe hydrogeological processes in the area.

4.2.2 Sampling design

The Hout catchment was assessed to develop a regional hydrogeological conceptual model of the factors that affect groundwater potential in the region at a catchment scale. The Ga-Mamadila community was then selected for the experimental component of the study. Geophysical methods and estimation of hydraulic parameters were applied on an experimental site to assess the local subsurface hydrogeology. A site reconnaissance visit was undertaken in October 2018 to establish the potential experimental sites for the present study, during this period, initial sites for groundwater level and quality characterization were selected based on the preliminary desktop review of the area along with a borehole survey in order to understand the spatial distribution of active monitoring wells in relation to the aforementioned desktop criteria. Access to sample sites was relatively easy as the boreholes were situated in areas close to roads or on private cadastral farms which made them easily accessible.

The experimental sites chosen for the present study were selected based upon desk study in a GIS environment in order to develop an understanding of various physiographic parameters such as; climate, drainage patterns, topography, geology, soils, vegetation and hydrogeology that facilitate groundwater flow processes in the fractured zone of the aquifer at a local scale

Aquifer physical and hydraulic parameters such as transmissivity and hydraulic conductivity, water levels, subsurface resistivity were collected from two experimental sites, however, focus was later placed on the Ga-Mamadila site due to limitations. Geological and topographic maps from the Council of Geoscience were used for sourcing information of the geology type and elevations within the study area. These were used to construct a hydrogeological conceptual model of the study area.

4.3 Research Methodology

Quantitative research, which is used in this study, is an approach for testing objective theories by quantifying variables and examining the relationships between variables. The current study adopted a combination of secondary data and primary data obtained through a desktop study, geophysics, drilling and hydraulic testing of the experimental site. This provided an integrated approach in determining aquifer characteristics and properties such as aquifer parameters. An integrated methodology that employed groundwater potential mapping, surface geophysical methods, drilling and hydraulic tests is seen as a viable approach because the methods complement each other, allow for a larger scale of application, and have the capacity to be implemented in various geological settings (Manyama, 2017).

4.4 Data collection and analysis methods

4.4.1 Groundwater potential zones

The first objective of this study was to delineate the groundwater potential zones in the study area through the GIS and remote sensing techniques. This was done firstly by the compilation of already existing data sets such as Geological, hydrological, climatological, and geographical data from pre-existing databases. Geological data sets collected included geological maps and previous reports in the area, production well data and monitoring well data, rainfall data, soil maps, land use maps, remotely sensed imagery, and topographic maps. This database was used in order to provide a spatially informed understanding and catalogue of the aquifer characteristics, structural and geological locations of interest as well as potential drilling targets for experimental purposes. Hydrogeological information was obtained from the National Groundwater Archive (NGA) of the Department of Water and Sanitation and the Groundwater Resource Information Project (GRIP) database**.** A total of six thematic maps were prepared based on the factors influencing groundwater potential in the hydrogeological setting of the study area. This was achieved by firstly identifying thematic layers which are relevant to groundwater potential. Identification of the relevant criteria during the mapping process was based on their relative importance as inferred from methods used in previous literature (Murthy 2000; Leblanc *et al.* 2003; Ganapuram *et al.* 2009; Abdalla 2012; Al-Abadi and Al-Shamma 2014; Rahmati *et al.* 2014 etc.). The methods used in these studies allow for assessment of available data in a GIS environment.

Crystalline basement aquifers in the study area were conceptualised by Holland (2011) using variations in transmissivity values influenced by different regional aspects such as geology, slope, lineaments density, soil, drainage density and land cover using various satellite data, topographic maps, and existing maps from related of South African governmental organisations. These factors were found to have influenced borehole productivity. High productivity locations were in areas where boreholes have been sited closer to drainage systems, on the bed rocks and closer to structures. It was also shown that structures (NE and ENE) perpendicular to the neo-tectonic stresses direction (NW) are associated with high transmissivity values. In determining the value given to each parameter and in establishing the level of desirability of each attribute, different measurements and ranges were used where most applicable to existing national norms and standards.

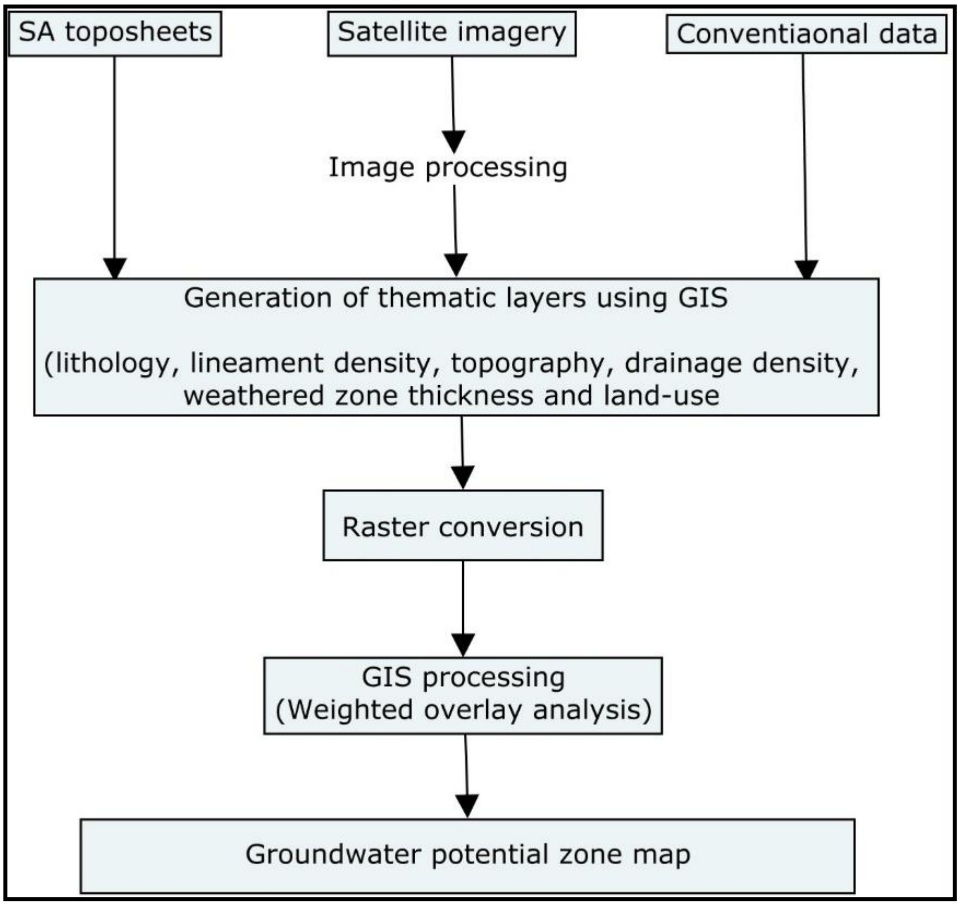


Figure 4.1 Flowchart for the delineation of groundwater potential zones

A geology shapefile of South Africa was clipped and reclassified according to literature the formations which characterise the Hout catchment, (Barker, 1983; Du Toit, 1998; Brandl, 1999; Du Toit and Sonnekus, 2010; 2011). A slope density map was then prepared from a DEM produced using 30 m by 30 m DEM. The spatial analyst surface slope feature in the ArcGIS toolbox was used to produce the slope degree thematic map. Flat areas tend to allow water to infiltrate and thus recharge the underground when compared to steep slope areas where there is more overland runoff compared to infiltration. A drainage density map was prepared from an available digitised drainage network of the catchment which was generated from a 5 m by 5 m DEM. A double ring buffer was also applied to the stream network of the catchment to demarcate areas which lied within 75 m from the streams and between 75.01 m to 150 m from the streams. The rest of the area, which lay more than 150 m away from any stream made the third category. All digitized vector layers and prepared input layers were changed and resampled to raster layers of 5 m cell size in order to allow for overlapping of the layers in a GIS environment.

The Analytic Hierarchy Process (AHP) of Saaty (1980) was used in the assigning of normalized weights of each thematic map/layer and weights of attributes in each layer. Weights were assigned to thematic maps because the magnitude of influence on groundwater occurrence is different for each theme. The AHP is a multiple decision-making method, which provides a measure of judgement consistency. It also simplifies preference ratings by using pair-wise comparison. AHP was selected over other multi-attribute value techniques because it includes systematic checks on the consistency of judgements (Chowdhury *et al.*, 2009 in Fashae *et al.*, 2013). The AHP was applied in three successive steps, which were pair-wise comparison of thematic importance, matrix normalisation and ranking and consistency check thematic factors were compared on a pair wise basis. Comparison of relative importance between two factors is measured according to Saaty's scale. The weighted maps were then overlaid using the raster calculator function in ArcGIS 10.2. A model was developed, using the model builder to overlay the thematic layers. Six influencing factors for groundwater potential mapping (geology, slope, lineaments density, soil, elevation, drainage density and land cover, are examined separately in the following paragraphs. The thematic maps represent the six factors that are extracted for the calculation of the final map. The values' range was reclassified based on the weighted spatial probability modelling, with equal intervals. The reclassification was performed based on the potentiality of groundwater occurrence.

Validation of the groundwater potential zones was done by comparing the map produced with available borehole information. A dataset of boreholes in the region was added to the groundwater potential map and the corresponding GWP classes they fell in were evaluated. The data was analysed to check the frequency and percentage of boreholes which occurred in each GWP class. Deep and high yielding boreholes were expected to occur in very high GWP zones.

4.4.2 Geophysical surveys

The various methods used in mapping of the subsurface in hydrogeological investigation are commonly surface and invasive geophysical methods, remote sensing including core and well logging. The application of geophysical methods in groundwater investigation, surface geophysical methods has become the standard for aiding in siting of new wells or well location investigations, and mapping of hydrogeologic units of shallow to relatively deep aquifers. Among surface geophysical methods (Electrical Resistivity methods; Electrical Resistivity Tomography; Electric Magnetism).

Integrated geophysical methodologies were applied in selected river sites based on the occurrence of lineaments and other geological features along and around the river segment that were identified during the compilation of the hydrogeological base map. The objective was to obtain information on the presence of indirect groundwater features through the discovery of structures such as faults, lineaments and dykes that form aquifer boundary or act as controls to subsurface flow in CBAs. Three geophysical techniques were conducted which comprised of magnetic, electromagnetic and resistivity methods.

The 1D ground magnetics method was performed using a proton magnetometer (Figure 4.2). The presence of fractures and dykes (which often control groundwater occurrence in crystalline aquifers) resulted in anomalous magnetic signatures thereby making the geomagnetic exploration method a useful tool in groundwater potential evaluation. The magnetic surveys were planned such that the lines were perpendicular to the regional trends in the geological strike of dykes and faults since they show up most clearly in a survey when traversed perpendicularly. Data was collected at 10 metre intervals within each line and collected using a proton precession magnetometer. A total magnetic profile line was produced and points with contrasting magnetic susceptibilities were identified.

Figure 4. 2 A G5 Proton Memory magnetometer used to conduct geophysical measurements.

The Frequency domain electromagnetic exploration method (FDEM) was performed using an EM34 unit as horizontal profiling methods to identify points of potential interest along the line. FDEM methods are widely used in groundwater investigation such as inferring preferential groundwater pathways, mapping fracture zones, dykes and faults. The EM method is sensitive to contrasts in electrical conductivity of the subsurface and involves the propagation of time-varying low-frequency (~100 Hz to 1MHz) electromagnetic fields in and over the earth (Telford *et al.*, 1990). A transmitter coil radiates an electromagnetic field which induces eddy currents in the subsurface. The eddy currents, in turn, induce a secondary electromagnetic field. The secondary field is then intercepted by a receiver coil and can be related to subsurface conditions. The conductivity of geologic materials is highly dependent upon the water content and the concentration of dissolved minerals (electrolytes).

Figure 4.3 Conducting the electromagnetic method with the support of the Department of Water and Sanitation.

The Resistivity survey was conducted with a metal probe (electrode) resistivity system. The most common mineral forming soils and rocks have very high resistivity in these dry conditions of Limpopo. The resistivity of soils and rocks is therefore normally a function of the variations in water content and the concentration of dissolved ions in the groundwater. The Wenner electrode configuration was used on selected potential sites in order to infer the variation and thickness of the underlying layers at selected anomalous regions. This particular method utilises direct currents or low frequency alternating currents to investigate the electric al properties (electrical resistivity) of the subsurface and is based on the principle of existence of electrical resistivity contrasts between different earth materials in accordance to rock matrix, moisture, fluid saturation salinity and porosity factors. The measured apparent electrical resistivity, which is determined by measuring V (potential difference) and I (current) and knowing the electrode configuration, gives an idea of the nature of subsurface material present within the medium. A schematic diagram of the principle of operation of electrical resistivity method along with images of equipment used is shown in figures 4.4 and 4.5 below.

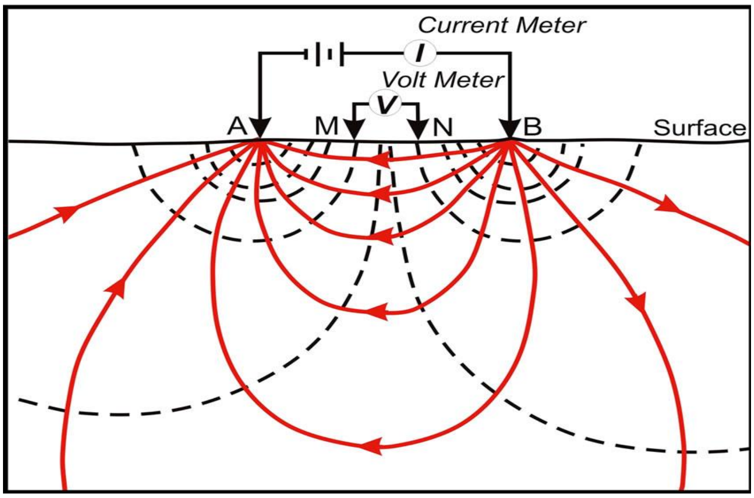


Figure 4.4 Schematic diagram of the principle of operation of electrical resistivity method. A and B are current electrodes while M and N are potential electrodes.

Figure 4.5 Two images display the field set up used for vertical electrical sounding on the experimental sites

4.4.2 Aquifer characterization

The second objective of this study is to characterize the aquifer system through geological mapping, drilling, and lithological logging of experimental boreholes, determining aquifer hydraulic parameters through the use of aquifer tests as well as monitoring the groundwater levels. The characterization of this data provides the basis of the hydrogeological parameters that will be used to inform the conceptual model to be developed.

The geological characterization was achieved with a comprehensive review of the geology of the study area and surroundings. Available structural and geological maps were used for examination and interpretation of geological features. The investigation entails field work based on direct observations. To obtain a complete geological knowledge of the study area, many tools were used, and data were collected manually. A GPS is used to obtain the geographic coordinates of each location on the map. Topographic maps combined with aerial photographs were used to find locations taken with a GPS as well as specific outcrops. The hand lens was used for description of the rocks in terms of grain size. A Freiberg-type compass was used to locate true north and measured dip direction and dip or the general orientation of trends of lineaments and dolerite dykes where exposed in the field.

The result from the magnetic approach from geophysical prospect also provided an idea of the trends of fractures and dolerite dykes in the field. The graph papers were used to generate the profiles for sites 7 and 8 in the area. To do this, 1:50 000 topographic map (2329 CC Ga-Mashashane) from the Department of Land and Survey in Polokwane were used as base maps for the study area, where the geology can be interpolated along the transect line that cut through various lineaments and dolerite dykes on the graph paper. By joining the interpolated points with the topography along the transect line, the profile of selected site can be produced. Software's (ArcGIS software package 10.3.1 and Surfer software package 11.1) were used for digitizing purposes and generating the geological map of the Ga-Mamadila area. The mapping aspect of the study is based on topographical and previously published geological maps, aerial-photographs and digital aerial photos to develop a visual understanding and representation of the study area. The 1:250 000, Limpopo geological map is used for the regional geology. The published 1:50 000 topographic maps (2329 CC Ga-Mashashane) from the Department of Land and Survey in Polokwane were used as base maps for the study area. The orthophoto map series at a scale of 1:10 000, combined with the aerial photographs and digital aerial photos were used to interpret the structures visible in the field.

The emplacement of well intruded and fractured basement gneissic rock underfoot may not be obvious due to the lack of rock exposures, alluvium deposits and vegetation in the area. The vertical extent of the fracturing cannot be determined from structural observations only, recourse has to be taken to geophysical exploration. The geophysical approach mostly used is that of electrical resistivity depth assessment with dolerite dykes that are not exposed or may be detected electromagnetically. The electromagnetic technique was combined with electrical depth probing which are essential for exploratory nature. The structural and geophysical techniques were combined to identify the dolerite dykes and fractures of a pristine area in Ga-Mamadila. These methods are useful way to select sites for the fieldwork or drilling prospect and to identify features not represented on the 1:250 000, Limpopo geological map.

After the geological interpretation and geophysical methods were conducted, borehole drilling sites were established. The drilling exercise was conducted in collaboration with the Department of Water and Sanitation. four experimental boreholes were drilled in the Ga-Mamadila site (Figure 4.6) from the 3rd – 8th of June 2019 by the Ramotse development company under supervision of the University of the Western Cape (UWC) and the Department of Water and Sanitation. The selection of drilled the sites was informed from a detailed desktop study, accompanied by on site geological mapping and geophysical investigations conducted in 2018.

Figure 4.6 Borehole sites within the Ga-Mamadila community

The study used air-rotary as a drilling technique in order to establish the characteristics of the aquifer materials and geological units within the study area. Air-rotary drilling is a technique which uses a rotating drill bit that grinds through soil and rock as the drill bit advances and then uses compressed air in order to transport the drill cuttings up to the ground surface. A driven steel casing (6 m in this case) was used to help reinforce the drilled borehole and prevent borehole collapse, while facilitating the transport of aquifer material out of the borehole. This then allows for the collection of soils at various intervals for borehole logging. The positioning of these boreholes was ideal for the monitoring of the water level fluctuations in comparison to the surrounding boreholes and obtained good data during high flow events within the area.

Figure 4.7 Air-rotary drilling on the Ga-Mamadila site

A pneumatic drill with a reciprocating piston-driven ‘hammer’ made from solid steel was used to drive a heavy drill bit into the rock. The hammer has ~20 mm thick tungsten rods protruding from the steel matrix as ‘buttons. The tungsten buttons are the cutting face of the bit.

Figure 4.8 Steel rods and drilling bit

Samples were collected at 1-meter intervals during the drilling process as the drill bit penetrated the geological material using a spade (Figure 4.9) and images of the samples were taken in order to identify the rock materials at respective depths. Air-rotary drilling is especially useful for drilling in very coarse and/or dense soils such as those found in crystalline bedrock environments, as it is relatively unaffected by the presence of hard material.

The lithological description of the area is dependent on the method of sampling used during the drilling process. The sampling method allowed for the collection of relatively undisturbed samples as the release of air constantly clears the bottom of the borehole and this allows for consistent contact between the drill bit and the rock formation. As this occurs, the air pushes the rock material to the surface, and this allows for systematic collection of samples. Properties of the rock such as, chip size, primary lithology, secondary lithology, trace elements, weathering, grain size, and colour were then captured into an excel spreadsheet. This allows a more precise delineation of weathered and hard rock material.


Figure 4.9 Lithological sampling during air-rotary drilling

The lithological description of the area is dependent on the method of sampling that was used during the drilling process. The sampling method allowed for the collection of relatively undisturbed samples as the release of air constantly clears the bottom of the borehole and this allows for consistent contact between the drill bit and the rock formation. As this occurs, the air pushes the rock material to the surface, and this allows for systematic collection of samples. Properties of the rock such as, chip size, primary lithology, secondary lithology, trace elements, weathering, grain size, and colour were then captured into an excel spreadsheet. This allows a more precise delineation of weathered and hard rock material. After drilling the boreholes were cased with 165 mm steel pipes, slotted steel pipes were installed at water strikes which were gravel packed on the outsides. Finally, the boreholes were capped and marked. The four newly drilled boreholes were marked HO4-3125, HO4-3126, HO4-3127 and HO4-3128 to keep consistency with pre-existing boreholes.

Aquifer tests were then performed in order to determine the maximum yield below which pumping must be done during constant discharge test as well as the strengths of the boreholes by determining their storativity and transmissivity values by using constant discharge methods and recovery tests. The hydraulic response to pumping is measured and analysed with the objective to 1) characterise an aquifer, 2) quantify its hydraulic properties, and 3) determine the efficiency and sustainable yield. The type and duration of a pumping test depends on the planned usage of the borehole, but typical tests include a multiple discharge test (step-drawdown test), a constant discharge test and a recovery test. In crystalline aquifers short-term pumping tests (i.e. 24-48 hrs) may be adequate to predict the sustainability of an abstraction if the abstraction rate is small and the aquifer relatively uniform. However, the sustainability at higher abstraction rates cannot be reliably assessed due to the short-term discontinuous nature of CBAs.

The sustainable yield of the pumping wells was determined prior to the constant tests through a step- down test. The choice of how long the test should be conducted depends on the required precision of the sustainable yield, also on the intended use of the borehole water. The constant discharge test is very important for the determination of aquifer parameters, especially in relation to high yielding boreholes. In this case, the borehole is pumped at a constant rate that is enough to cause a drawdown in the borehole and not too much to cause the drawdown to reach the pump inlet or main water strike (Kotze, 2001). Once a constant discharge test is performed, recovery data is logged and evaluated. The recovery of the water level should be measured from the time the pump is switched off, at the same interval as during constant discharge for a period equal to the duration of the main test or until the water level has fully recovered. Most pumping tests in South Africa are conducted within 48 hours, often because of the expenses associated with long pumping hours (Kotze, 2001). Analysis of aquifer tests data was done according to characteristics of the borehole, aquifer system and test configurations (Kruseman and de Ridder, 1994). These include Theis (confined), Cooper-Jacob time drawdown (confined), Cooper-Jacob distance drawdown (confined), Hantush and Jacob (leaky-confined), Nueman (unconfined), Moench (unconfined) and Moench (fracture flow) (Kruseman and de Ridder, 1994).

4.4.4 Developing the hydrogeological conceptual model.

Data integration of the geologic, geophysical, and hydrologic properties of the study area was used to develop the hydrogeological conceptual model. Information from the borehole logs and geological maps are compiled to construct the geological framework while the hydrological framework was developed from the aquifer hydraulic parameters and groundwater level data. This means that components of the study (findings from objective one and two) were used for the model development. Having collected all the necessary data, hydrogeological conceptual model that explains the role of fracture networks in the flow of groundwater in the study area was produced using Quantum GIS (QGIS) using information from water level data.

The potential groundwater flow direction was determined by creating a groundwater level contour map. The depth to groundwater levels were measured using a water level dip meter while the elevation was determined using the GPS receiver. Therefore, the elevation of the groundwater level (hydraulic head) was calculating by subtracting the depth to water level from the ground surface elevation. Given this kind of data of more than three points, the groundwater contour map was produced to deduce the direction of groundwater flow direction. The contours can be drawn manually by connecting points of equal heads (equipotential lines) from a minimum of three wells in a triangular configuration. However, a hand drawn procedure is labour intensive and time consuming, therefore, this study used the ‘interpolation’ and ‘extract contours’ tool in QGIS since the software provides a quick and automated way of analysis and representation.

4.5 Quality assurance and quality control

To confirm the reliability of the data used in the study, various data quality assurance and control measures were put into consideration. Spatial analysis of the datasets was carried out through georeferencing because some of the satellite images were either unprocessed or under a different coordinate system. Georeferencing therefore ensured that the spatial datasets are representative of the study area. To ensure reliability and validity of the results, the secondary datasets were obtained from accredited sources. Lastly, the thematic maps were converted into the same geographical coordinate system before being integrated to ensure that they are covering the same region on the study area. A GPS was used to identify accurate coordinates for both the geophysical survey and the boreholes that were to be developed and monitored. A cap was placed on every borehole site for security against vandalism and for easy identification.

4.6 Research integrity

In this study, some of the study sites were located in private boundaries such as farms and a community, with the area characterised by cropped fields and livestock grazing fields. As a result, permission to carry out the research in such case was required, of which was submitted to the relevant authorities. All the relevant precaution was adhered to, in order to ensure that all the legalities and requirements are met as per the ethics of this study. This research was structured to adhere to all several principles of ethical consideration. These include meeting held with the community of Mamadila where this experiment was conducted. The leaders of the community were verbally informed about the study and agreement between them and the ‘Enhancing Sustainable Groundwater Use in South Africa project was done. Other parties like Department of Water and Sanitation in Polokwane were engaged in the research and permission was granted by the Department of Water and Sanitation to use the secondary data obtained from the. Permission to use data from the South African Weather Service was obtained through the agreement between the researcher and the institution and non-disclosure form was signed. Furthermore, all the data requiring confidentiality were kept under such way such that they were not shared among other third parties neither used for other purposes apart from this research.

4.7 Limitations of the study

The thesis uses a case study approach and has limitations on data acquisition over the entire catchment. In addition, the study is only focused on determining the key hydrogeological properties of the aquifer, such as borehole yields, transmissivity and storativity, and groundwater flow directions. As a result, this study does not provide full characterisation of the aquifers. This study thus provided preliminary understanding on aquifer properties; an approach not comprehensive. Other limitations include the high cost of equipment involved and in borehole drilling process. The spatial coverage of sites chosen for the experimental phase of the study is also too small of an extent to form a comprehensive understanding of the fracture system at a catchment scale. However, the DWA provides a database of the groundwater monitoring network within the study area and this was used as complimentary secondary data. While all observations are made, it must be noted that the validity of a lineaments positioning and its influence on the flow of water within an aquifer depends on subjective analysis from the user. Mapping and interpretation of lineaments used in the current is conducted by geological remote sensing consultants on behalf the DWA Limpopo regional office.

This study required recent (preferable current year) remotely sensed data to represent current groundwater potential zones for the area since influencing factors such as land use change over time. Due to the level of study, which was predominantly a desktop research, such was not possible, hence secondary data was used in conjunction with field data from the experimental site in order to infer the results produced by the secondary data.

Chapter 5: Groundwater potential zones

5.1 Introduction

The following section presents the results on thematic mapping of groundwater potential zones in the study area and integrated geophysical methods, which form the first objective of the study. Firstly, interpretation of different thematic layers and their reclassified maps is provided. This is in order to provide a more comprehensive understanding of the hydrogeological characteristics that influence the occurrence of groundwater in crystalline basement environments. The maps were then overlaid using GIS software in order to delineate the groundwater potential areas for the study region. In addition, the results of the AHP process used to assign weights of themes and the final overlay groundwater potential are provided.

Interpretation of the three geophysical methods that were sequentially implemented is also provided. This aims to provide more understanding on the subsurface structural features that are present on the experimental site as these determine the trends in fracture connectivity. This chapter argues that in order to assess the fracture connectivity of the aquifer, it is important to understand the structural controls and lithological properties of an area. Geological characterization is used to refer to the geophysical mapping, the lithologic variations and the structural description.

5.2 Thematic layer mapping

To evaluate the different ground water potential zones, parameters that were considered to influence the occurrence of groundwater were prepared for each layer based off previous literature. These maps were converted to raster data sets having the same pixel size and different weightages were assigned as per their groundwater potential controlling capacity within the study area.

Table 2 Interrelationship between Multi influencing factors of groundwater potential zones

Parameter	**Geology**	**Lineaments**	**Faults**	**Slope**	**Land Use**	**Drainage**	**Relative Weight**	**Assigned Weight**
Geology	-	1	1	1	1	1	5	25
Lineaments	1	-	1		1	1	4	20
Faults	-	-	-	1	1	1	3	15
Slope	-	-	1	-	1	1	3	15
Land use	-	0.5	1	0.5	-	1	3	15
Drainage	-	-	-	1	1	-	2	10
						Total	20	100

From table 2 above, it can be noted that Geology and lineament density hold highest values relative to the other parameters for the complex spatial and temporal distribution of the crystalline basement rocks, their different intricate stratigraphic and structural relationships, wide compositional variability, and different degree of weathering and topographic position highly control the groundwater potential in the area. However, even though precipitation is presumably the main source of recharge and groundwater, it shows least significance in literature and was not accounted for due to the extreme variability of daily and monthly precipitation amounts all over the catchment area. This variability essentially limits the exact assessment or even prediction of water resource availability. After categorization, all the reclassified thematic layers were integrated with one another through GIS using the weighting overlay analysis. Reclassification of each map was weighted in the GIS based on the weight values produced. Accordingly, the higher values ranging from 7-9 were given for highly controlling attributes, 4-6 for moderately controlling units and 1-3 for poor controlling reclassified units. Finally, the maps integrated using GIS software with the purpose intended to delineate the groundwater potential areas for the study region.

5.2.1 Geology

The geological factor is associated with the permeability and capacity of the formations in the occurrence of groundwater and is significant in governing recharge, movement and storage of groundwater because it mainly controls the primary porosity and permeability of rocks (Mukherjee *et al.*, 2012). The Goudplaats Gneiss is assumed to be the oldest of the basement rocks that occur within the area and covers in the eastern part of the Hout river catchment (Figure 5.1). It is also assumed to be the basement rock of the bandelierkop complex which comprises of mainly mafic, ultramafic and pelitic gneisses. The gneiss predominantly underlays the study area and forms part of the Limpopo Mobile Belt. The formation was formed from metamorphosed granite (Chinoda *et al.*, 2009) and one of its main structural features, the Hout river Shear Zone (HRSZ) is located on the southern side of the Limpopo Mobile Belt and consists of steeply northward-dipping thrusts and reverse faults, as well as several NE-SW striking strike-slip faults (Smit *et al.*, 1992; Smit and Van Reenen 1997). More often the gneiss formation is intruded by dykes with rocks belonging to the Bandelierkop Complex that predominantly trends northwest and northeast (Du Toit and Sonnekus, 2014), occur as highly deformed keels within the gneiss. The geology aspect has been given 25 % influence on a scale of 100 %, in the study area as far as groundwater potential and occurrence is concerned based on the hydrogeological properties of different lithological units as described in chapter three. The scale value (1 to 5) to individual classes within the geology map and its overall distribution within the study area was also taken into consideration (see table 1).

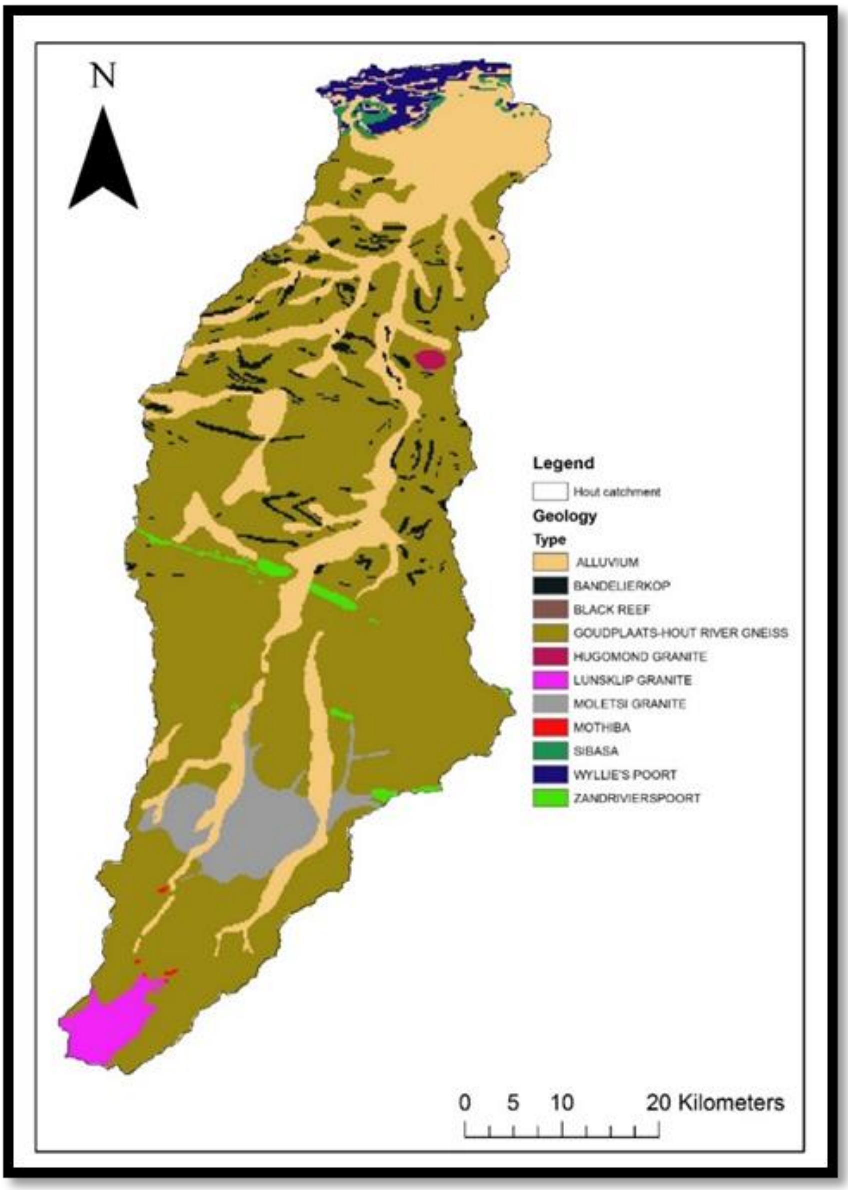


Figure 5.1 Geological map of the study area (based on the geological map of South Africa)

5.2.2 Slope

The slope is an important factor in groundwater potential mapping as this aspect determines the rate of infiltration and runoff of surface water in an area. It is therefore expected to observe low levels of recharge in steep slopes as water flows rapidly downwards providing insufficient time for infiltration while flat terrains facilitate groundwater recharge due to extensive retention of rainfall (Arkoprovo *et al.*, 2012). The slope of the study area was calculated in degrees based on the 5m DEM model and ranges between 0°-58°. Majority of the study area displayed a gentle slope that ranges between 0°-4.9°, however, the northern region of the catchment exhibits a significant increase in slope (yellow and orange in Figure 5.2) as this is where the Soutpansberg Mountains are located. Groundwater potential was expected to be lower in this area.

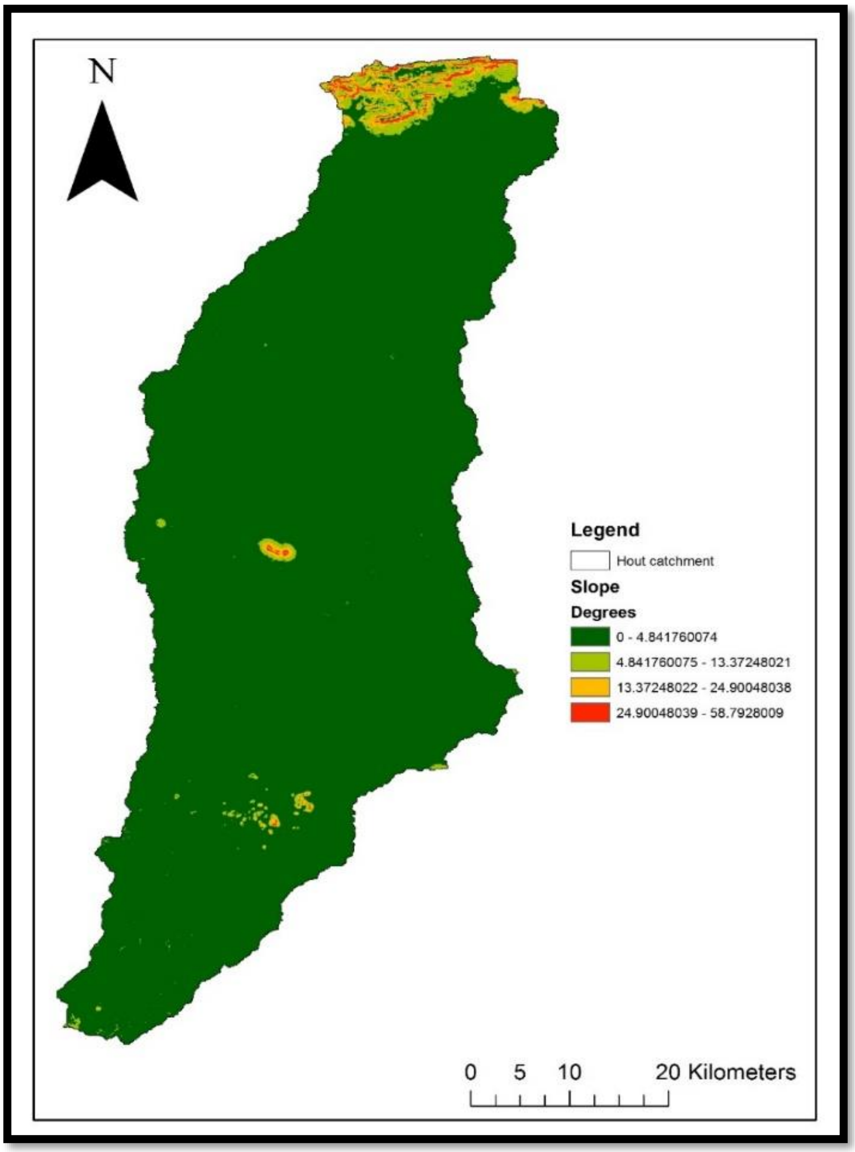


Figure 5.2 Slope map of the study area

5.2.3 Lineament density

The presence of lineaments can be an important factor in controlling groundwater flow at regional and local scales. Lineaments that extend over wide spatial areas may act as groundwater divide similar to surface water divide which can be controlled by topographic relief or rock layering. On the other hand, lineaments that extend over short distance and control local groundwater flow (Vries and Simmers, 2002). Remotely sensed data helps in understanding and mapping of lineaments at a regional and local scales. Use of remote sensing technique is quite easy to analyse the lineament with different spectral bands (Alonso-Contes, 2011). The lineaments occurring in the study area were extracted from the Landsat 8 OLI images. The Hout catchment displays an overall lineament density that ranges between 0-15. Upstream of the catchment, a lower range of 0-1 is observed when compared to the downstream of the catchment with lineament density ranges that fall between 1-4, 4-8 and 8-15.

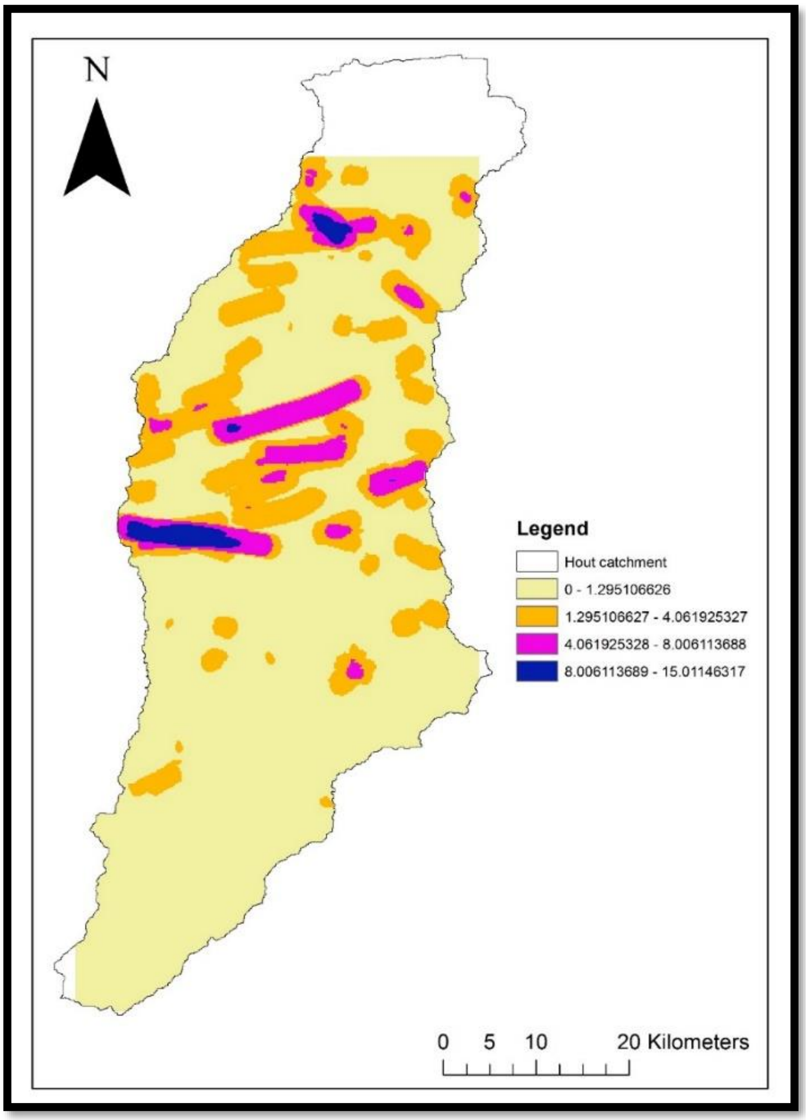


Figure 5.3 Lineament density map of the study area using pre-existing structural data (source: CGS)

5.2.4 Land cover

Land cover is one of the factors that influence the occurrence of sub-surface groundwater occurrence. Land cover can either reduce runoff or facilitate it. Plants trap water droplets which eventually infiltrate the subsurface to recharge groundwater (Mukherjee *et al.*, 2012). Land cover of the study area was interpreted from satellite imagery and is characterized predominantly by grasslands and cultivated land (Figure 5.4). Magesh *et al.* (2012) highlighted that classification of land cover for analysis should be based on their character to infiltrate water into the ground and to hold water on the ground. Therefore, urban areas within the study sites were found to be the least suitable for infiltration hence given the least scale value of one while the cultivated land, grassland and water bodies were given higher scale values. Agricultural activities and presence of water bodies in the area facilitate focused and natural recharge respectively. Land cover was assigned an influence of 15% on a scale of 100% with regards to groundwater potential in the area.

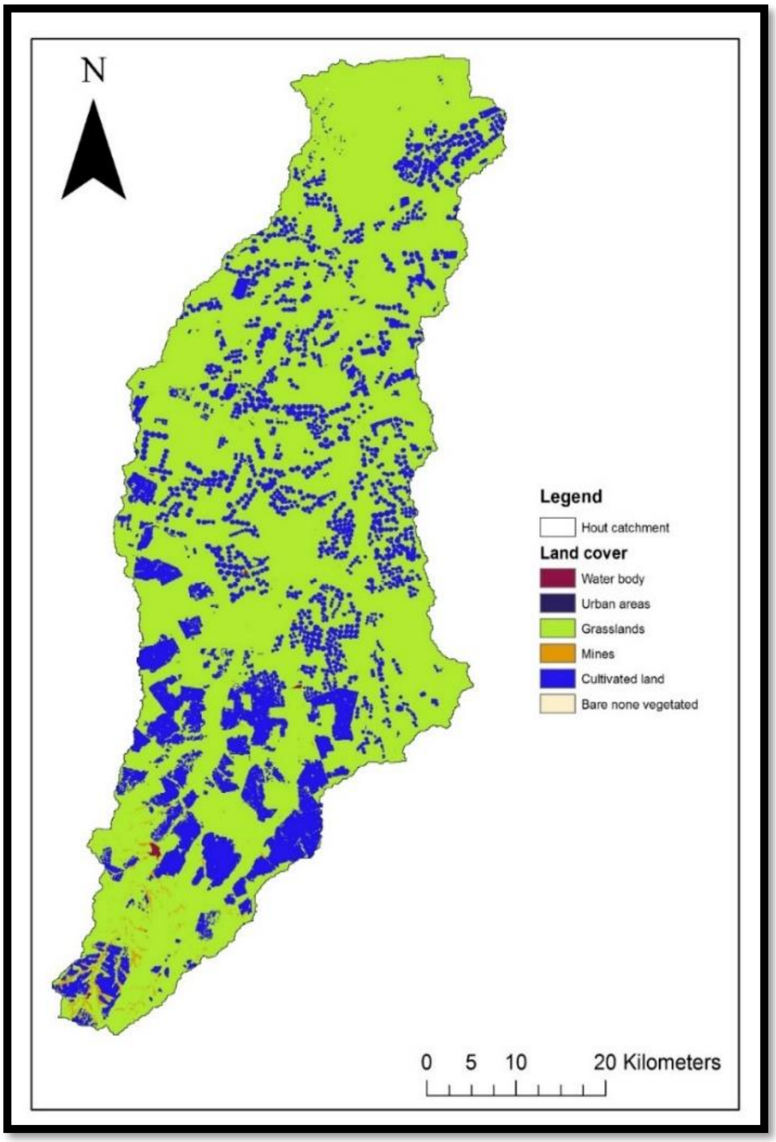


Figure 5.4 Land cover map of the study area

5.2.5 Drainage density

Drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin is calculated as a ratio of the sum of stream lengths to the size of the area of the grid. It is one of the most important indicators of hydrogeological features, because drainage network and density are controlled in a fundamental way by the underlying lithology, vegetation type, infiltration rate, slope angle and the capacity of soils to absorb rainfall. The drainage density of the study area was produced from the SRTM global elevation data through in ArcMap 10.3. Figure 5.5 below showed the drainage density of the Hout catchment to be within the range of 0-5100. According to the map, it is observed that the drainage density of the catchment is higher upstream than it is downstream of the catchment, with upstream values ranging between 2260 - 5100. This was followed by reclassification into five drainage density classes from very low to very high.

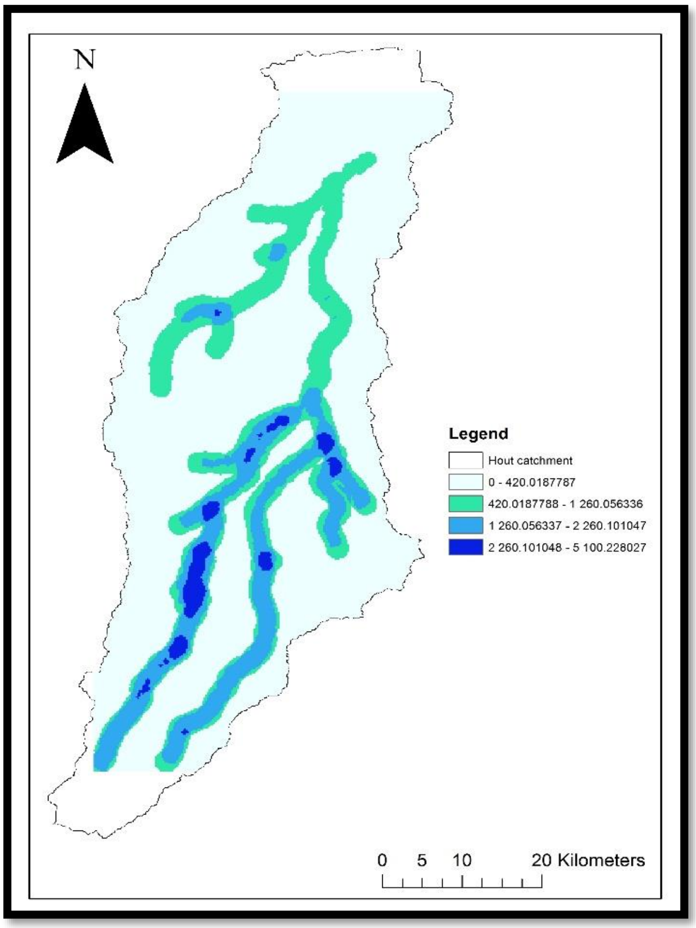
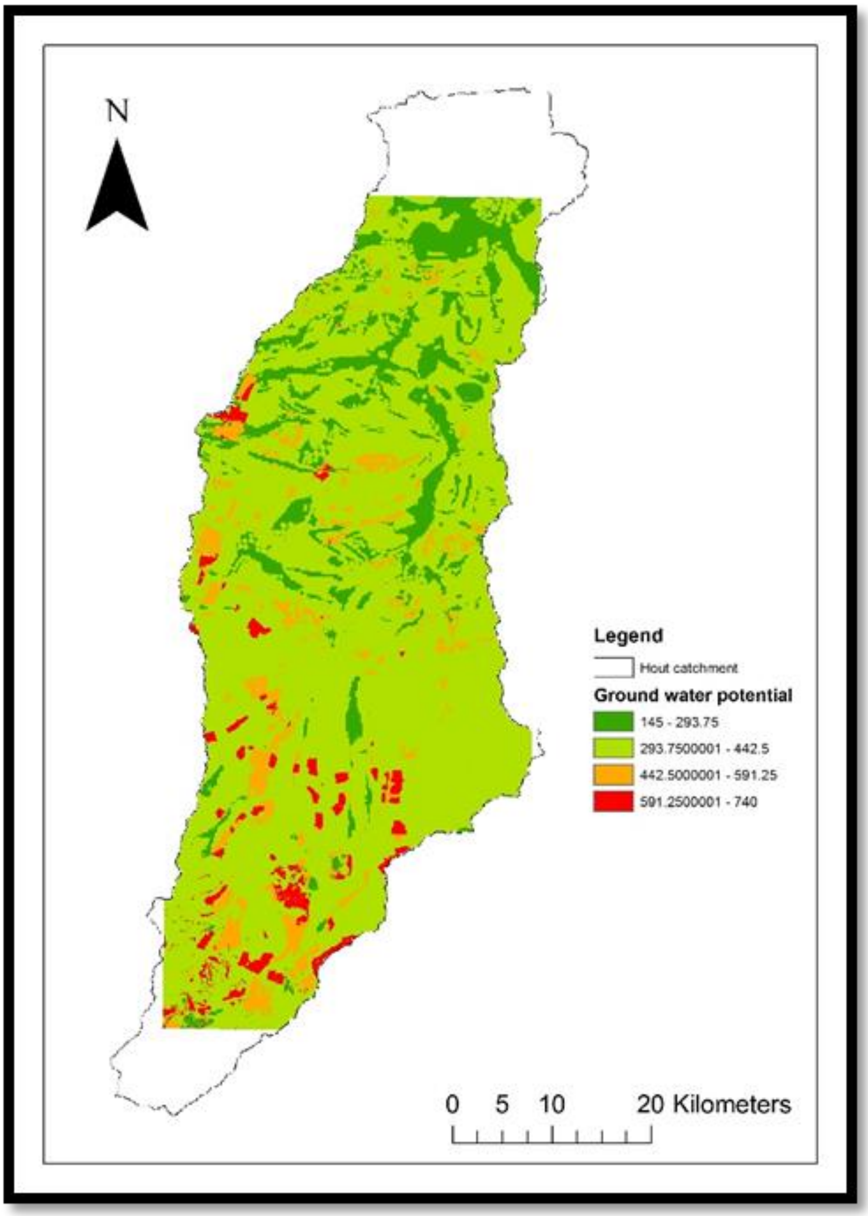


Figure 5.5 Drainage density map of the study area

5.2.6 Output/Groundwater potential zone map

Integration of the thematic layers was carried out using the overlay analysis tool in ArcGIS based off Saaty's Analytical Hierarchy Process (AHP). Groundwater potential zones were delineated and classified as; high potential, moderate potential, low potential, and poor potential zones (Figure 5.6a and b). The high groundwater potentiality areas were found mainly in the Southern regions of the Hout catchment. This indicates that the geology, slope, faults, lineament density, drainage density and land cover affect the ability for groundwater to infiltrate the system. The high potential zones coincide with gentle slopes.



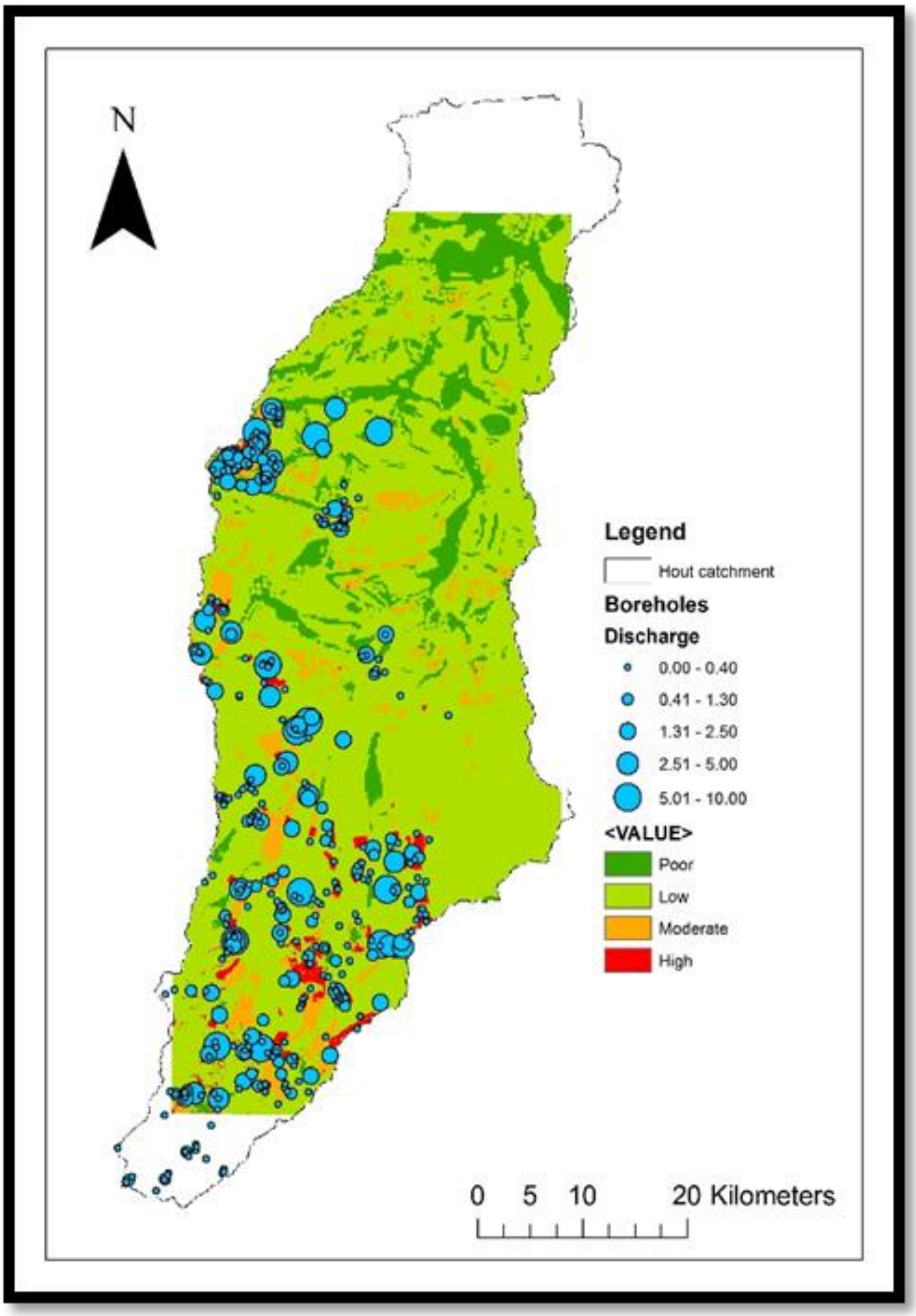


Figure 5.6 a) Groundwater potential map of the study area b) overlaid with borehole data

5.3 Geophysical mapping

Three sites (regions 1-3) were described for the Ga-Mamadila experimental site and one site was described for Kalkfontein experimental site and were used to provide a representation of the structural conditions mapped at the four sites.

5.3.1 Region 1

Two profile lines were carried out during the field survey in region 1 and are described below as profile 1 and 2 respectively. Firstly, a 1D magnetics survey was carried out, followed by the horizontal and vertical electromagnetics were performed on profile line 1 (Figure 5.8a). An anomalous region was observed 20m away from the start of the traverse mark point, this is shown along the line in Figure. This point was further investigated in order to deduce the depth variation using electrical resistivity sounding. The results suggested a single fractured region between depths 24m to 54m from the ground surface (Fig 5.8b). Other than the station 1-20m, there were no other distinct anomalies that suggested groundwater potential in the selected region.

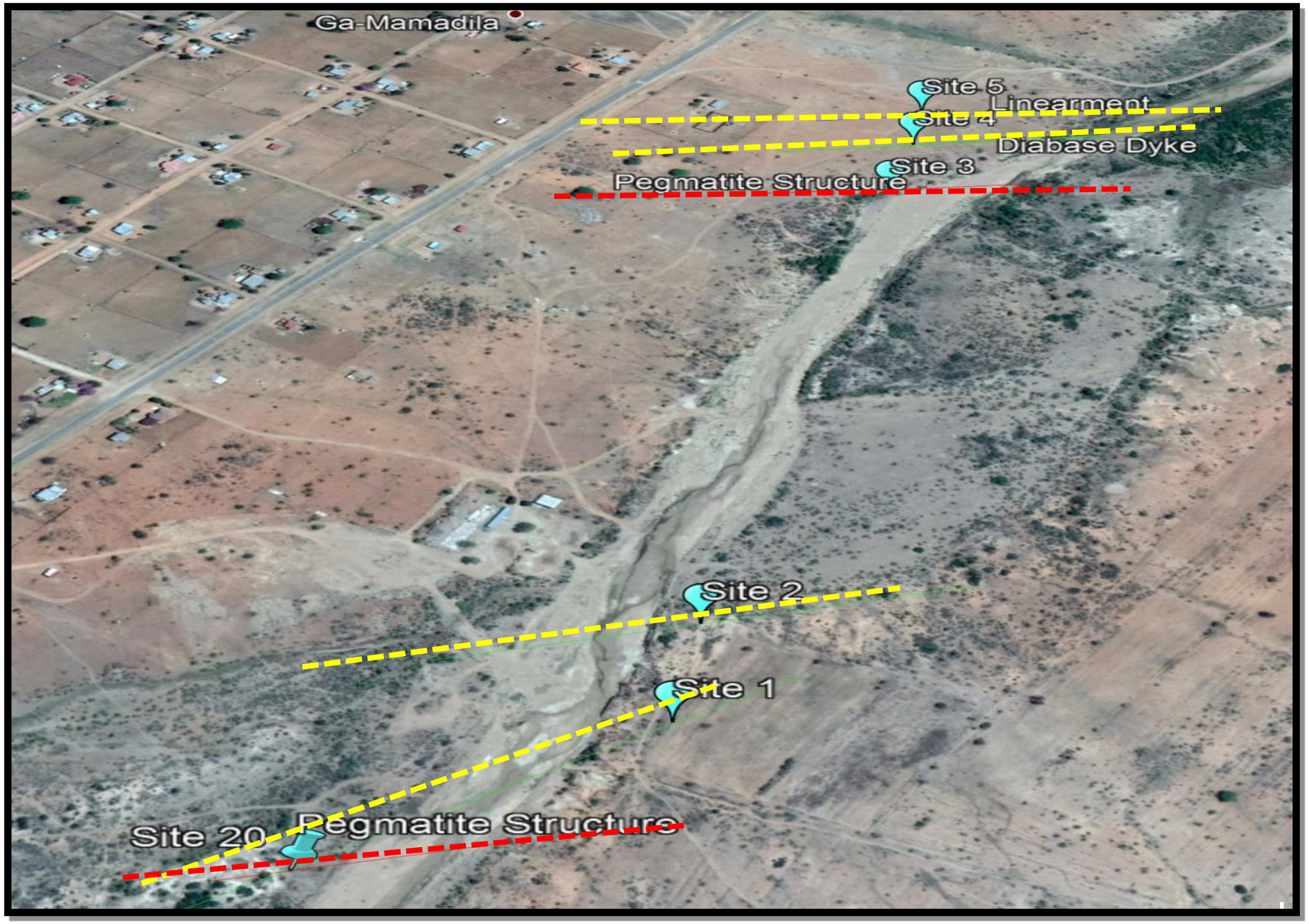
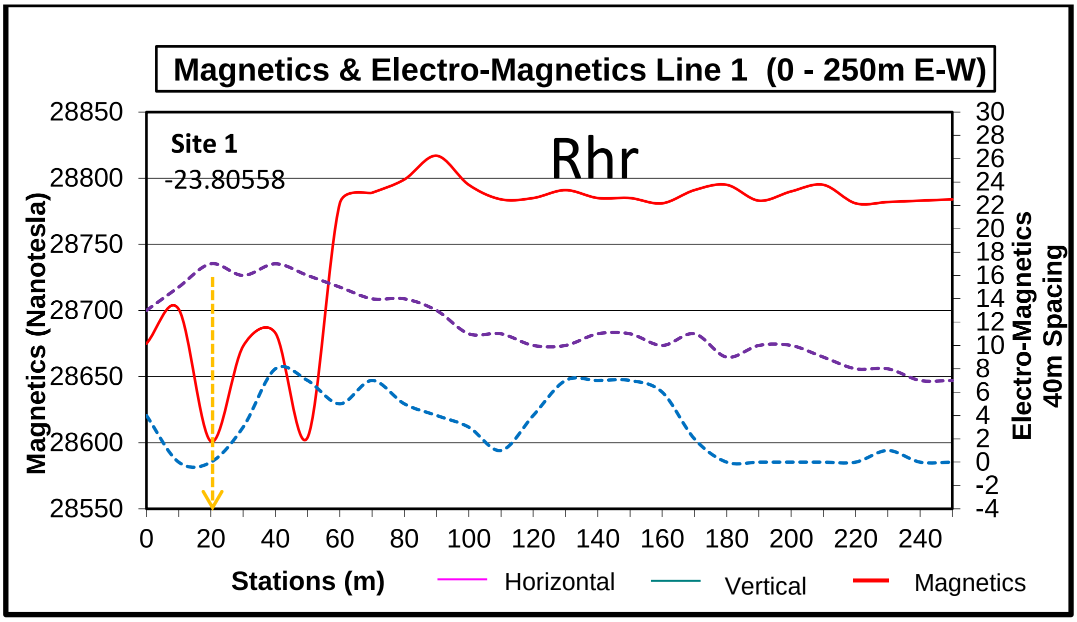


Figure 5.7 Google earth images showing the positions for vertical sounding points for survey region 1 within the study area.



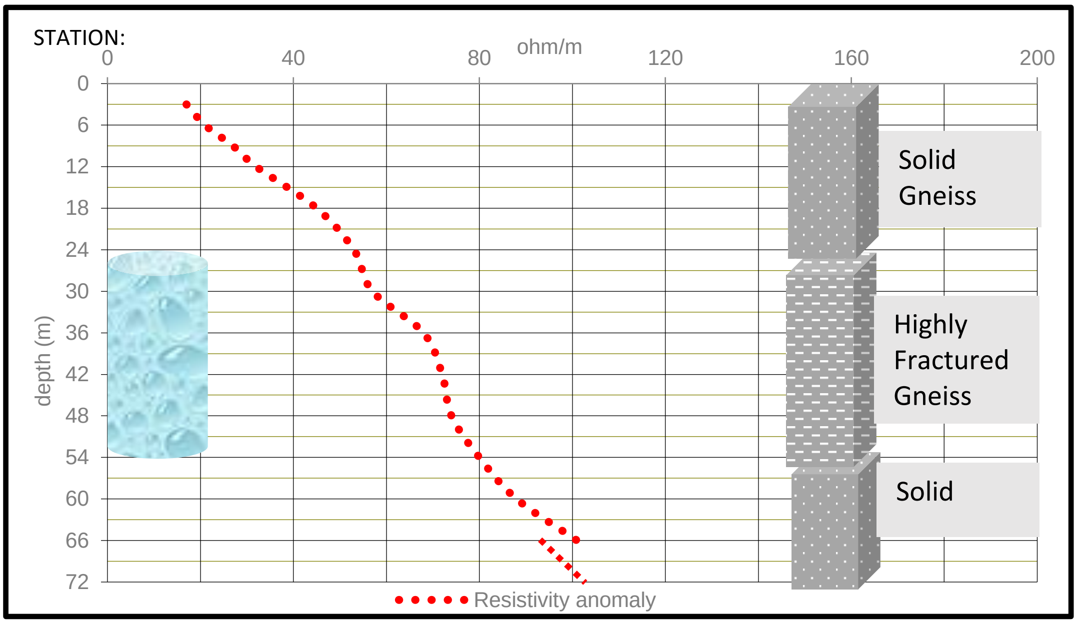
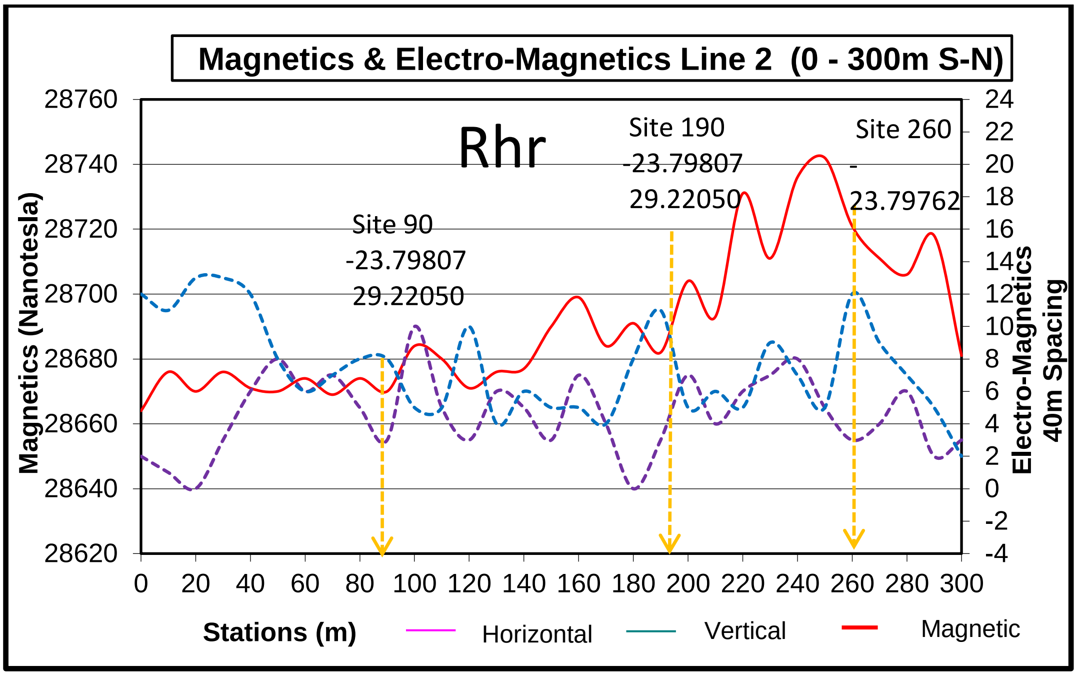
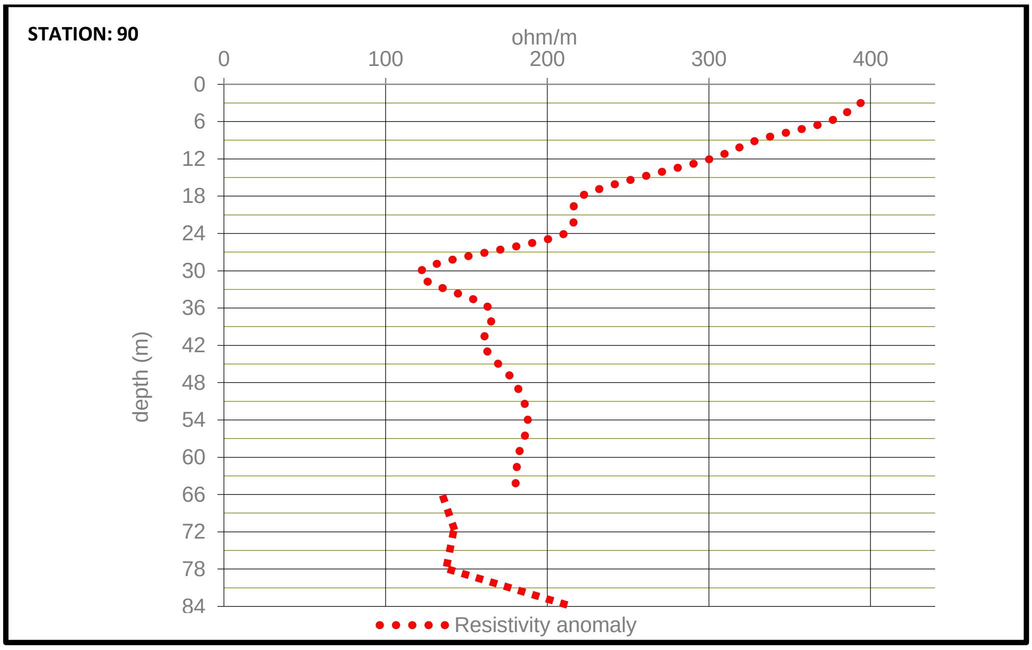
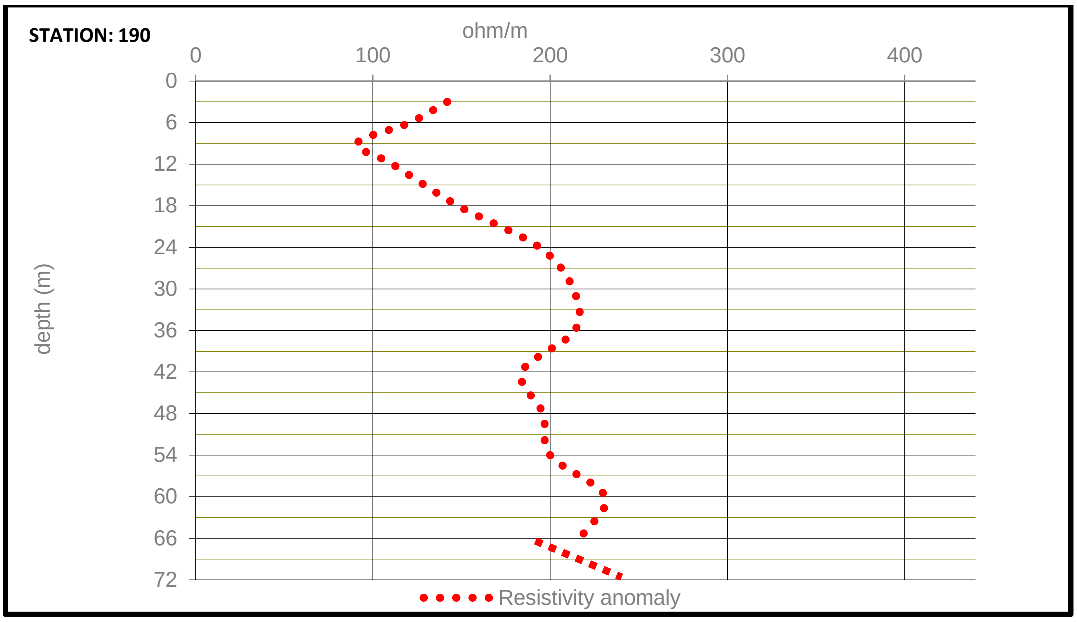


Figure 5.8 a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 1 (b) The corresponding vertical electrical resistivity section together with the inferred depth variation profile from electrical resistivity result.

Profile line 2 was done on the upstream of the Hout river dam at a total length of 300m as described in Figure 5.9a and b. Three main anomalous regions were identified using the magnetic profiling and electromagnetic methods (both horizontal and vertical), (Figure 5.9a). The main anomalous points that needed further investigation in terms of groundwater potential were observed at sites 90m, 190m and 260m. The vertical electrical resistivity sounding investigations on the three identified sites suggests a predominantly multiple layered variation on the nature of the underlying Hout river gneiss formation, (Figure 5.9b). The sections have a varying thickness as shown in the constricted sections, even though they all consist of an inferred weathered regolith and a fractured zone confined by the solid gneiss formation. The weathered zone and fractured region have a high groundwater bearing potential and the big, inferred thickness of these layers in line 2 makes the area potentially high groundwater yielding. The inferred fractured region thickness varies from around 20m at 190 m to over 40m at 90m thus increasing the groundwater potential of the area.







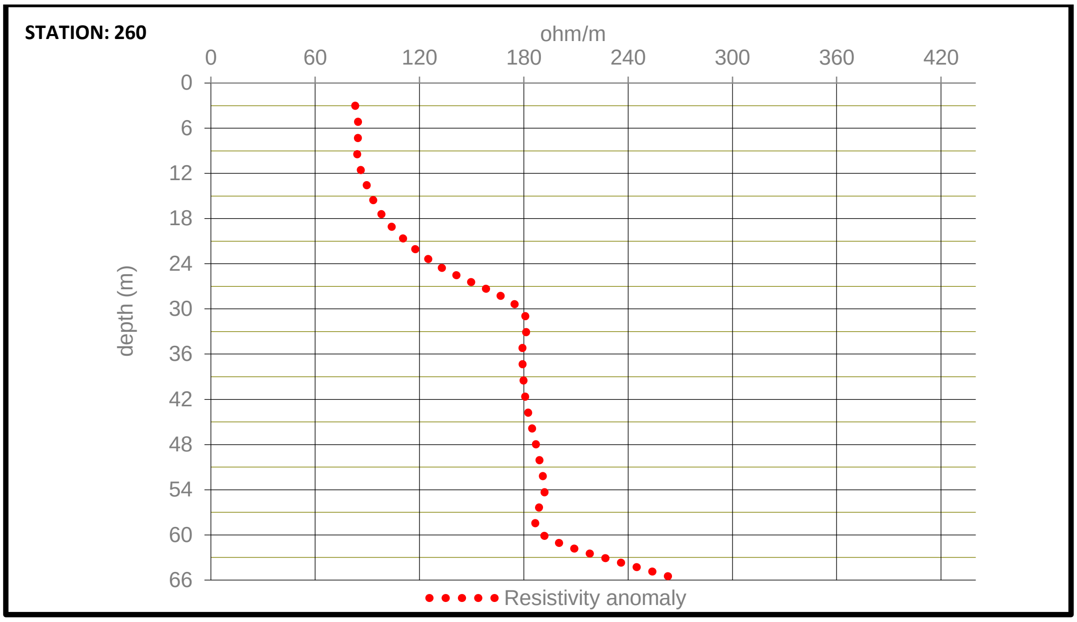
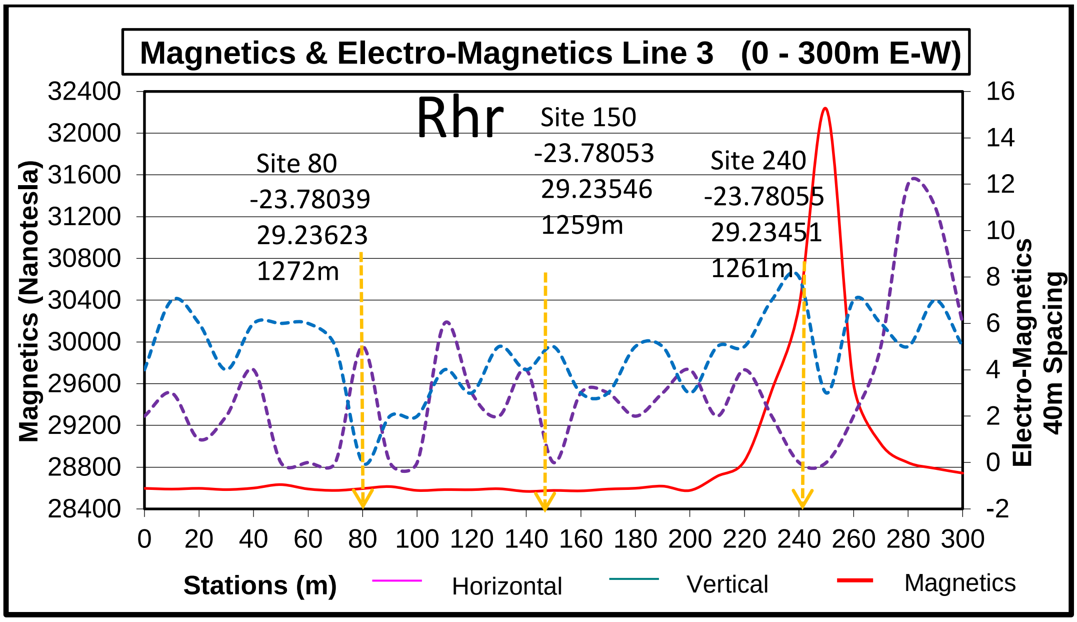


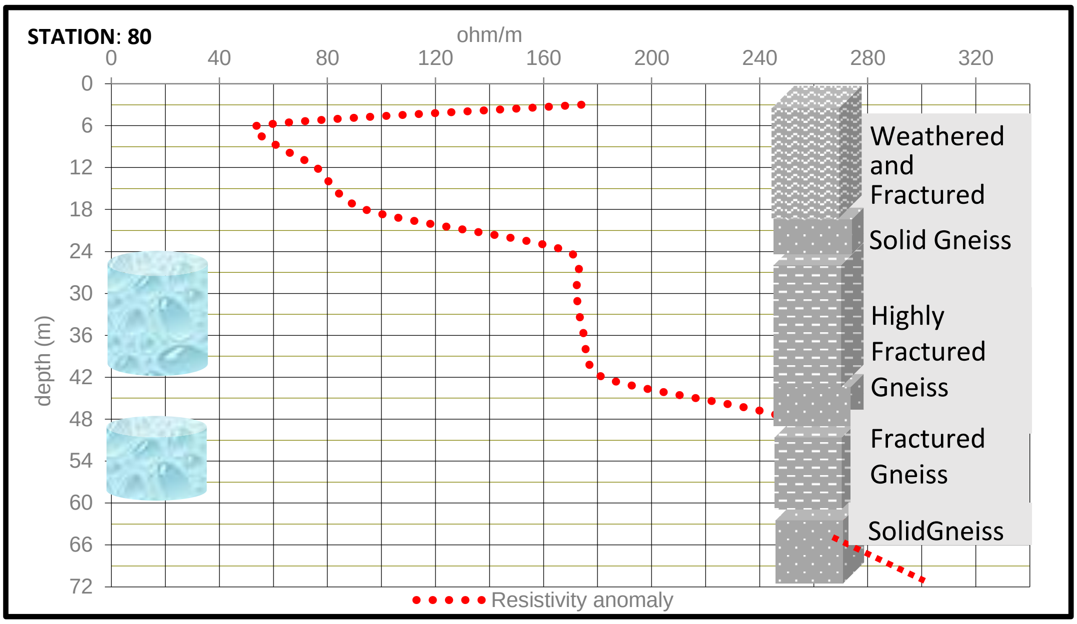
Figure 5.9 (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 2 (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from electrical resistivity results

Figure 5.10 Google earth images showing the positions for vertical sounding points for survey region 2 within the study area

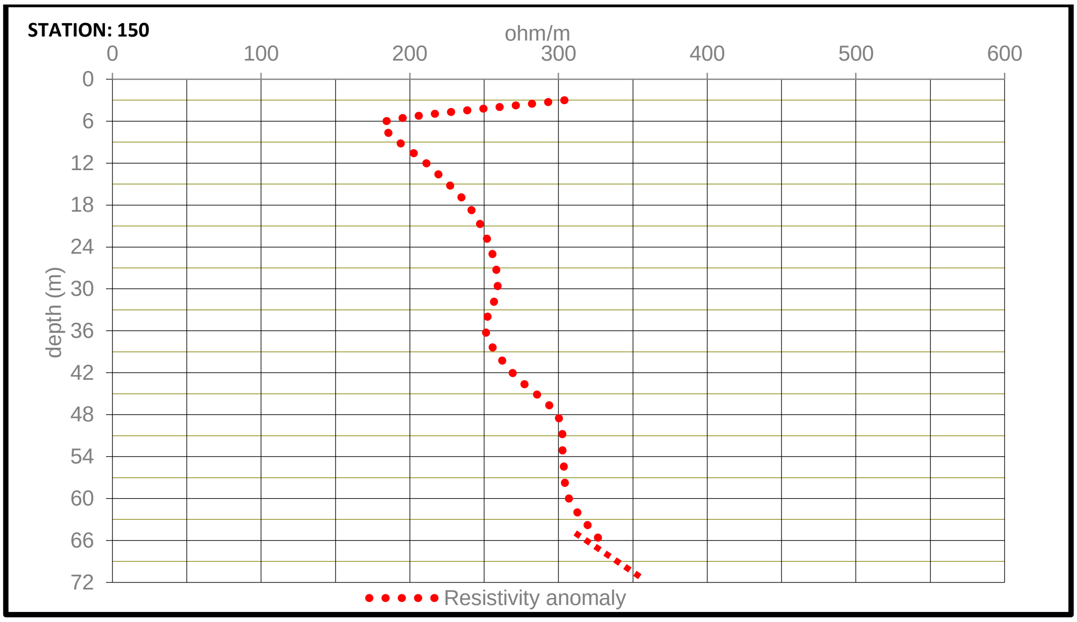
5.3.2 Region 2

Region 2 was described by profile line 3 and was done with an orientation towards the East-West direction towards the Hout river dam and lying on a lineament as indicated in the map in Figure 5.11. The total length of the line was 300m. Three major anomalous regions were picked at 80m, 150m and 240m using the magnetics and both horizontal loop and vertical loop electromagnetic methods (Figure 5.11a). The cross-sections inferred from the vertical electrical resistivity sounding suggest highly weathered zone and several fractured sections as indicated in Figure 5.11b. Multiple fractured layers being suggested from the resistivity cross sections suggest a high groundwater potential within the site





STATION: 80
ohm/m
0
40
80
120
160
200
240
280
320
0
6
12
18
24
30
36
42
48
54
60
66
72
depth (m)
Weathered and Fractured
Solid Gneiss
Highly Fractured Gneiss
Fractured Gneiss
SolidGneiss
Resistivity anomaly



STATION: 150
ohm/m
0
100
200
300
400
500
600
0
6
12
18
24
30
36
42
48
54
60
66
72
depth (m)
Resistivity anomaly

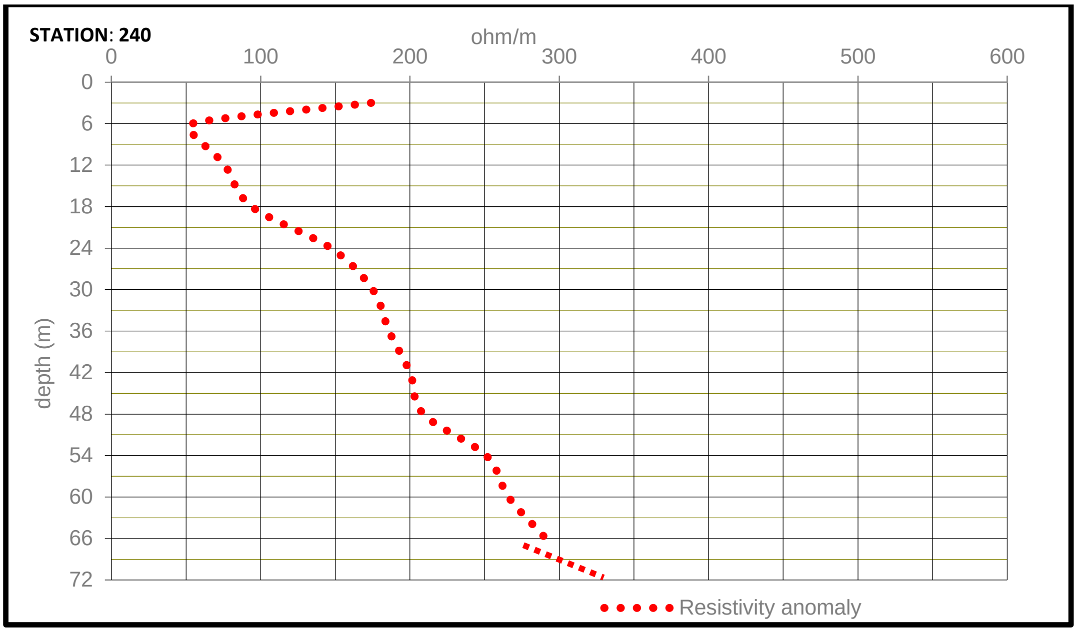
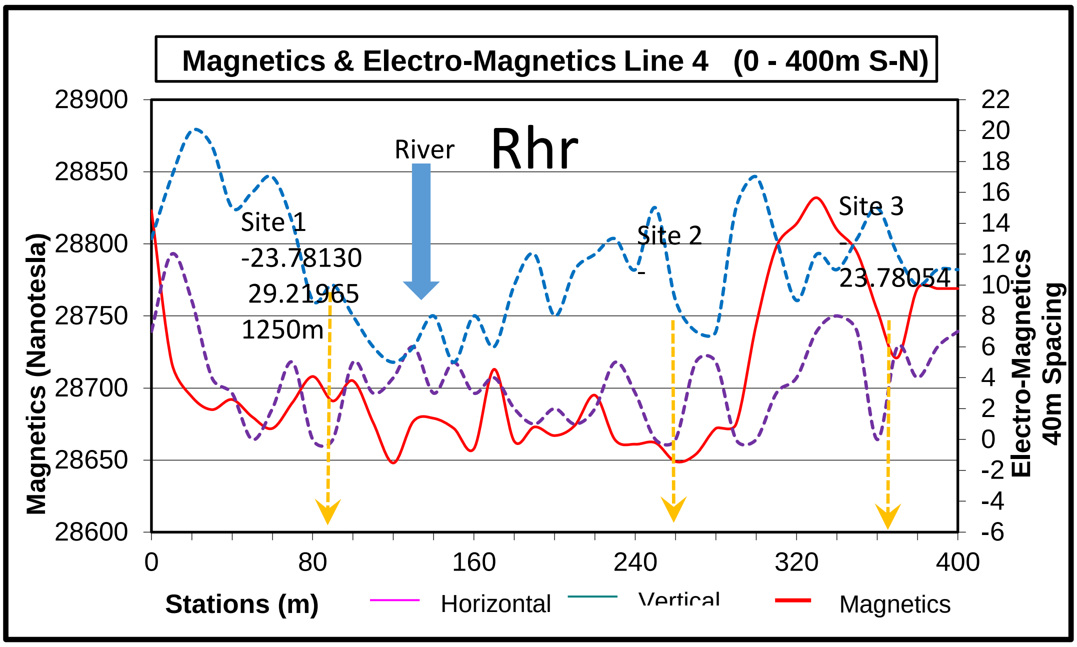


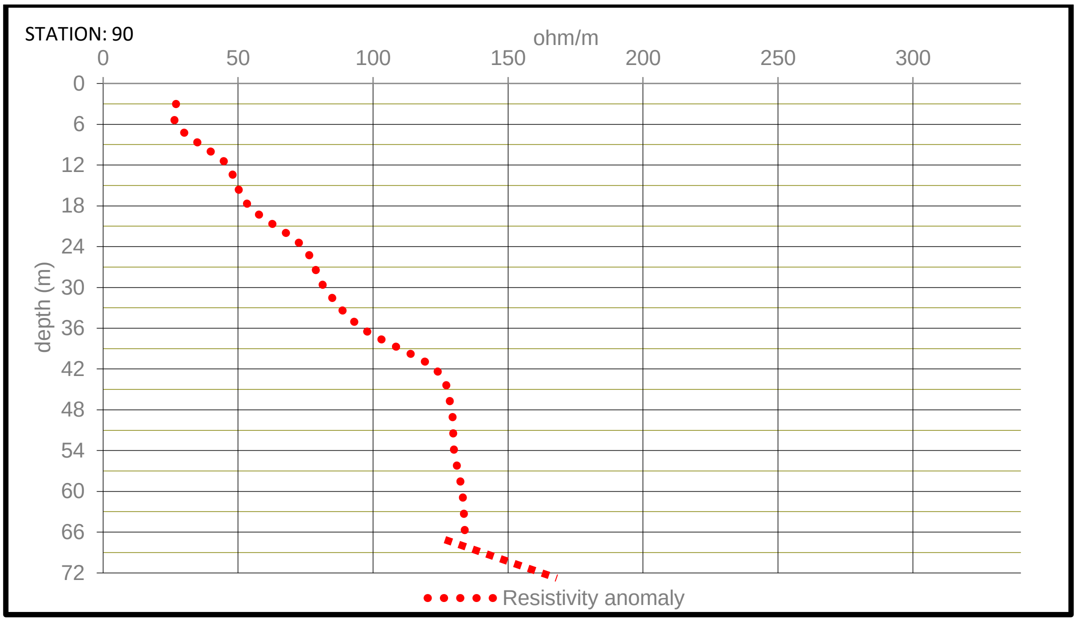
Figure 5.11 (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 3 (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from electrical resistivity results

5.3.3 Region 3

Region three comprised of profile line 4 which was done with a total length of 400 m and a North South orientation as shown in Figure. The magnetics and electromagnetic survey results showed three anomalous regions at 80m, 260m and 360m (Figure 5.13a). These were further investigated using the electrical resistivity sounding for vertical investigation on the variation of weathered and fractured regions. Results suggested a fractured region mainly in the depths from 42m to 70 m with less potential to get any groundwater strikes before this region, except on the 360m mark which has two fractured sections (18m-36m and 40m-60m) that are inferred from the results

Figure 5.12 Google earth images showing the positions for vertical sounding points for survey region 3 within the study area


Magnetics & Electro-Magnetics Line 4 (0 - 400m S-N)
Magnetics (Nanotesla)
28900
28850
28800
28750
28700
28650
28600
River
Rhr
Site 1
-23.78130
29.21965
1250m
Site 2
Site 3
23.78054
0
80
160
240
320
400
Stations (m)
Horizontal
Vertical
Magnetics
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
Electro-Magnetics
40m Spacing


STATION: 90
ohm/m
0
50
100
150
200
250
300
depth (m)
0
6
12
18
24
30
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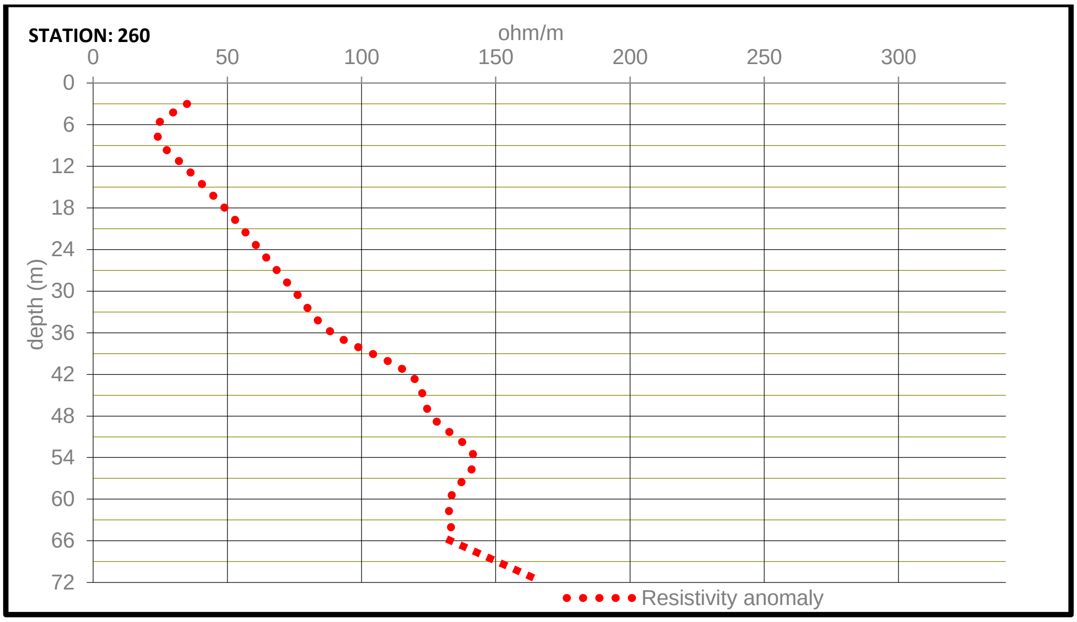
60
66
72
Resistivity anomaly



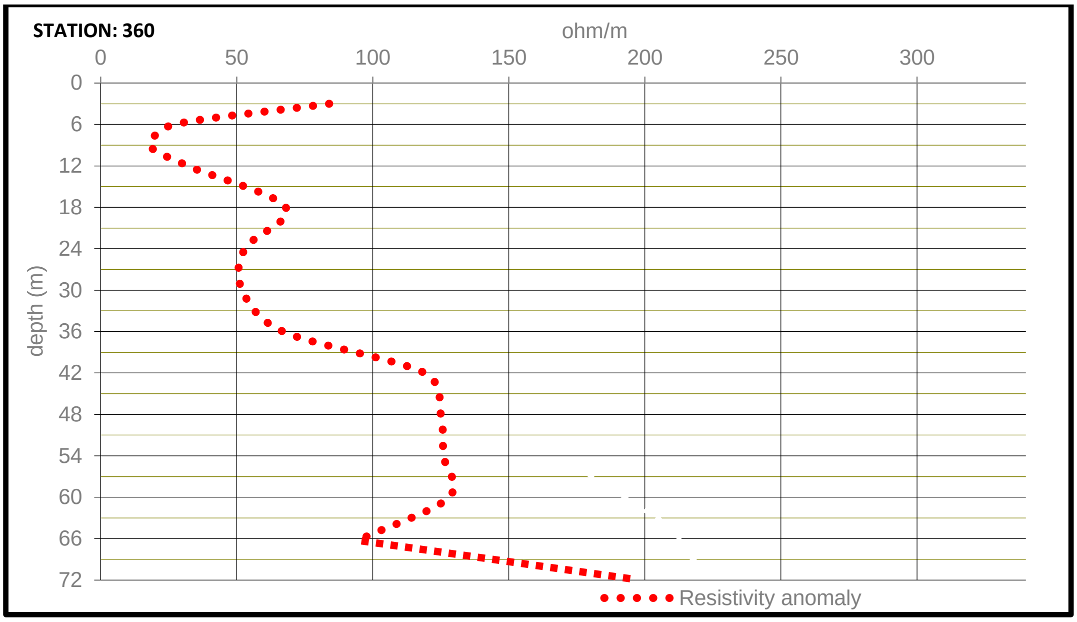


Figure 5.13 (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 4 (b) The corresponding vertical electrical resistivity sections.

In summary, the geophysical surveys and analysis provided the necessary data to identify suitable positions for the drilling of the boreholes and obtaining groundwater. It also provided preliminary information on the geological characteristic of the study site.

Chapter 6: Aquifer characterization

6.1 Introduction

The current chapter provides results on aquifer characterization of the study area and forms the second objective of the current study. Findings on the geological characteristics and the hydraulic tests of the experimental sites are provided. It also attempts to present and discuss the characteristics of groundwater flow as determined by the heterogeneities of the subsurface with the location situated upstream of the Hout catchment. Groundwater level results are also discussed in this chapter. Thus, in this study aquifer characterization was used to refer to the subsurface lithologic variations, the distribution of the aquifer geometry, hydraulic head and the aquifer hydraulic properties.

6.3 Geological characterization

Structural and geophysical approaches were applied for the better understanding of the trend of fractures and dolerite dykes which possibly play as conduits for the occurrence and flow of groundwater in the Ga-Mamadila area (Scanlon *et al.*, 2006). The elaboration of cross-section and geological conceptual model from sites 7 and 8 would rely on geophysical mapping (electromagnetic measurements and multi-electrode profiling) in the riverbed and in transects across the river provided insights for the subsurface structure in the Hout catchment within the Ga-Mamadila area.

6.3.1 Rock types

The stratigraphy in sites 7 and 8 is comprised of sedimentary and magmatic rocks. In this report, detailed mapping revealed a complex distribution of the rocks in the Ga-Mamadila area. The plutonic rocks were identified and differentiated by means of criteria such as presence of felsic or mafic xenoliths, texture, and mineralogy. Sedimentary features, such as bedding, presence of pebbles, and grains size. Sedimentary rocks in the area are made of alluvia mostly arenaceous river sand. The grains size varies between coarse-to-medium grained. The sand deposits are widespread in the Ga-Mamadila area, where they obscure the underlying rocks to such an extent that the delineation of the underlying lithologies is hidden in certain localities, thus impeding the field observations. These alluvia overlay an Archean gneissic basement composed of Hout river gneiss truncated by various fractures and dolerite dykes (Figure 6.1) trending mostly NE-SW, E-W and ENE-WSW in which mafic rocks were emplaced in sites 7 and 8. Fewer NW-SE trends of fractures and dolerite dykes were also recorded in the field. In some places, the dolerite dykes are well exposed along the river channel. The Hout river gneiss is suggested to have an intrusive origin based on xenoliths and lit-par-lit contact relationships. The Hout river gneiss is medium-to coarse-grained, with granular texture, foliated, and contains alkali feldspar, quartz, biotite, hornblende and plagioclase. The contacts with the surrounding crosscutting dolerite dykes are sharp and obscured in some places by sand deposits. The dolerite dykes are filled with fine-grained rocks, black in colour, with fractures varying in thickness from a few millimetres. The prominent northeast-southwest trend of fractures is concordant with the regional northeast-southwest structural patterns in sites 7 and 8.

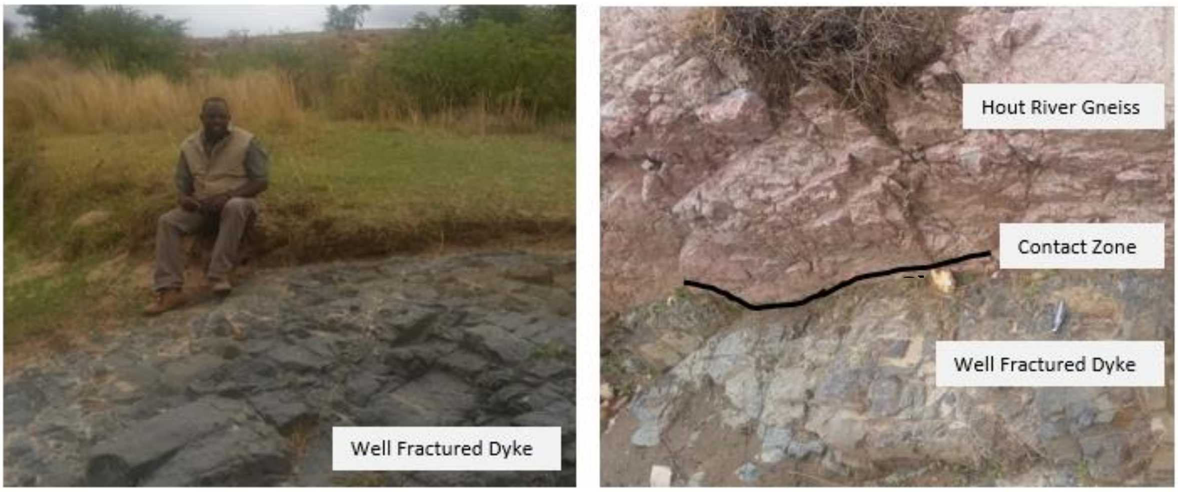


Figure 6.1 (a) Dolerite dyke in the field displaying fractures trending NE-SW and covered by alluvium in some places. (b) Outcrop of Hout river gneiss well truncated by dolerite dyke and displaying sharp contact.

6.3.2 Cross-sections

Cross-sections were produced from sites 7 and 8 in Ga-Mamadila area using Photoshop (Figure 6.2). The geology from each site is illustrated reflecting the trends of fractures and dolerite dykes in the sub-surface. The fractures are either parallel or crosscutting the dolerite dyke.

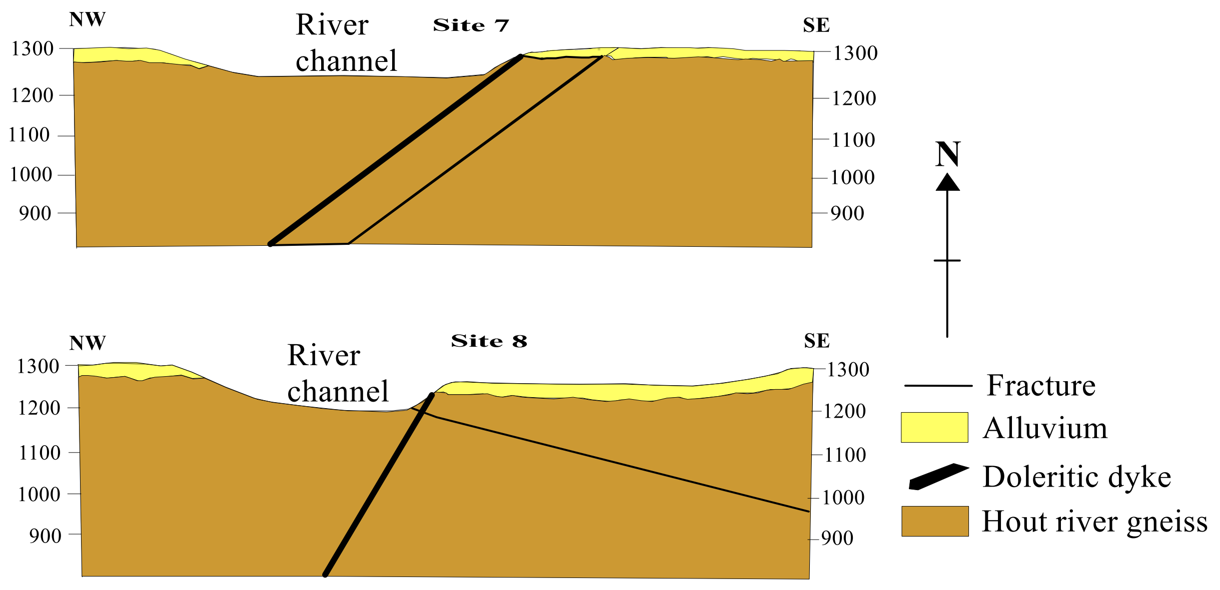


Figure 6.2 a) Cross-section showing parallel trend between fracture and dolerite dyke from site 7 in Ga-Mamadila. b) Cross-section displaying cross-cutting fracture and dolerite dyke from site 8 in Ga-Mamadila.

6.3 Borehole drilling and lithological characterisation

A total of four boreholes were drilled on the Ga-Mamadila site following the geophysical survey. This was due to the low distribution of active monitoring sites in the study area. The boreholes were also drilled within close proximity to assumed geological structures that may influence high blow yields.

The drilling method used was the air rotary percussion method. Blow yields were measured as each borehole was drilled in an attempt to drill into layers that provide high borehole productivity prior to pumping tests, a summary of the criteria is provided in Table 3. The four boreholes were named according to an index used by the DWS in order to maintain consistency with existing boreholes in the study area.

Table 3 Information summary of boreholes drilled at the Ga-Mamadila site

Number	Depth (m)	Blow yield(l/s)	Summary
HO43125	60	0.34	Drilled into the shallow alluvial layer and shallow weathered regolith of the aquifer underlain by a solid diabase dyke
HO43126	84	5	Cutting across different bands of solid Hout river gneiss and highly weathered and potentially water bearing weathered pegmatite lineament
HO43127	120	5.6	Cutting through a highly fractured pegmatite layers and weathered diabase dyke
HO43128	48	8.4	Cutting through highly fractured pegmatite layers and at the edge of a diabase dyke

Sampling of the drill chippings were collected at meter intervals for the description of lithostratigraphic layers. The boreholes on the Ga-Mamadila site, which are situated along the Hout river consists mainly of quarzitic-gneissic rocks whose properties range between weathered and coarse-grained units. The following lithological logs are described below.

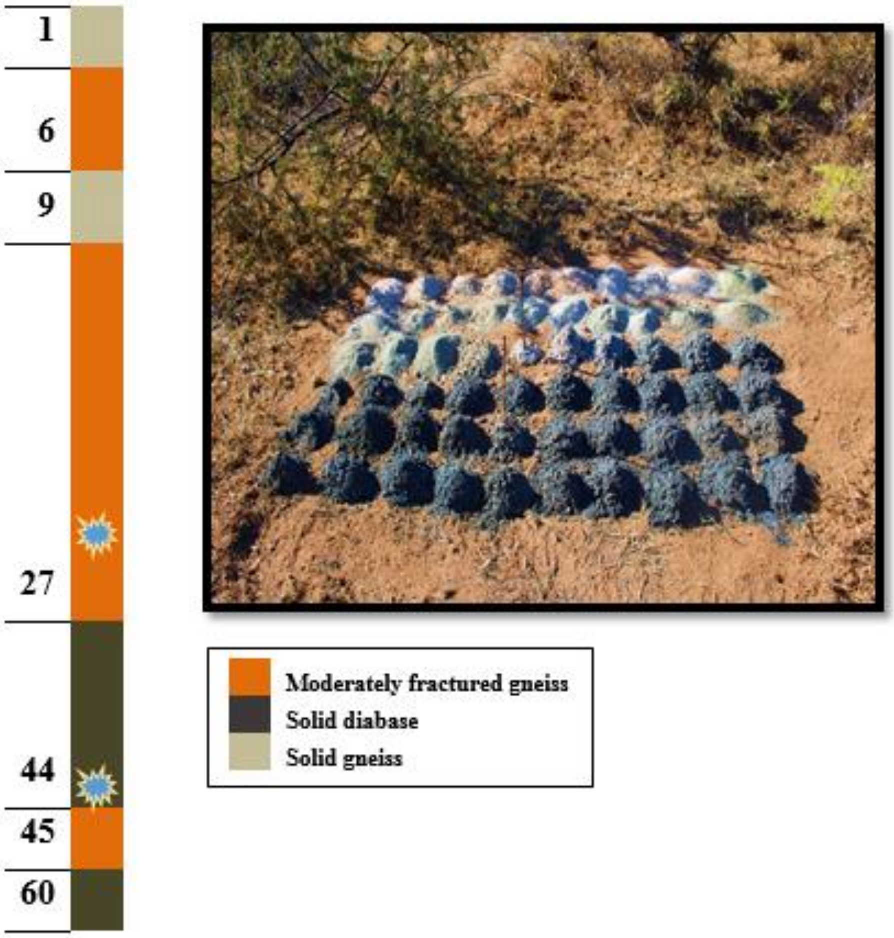


Figure 6.3 Well profile and sample images for borehole HO4-3125

Lithological analysis of borehole HO4-3125 showed that the drill penetrated through various layers of gneissic rock that displayed different states of weathering. The first 9 m displayed instances of solid and fractured gneiss. This was followed by a layer of Mica-rich gneiss at 10 m for roughly a meter. Layers of weathered and solid gneiss were then penetrated up until 24 m where the material changed to fractured gneiss. The fractured layer occurred up to 27 m where it changed to a layer of solid diabase. The diabase layer extends to 44 m before the drill bit penetrated into a 1 m layer of fractured gneiss before returning to a diabase layer that extended a further 5 m, drilling stopped at 60m. Water strikes were observed at 25m and 45m.A final blow yield was measured to be 0.3l/s.

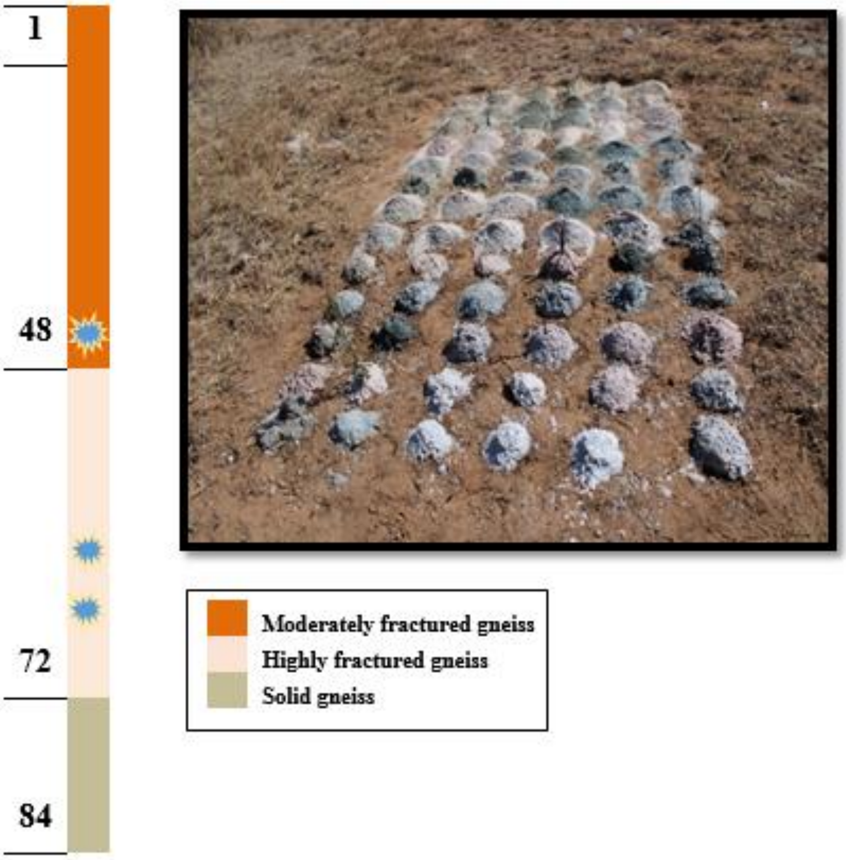


Figure 6.4 Well profile and sample images for borehole HO4-3126

At borehole HO4-3126, fractured gneiss occurred from the surface to a depth of around 48 m, this is then followed by a highly fractured pegmatite layer that extends for 24 m before it changes to solid gneiss. Three water strikes were observed during drilling: 48 m, 65m and 69m with a final blow yield of 5 l/s.

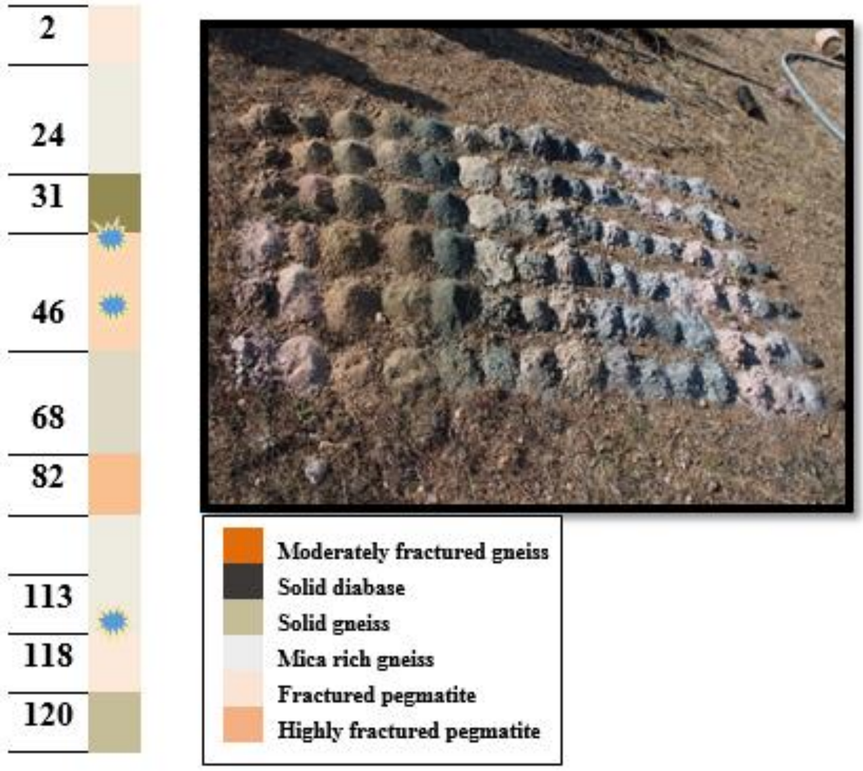


Figure 6.5 Well profile and sample images for borehole HO4-3127

Figure 41 displays borehole HO4-3127 which shows the first 2m to be comprised of fractured pegmatite. Alternating layers of gneissic and pegmatite rocks occurred within the unit. This is then followed by 24m of mica rich gneiss before a water strike is exhibited at 33m. Thereafter, two more water strikes occurred at 43m and 114m. A final blow yield of 5.5l/s was encountered.

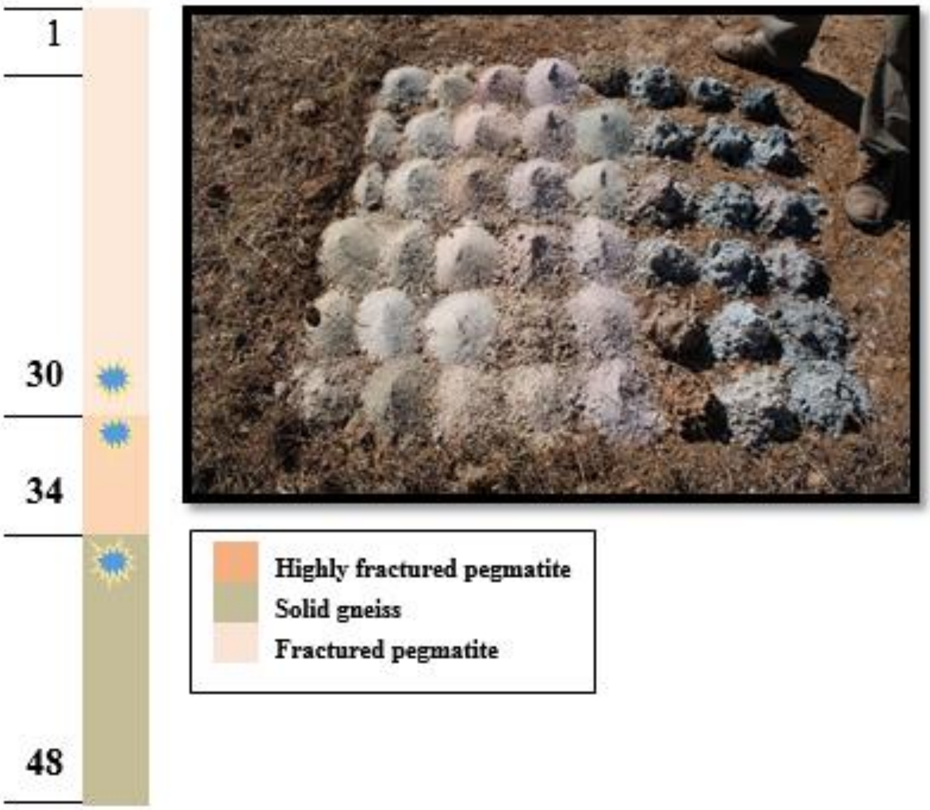


Figure 6.6 well profile and sample images for borehole HO4-3128

The first 30m of borehole HO4-3128 were characterised by predominantly fractured pegmatite rocks. Highly fractured pegmatite was found below the predominantly fractured pegmatite just before two water strikes at 30m and 32m. This was then followed by a final water strike at 37m. The final blow yield of 8.4l/s was measured. Lastly, solid gneiss was observed from approximately between 35-48m.

The lithography on the experimental site is mainly made of highly fractured pegmatite, dolerite dykes and Hout river gneiss. The size of the grains varies from fine to coarse grained in these lithologies, with an expected high porosity and permeability parameters that can impact on water retention. This highlights the connectivity between the surface water and groundwater through the fractures and dykes observed in the field. It is substantial to mention that no clay lithology was identified during field mapping in sites 7 and 8, as being known for their high capacity in water retention. The results obtained by combining the geophysical and structural techniques in sites 7 and 8 in Ga-Mamadila allowed to trace the dolerite dykes and fractures not exposed and determined the depth of fracturing by electrical resistivity probing. The electrical resistivity investigation also highlighted that the probability of striking groundwater is between 22 m and 41 m below surface in the Hout river, a trend which can be seen in the water strikes that were exhibited during the drilling exercise. Among the five electrical resistivity prospects done, three are consistent with striking the water between the above given depth. While two others are not suitable targets for drilling. Dolerite dykes and their contact zones respectively can also be targeted if fractured and weathered till to the groundwater level.

6.3 Pumping Test Results

Due to the difficulty that comes with the identification of a single representative theoretical model in Crystalline Basement Aquifers', results from the pumping tests were visually compared to a set of typical diagnostic plots as discussed in chapter 3. This was done to deduce which model is best fitted to the observed results with regards to properties such as transmissivity (T) and storativity (S) values. Theses hydraulic properties facilitate the movement and storage of groundwater. In this study, step-down and constant rate pumping tests were performed on two boreholes; HO4-3126 and HO4-3127 as these were the deeper boreholes on the site. The tests were analysed as multi-tests with either one of the boreholes as a pumping well while other boreholes acted as observation wells. Recovery tests were then performed to establish the aquifer response in a natural state; however, this is also essential as it accounts for disturbances such as turbulence to the water during the pumping test.

6.3.1 Borehole H04-3126

A step-down test was performed to determine a sustainable yield for the constant rate test that was to follow. The stepdown test was carried out in four phases of increasing discharge: 2.5 l/s, 4.2 l/s, 6.2 l/s and 8.1 l/s. The rates were used until an available drawdown was achieved.

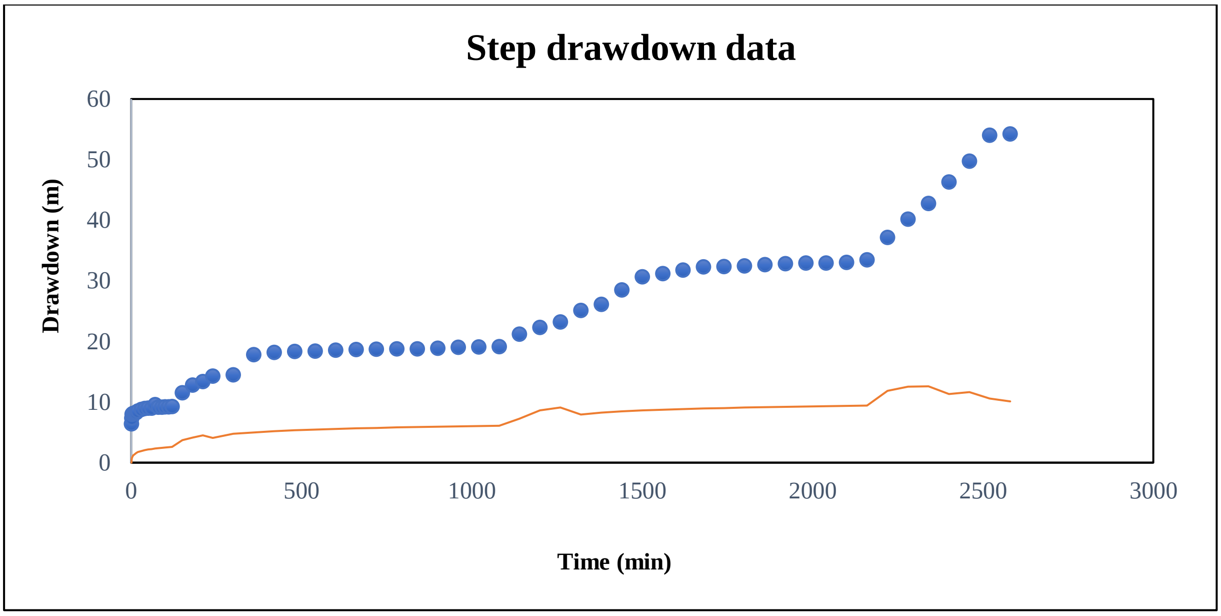


Figure 6.7 step-down test results of borehole H04-3126

Based on the step-test data, a T-value of 36 m^2/d was determined using the Birsoy- Summers method. The static water level (SWL) prior to the pumping test of H04-3126 was measured to be 10.38m below natural ground level. The constant discharge test was done with a pumping rate of 4.2 l/s for a period of 48hrs; the results are shown in Figure 6.8 below.

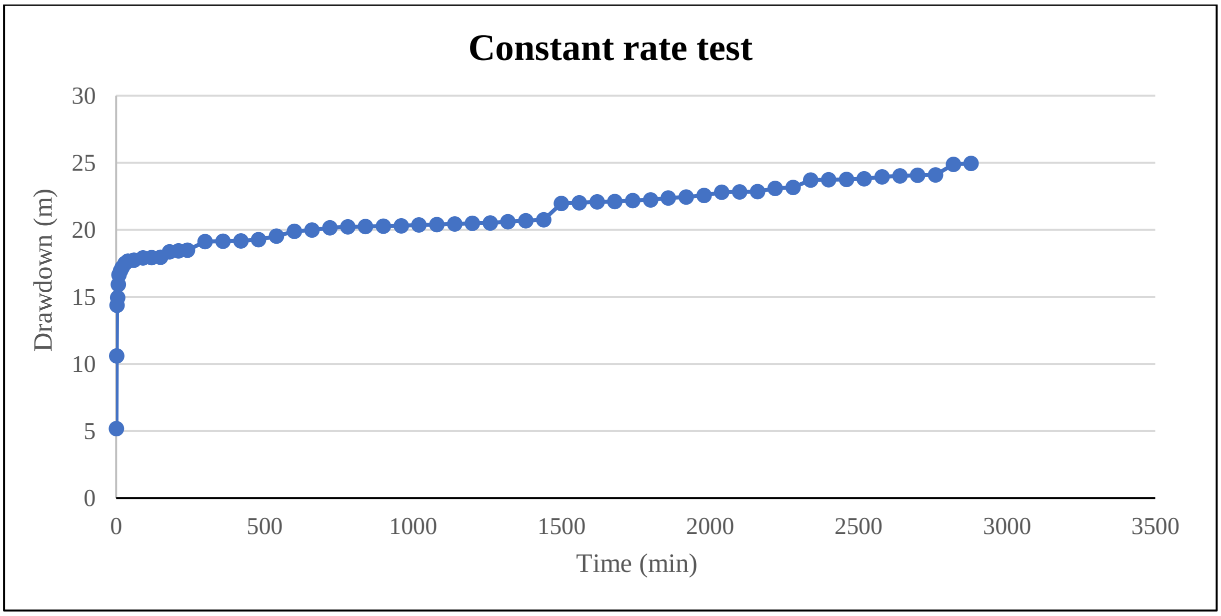


Figure 6.8 Constant rate test results of borehole H04-3126

For this borehole, the transmissivity was determined as 44 m^2/d according to the Cooper-Jacob and Theis approximations. These functions are incorporated in the FC Programme where drawdown is plotted against time in minutes on a semi-log plot (Figure 6.9)

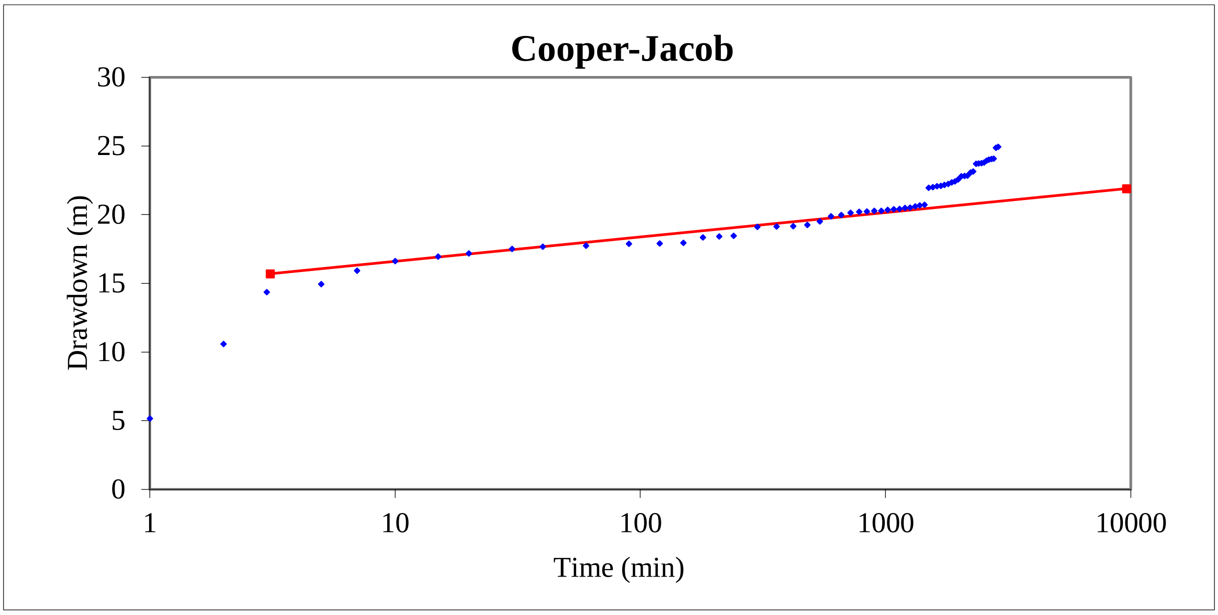


Figure 6.9 Cooper-Jacob fitting results of borehole H04-3126

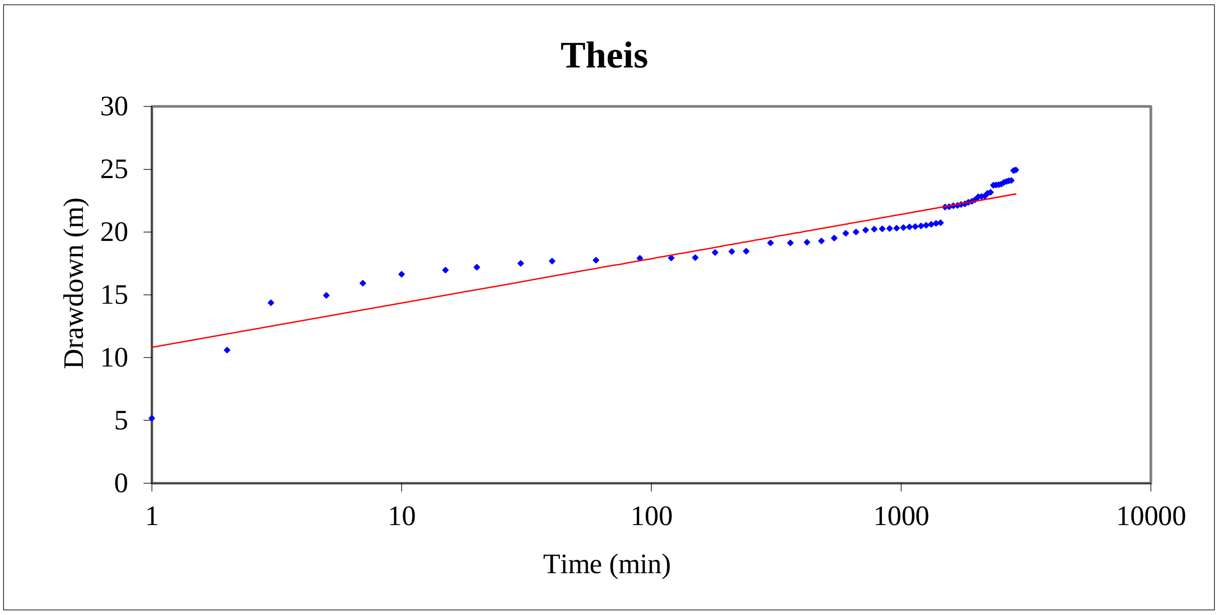


Figure 6.10 Theis fitting results of borehole H04-3126

Based on these two approximation methods, transmissivities (T) of 37,4m^2/d (Cooper-Jacob) and 50 m^2/d (Theis) were calculated, respectively. The T-value from the Cooper-Jacob method represents late-time data. In the Theis method, the storativity (S) was estimated to be ~$1x10^{-5}$ by means of graph fitting.

6.3.2 Borehole H04-3127

The stepdown test was carried out in four phases of increasing discharge: 2.5 l/s, 4.2 l/s, 6.2 l/s and 8.1 l/s. the rates were used until an available drawdown was achieved. The stepdown test was performed to determine a sustainable yield for the constant rate test to follow. The static water level (SWL) prior to the pumping test of H04-3126 was measured to be 10.38m below natural ground level. The constant discharge test was done with a pumping rate of 4.2 l/s for a period of 48hrs; the results are shown in Figure 6.11.

The constant rate test was then conducted at a rate of 5.88 L/s for a duration of 48hrs. Three observation wells: HO4-3128 (84.26m away), HO4-3126 (194.70m away) and HO4-3125 (204.61m away) were monitored during the pump test. Derivative analysis and diagnostic plots are equally important as the conceptual understanding of the geological setting when interpreting pumping tests. To evaluate aquifer and flow conditions during this test linear flow plot was used (Figure 6.11). Before 25 minutes, the drawdown exhibits the typical response associated with infinite conductivity fracture in which the drawdown exhibits half unit slope. At intermediate time the is a dip in the derivative curve which suggest the effect of fracture skin (restricted block to fissure flow). At late times the drawdown data exhibits unit half slope suggesting the effects of linear flow conditions to a well in a channel strip aquifer. The changing flow regimes suggests well-connected fracture network.

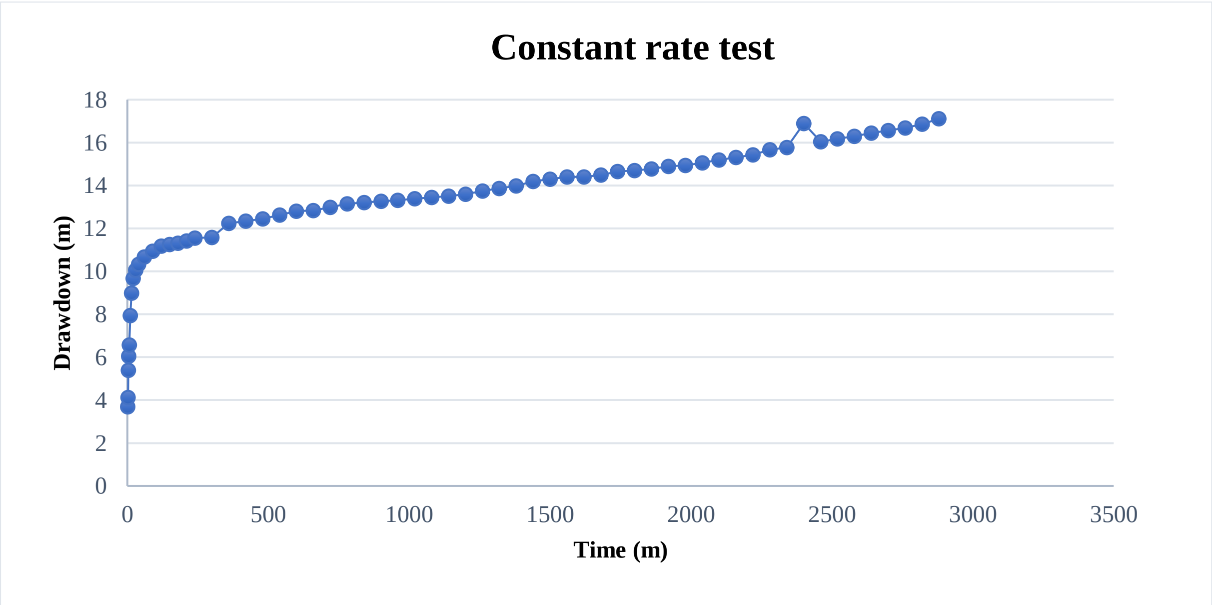


Figure 6.11 Constant rate test results of borehole H04-3127

For this borehole, the transmissivity was determined as 56.6 m²/d according to the Cooper-

Jacob approximation and 57 m^2/d for the Theis method. (Figure 6.12 and Figure 6.13).

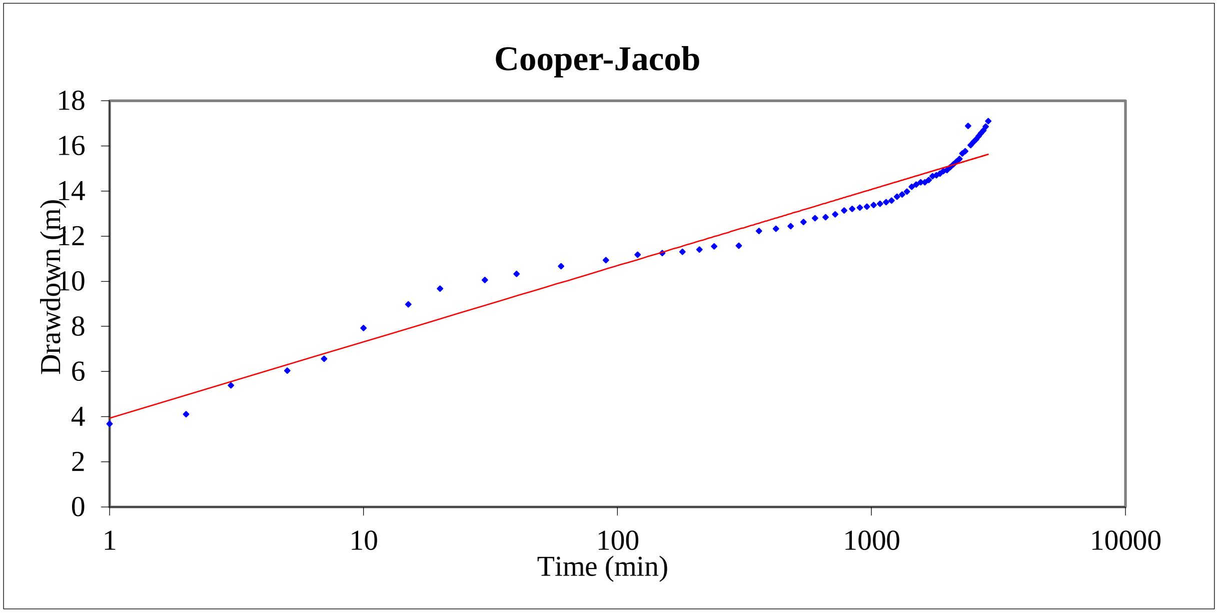


Figure 6.12 Cooper-Jacob fitting results of borehole H04-3127

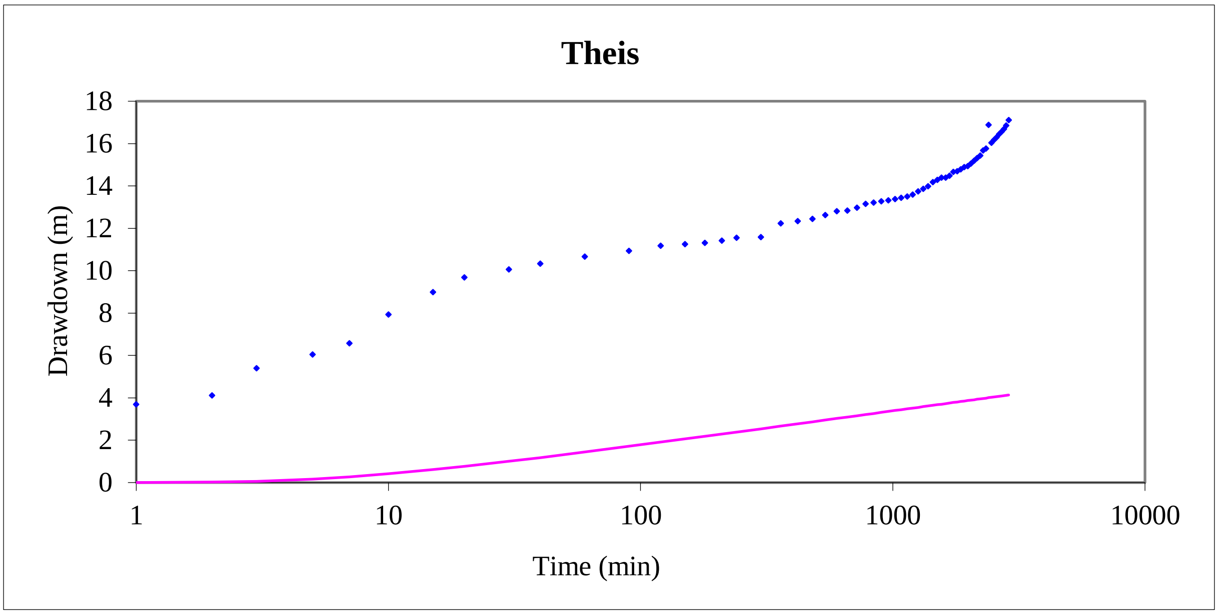


Figure 6.13 Theis fitting results of borehole H04-3127

Based on these two methods, transmissivities (T-value) of 20 m^2/d (Cooper-Jacob) and 20 m^2/d (Theis) were calculated. The T-value from the Cooper-Jacob method once again represents late-time data. In the Theis method, the storativity (S-value) was determined to be ~1.6×10^{2} by means of graph fitting.

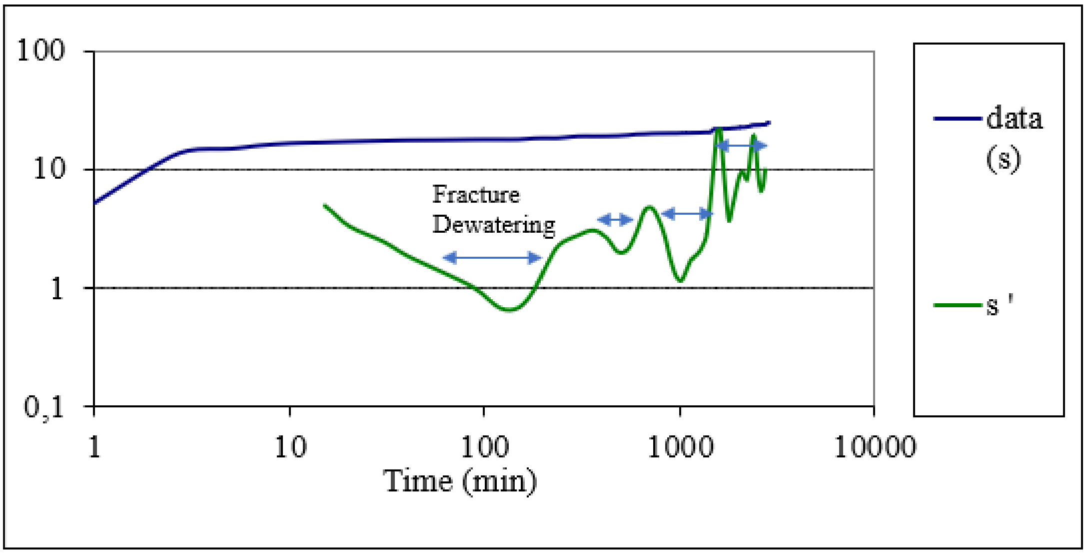


Figure 6.14 Intermediate T Scenario: derivative plots for constant discharge test, borehole H04-3126

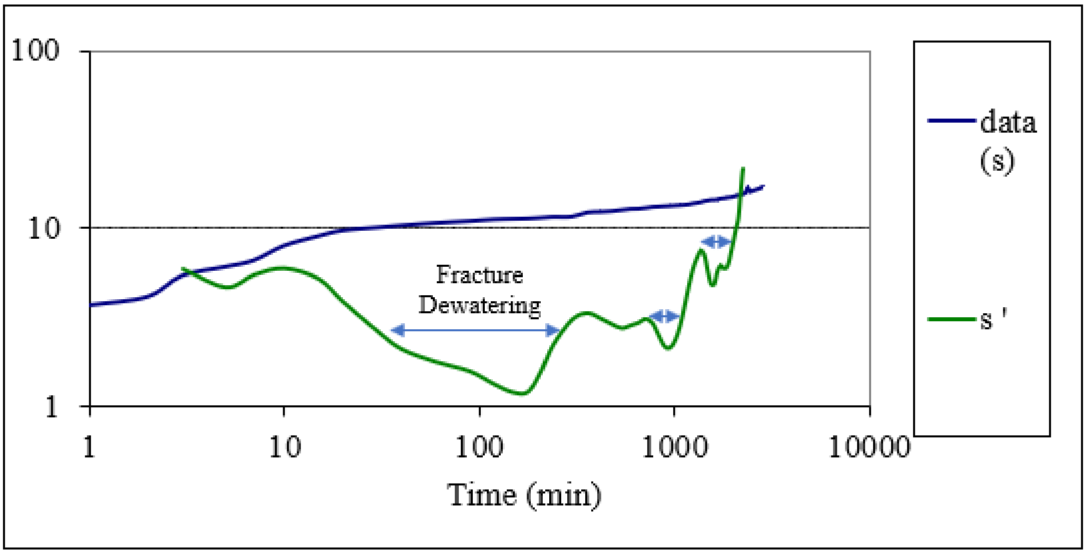


Figure 6.15 Intermediate T Scenario: derivative plots for constant discharge test, borehole H04-3127

Groundwater in the study area exists predominantly within the fractured zone, as opposed to main pores within the rock layer and the weathered region. This is shown by the strong evidence of fracture dewatering in time-drawdown plots and the derivative plots from the pumping tested above. Analysis also suggests a strong fracture influence in by far the boreholes.

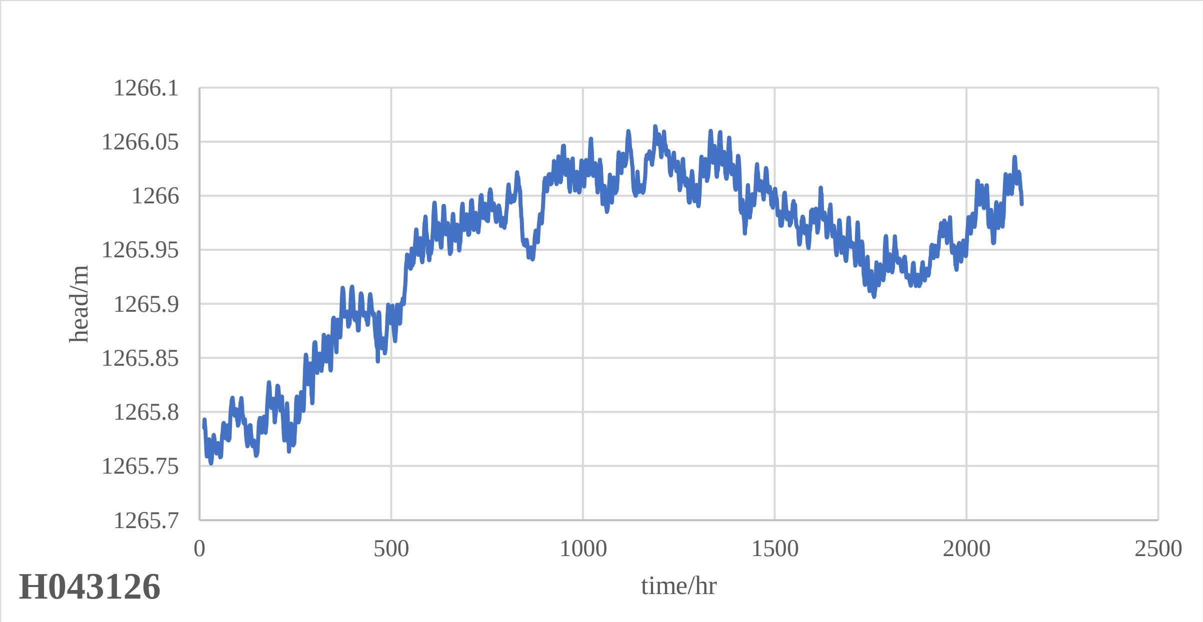
6.3 Nature and trends of groundwater levels

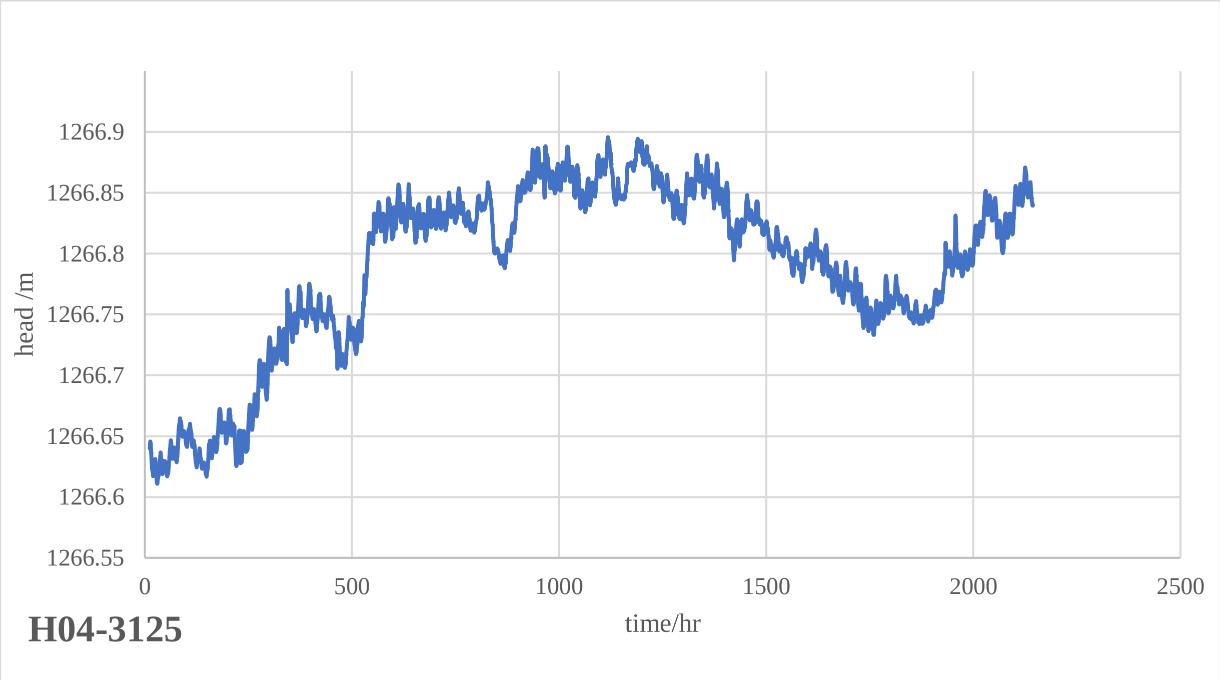
After the establishment and testing of monitoring wells, all four boreholes in the experimental site were equipped with automatic water level loggers (one for each monitoring well) and a single barologger for data compensation. The water level loggers were programmed to be able to remotely measure and store depth to water level measurements at hourly intervals. Data download and compensation was done in the Solinst software. Trend analysis of variation of hydraulic heads (converted from depth to water level as at 27 January 2020) are presented in Figure 6.16(a-d).

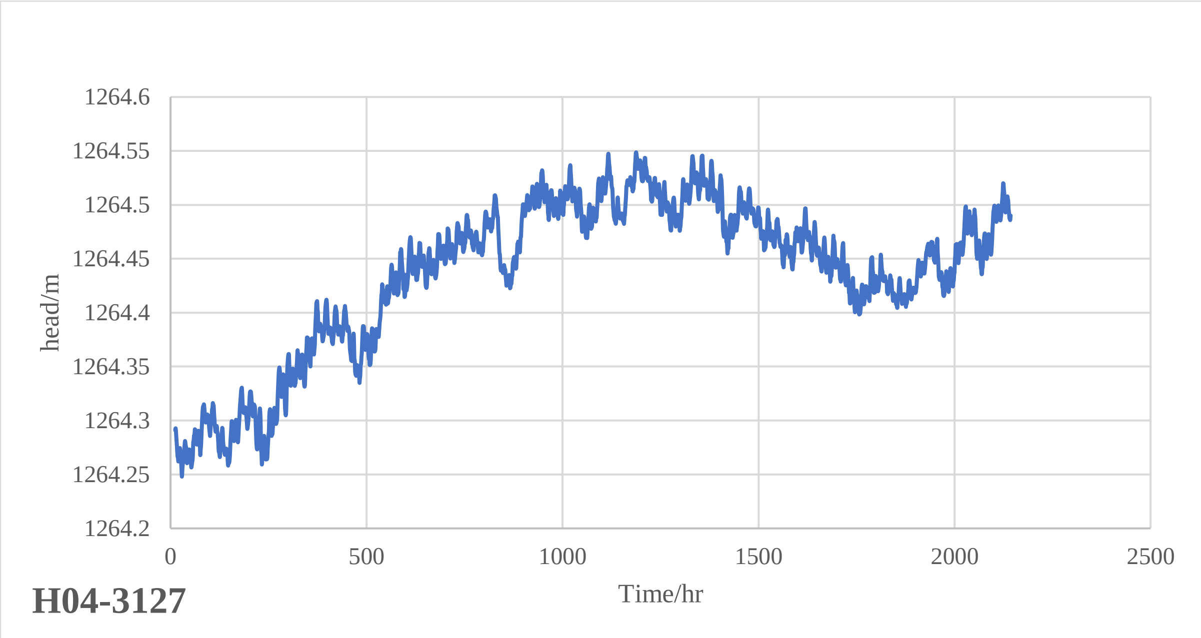
Table 4 Locality and elevations of drilled boreholes where new monitoring instrumentation was established for the ESGUSA research project

Number	X	Y	Elevation (m.a.m.s.l)
H04-3125	-23.79785	29.22157	1272
H04-3126	-23.79762	29.22096	1276
H04-3127	-23.79872	29.21987	1278
H04-3128	-23.79836	29.22057	1275

The Time series hourly data for the Ga-Mamadila experimental site from 30/10/2019 – 27/01/2020


1266.1
1266.05
1266
1265.95
1265.9
1265.85
1265.8
1265.75
1265.7
head/m
0
500
1000
1500
2000
2500
time/hr
H043126


1266.9
1266.85
1266.8
1266.75
1266.7
1266.65
1266.6
1266.55
head /m
0
500
1000
1500
2000
2500
time/hr
H04-3125



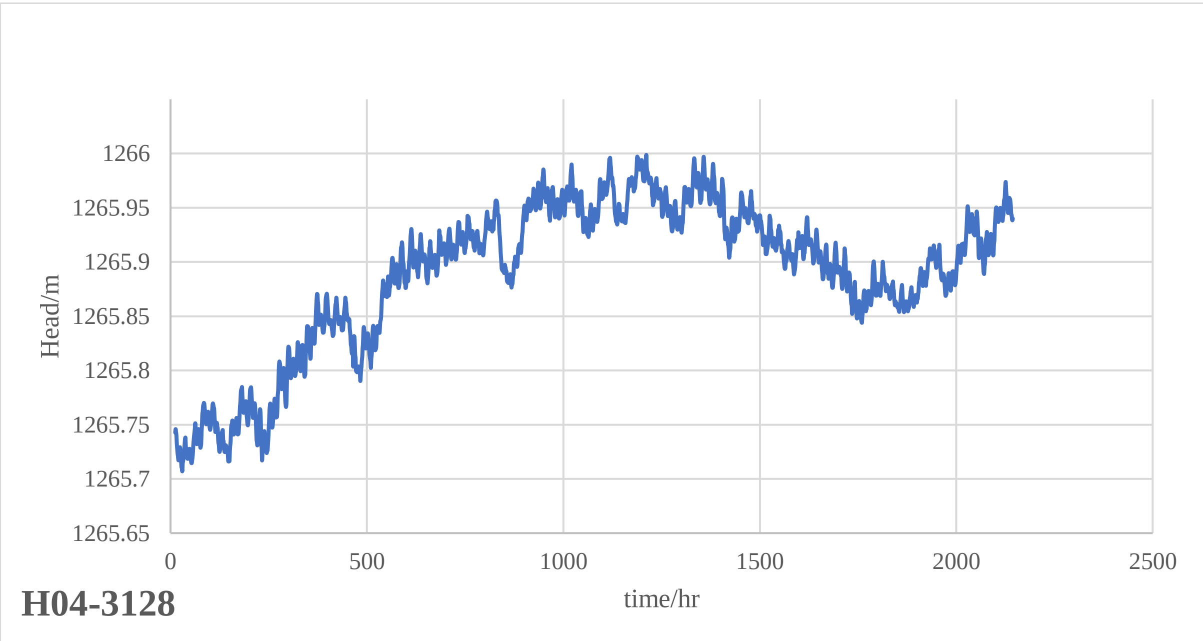


Figure 6.17 (a-d). Time series variation of hydraulic heads with time from 31 October 2019 to 27 January 2020

Groundwater level data from the four boreholes was added to water level data from 77 boreholes obtained from the GRIP database. This data was used to construct a groundwater contour map of the catchment. The local groundwater flow direction map of the catchment displays a general trend of groundwater levels which transition between elevated groundwater levels along positive magnetic anomalies to lower groundwater levels in areas with negative groundwater anomalies. Locations which display trends in response to positive magnetic anomalies seem to represent boreholes with high groundwater levels. High hydraulic heads are also linked to the topography within the study area. Structures with positive magnetic anomalies have created ridges trending NE where regional groundwater flow seems to be following this pattern; after flowing from areas with a slightly higher topography and areas associated with positive magnetic anomalies. Regional groundwater occurrence and flow is assumed to occur parallel to positive magnetic ridges (Figure 6.17). Generally, groundwater levels are higher where structures are densely concentrated and deeper in areas with less structural concentrations. The patterns observed here most likely indicate situations where the presence of lineaments and dykes are acting act as preferential pathways for the movement of groundwater.

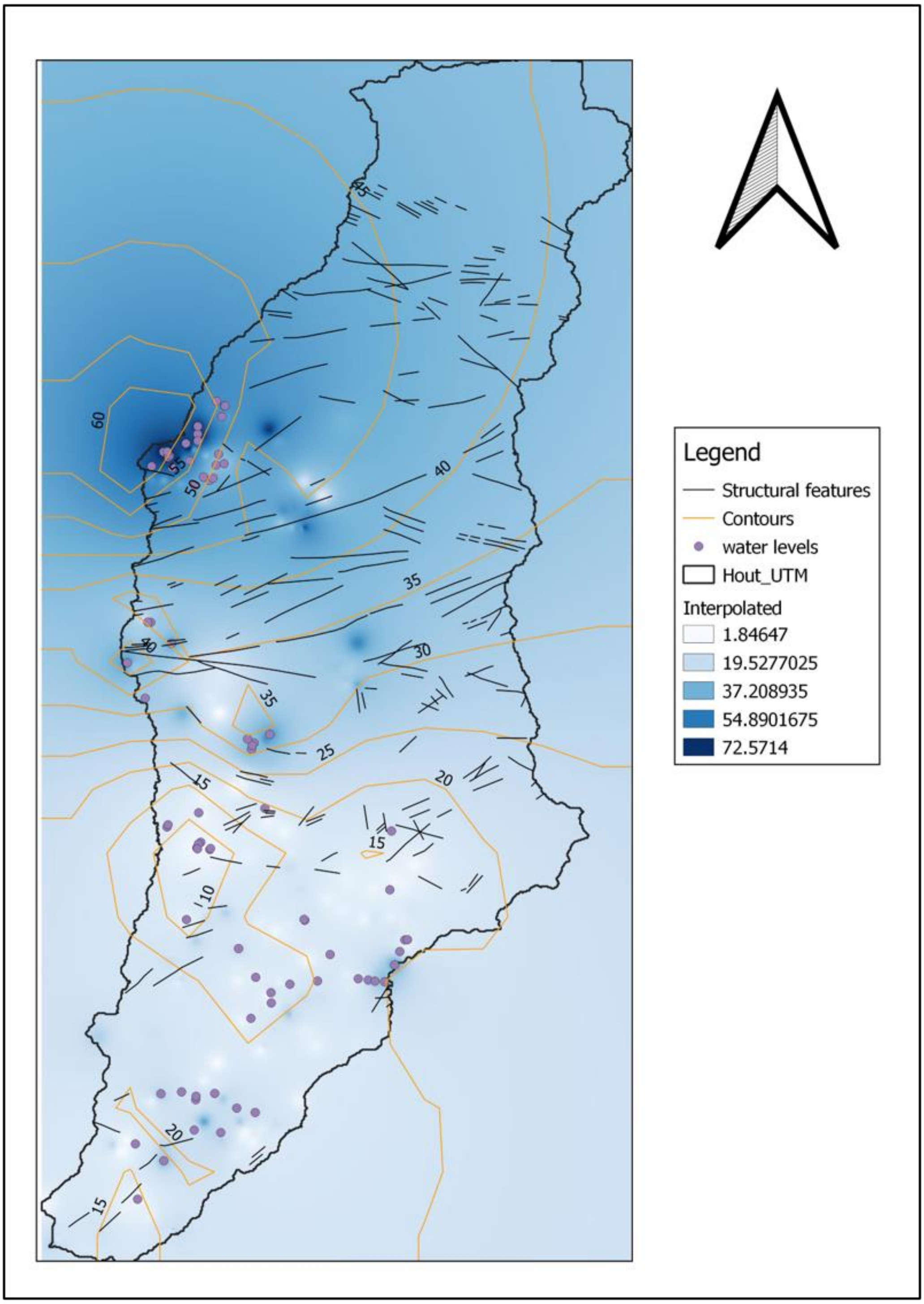


Figure 6.18 Groundwater level patterns in the Hout catchment.

Groundwater level analyses in the study area have shown that boreholes with shallower groundwater elevations are related to high magnetic anomalies coinciding with granite batholith, Soutpansberg rocks and high dense structure concentrations like the HRSZ in the structural map as compared to areas with less structural concentrations and low magnetic anomalies. These areas have groundwater levels of less than 15 m.b.g.l. Boreholes with deeper groundwater levels seems to coincide with areas showing low magnetic anomalies. It is apparent from the structural and geophysical maps that major structural direction trends are NE-SW and less towards NW-SE, which coincide with what was previously described by Holland (2011). The general trend of groundwater based on the contour maps shows that groundwater is moving from north, southwestern and north-western part of the catchment towards the southern and south-eastern part of the catchment. This groundwater flow has variable patterns with high groundwater levels associated with positive magnetic anomaly areas and moving towards areas of lower magnetic signatures.

Chapter 7: Conceptualization of groundwater flow system

7.1 Introduction

This chapter integrates different hydrogeological data to create a hydrogeological conceptual model for the study area. Geology, hydrogeology, groundwater flow and hydrology data were used to construct the conceptual model. The conceptual model provides information on how groundwater flows within the aquifer system. In the current chapter, hypotheses on the dominant groundwater flow paths which govern the extent of water interchange between the aquifer and the river were tested with relevant data analyses. The conceptual model forms the aim of this study thereby assessing the influence of fracture connectivity in crystalline basement aquifer systems.

7.2 Groundwater flow conceptual model

A conceptual illustration of the aquifer systems found in the experimental area is provided in Figure 7.1**.** The aquifer systems developed in the Hout catchment are characterized by a variable thickness of regolith overlying bedrock, the upper part of which is frequently fractured. The catchment also displays the presence of deep fractured aquifers; composed mainly of crystalline material (i.e., igneous, and metamorphic rocks) characterised by an intact and relatively unweathered matrix with a complex arrangement of interconnected fracture systems. The alluvial material overlies or replaces the weathered overburden and creates a distinct intergranular aquifer type. These elongated aquifers follow rivers (so- called valley trains), sand rivers or drainage lines with limited width and depth, which typically vary according to the topography and climate (Holland and Witthüser, 2011).

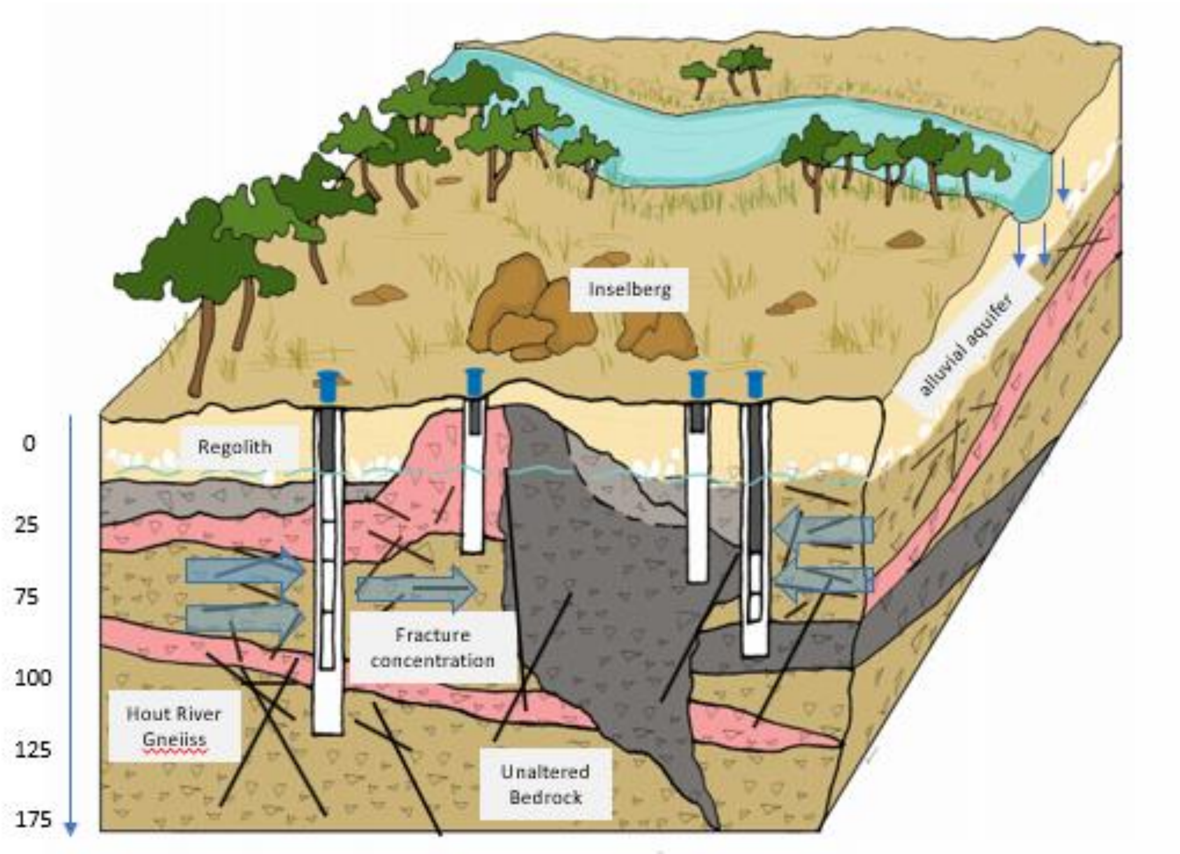


Figure 7.1 Hydrogeological conceptual model of Ga-Mamadila experimental site

A previous study that aimed to understand the correlation between the presence of structural features such as dykes and lineaments with borehole productivity showed that high mean transmissivities are associated to the presence of dykes that are orientated NE, ENE and WN and lower transmissivity in the NW and NNE trending dykes (Holland, 2011). This implies that dykes that are orientated perpendicular to the neo-tectonic principal horizontal stresses allow for the flow of groundwater as opposed to those that occur parallel to the stresses. This is evidenced by the high degree of fracturing of these dykes observed during field observations and groundwater contour maps that shows general groundwater flow along channels parallel to the NE and WNW structures. However, it is difficult to deduce which dykes and structural features act as barriers or conduits within the catchment as the research was not able to conduct a detailed study on the thickness and degree of fracturing in detail.

7.3 Conclusion and recommendations

Constant rate pumping tests were conducted in three sites across the catchment, two sites in the upstream area and one site in downstream area. The purpose of the tests was to estimate the aquifer parameters which influences groundwater flow system. Results show that the study area is characterised by high transmissivity (T) values. Secondary porosity is dominant in the study area, as such the occurrence and movement of groundwater is largely controlled by the extent of fractures. From the drilling, pumping tests and electrical conductivity borehole logging it is found that there is a significant occurrence of fractures in the area which signifies the prospect of groundwater flow that is facilitated through fracture connectivity.

Different aspects involved in fracture characterisation were presented in the present study, with special focus on fracture connectivity in the study area. Valuable information on the kinds of fractures that tend to form in the different geological settings of the Hout catchment and their commonly associated patterns were documented from desktop and field investigations. This information is key and should help in decision making when connected fractures identified, located, and quantitatively evaluated (geometry, flow, and transport).

While a fractures geological and physical characters describe the geometry of the fracture, its location, and its general physical presentation, its hydraulic and mass transport character control the flow and mass transport processes (behaviour) under natural or stressed conditions. Laboratory and field studies of fracture properties, and geophysical, hydraulic and tracer testing can be carried out to help determine these parameters. Each of these developed tools has its own benefits and limitations.

At the small scale (in a radius of approximately 150 m) a combination of the surface mapping, geophysical surveys or logs, and hydraulics and tracer tests can provide an understanding of the possible locations and the hydrological and mass transport properties of main flow paths in the subsurface. At a larger scale, the resolution of the geophysical survey becomes problematic, hydraulics test responses are no longer detectable, and tracer test lengths are not practicable. Large-scale studies usually involve monitoring the response (spatial variation of groundwater age, and temporal variation of the heads) of the groundwater system to natural perturbations (recharge and discharge) and long-term human disturbances (water production, manmade chemical tracing) to characterise the large-scale flow of groundwater.

The temporal and spatial variability of the fractures that control flow and mass transport through transmissive fractures, require fracture characterisation studies to be an iterative sequence of characterisation, scenario testing, evaluation, and comparison. Modelling is a powerful approach for scenario testing, whereas in situ fieldwork research facilities are important to evaluate the accuracy of the characterisation results. Additional in situ facilities should be developed in the Hout river aquifer system for fracture characterisation purposes.

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