Assessing the role of groundwater recharge in semi-arid catchments, Hout River Basin, Limpopo Province, South Africa

Lusanda Vinqi

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Department of Earth Sciences, Faculty of Natural Sciences

University of the Western Cape

Supervisor: Dr. Thokozani Kanyerere

Co-supervisor: Dr. Kevin Pietersen

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Declaration

I, Lusanda Vinqi, declare that project tittle “*Assessing the role of groundwater recharge in semi-arid catchments*, *Hout River Basin, Limpopo Province, 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 acknowledge by complete reference.

Full name: Lusanda Vinqi

Date: 23 April 2021

Signature:

Dedication

I would like to dedicate this thesis to my late dad and mom as a gift and appreciation to their hard work and all the sacrifices they have made to ensure my success.

I am grateful to you my husband for your endless support "Ahhh!!! Zilamkhonto, Shweme, Limakhwe, Malilelwa zintombi". To my siblings, I appreciate the love and support and I believe that you will obtain yours soon "Aaa Mavundle"

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Abstract

Many countries in sub-Sahara African region are characterised by crystalline basement aquifers where groundwater explorations are often described as complex. This is because groundwater availability in such aquifers is largely a consequence of the interaction of several processes related to groundwater process [recharge-flow-discharge process], underlying geological features and fracture connectivity of the aquifer rock matrix. At a local scale, crystalline basement aquifers are heterogeneous and anisotropic due to fractures, geological structures and discontinuities including varying hydraulic characteristics which need to be understood. The lack of detailed investigations of site-specific conditions to assess influence on groundwater recharge process limits implementation of initiatives for groundwater abstraction that supports environment and socio-economic projects. Based on such a gap the current study characterised and conceptualised site-specific conditions to demonstrate their influence on groundwater processes. The Hout River catchment in Limpopo province of South Africa was used as a case study. In this study the argument is that that thorough evaluation of hydrogeological characteristics of aquifers is essential to adequately establish the influence of hydrogeological conditions on groundwater occurrence, recharge, discharge and flow. To validate such argument, the study (i) Evaluated the hydrogeological characteristics of the aquifer system (ii) Characterised spatial variation in aquifer-river interaction and (iii) Conceptualise the influence of site-specific hydrogeological conditions to groundwater processes and associated river. Record review and hydrogeological field work were conducted to collect data. Analytical and laboratory-based methods were used for analysis and interpretation of geophysics, geological, groundwater level, pumping test, hydro-chemical and environmental stable isotopic data sets. Insights from geophysics results showed that groundwater occurrence is characterized by a multiple layer of varying depths inferred to be caused by different levels of weathering, geology and fractures. Furthermore, Vertical Electrical Sounding (VES) sections constructed from field measurements suggested a high groundwater potential zone to be mostly in range of 30m to 72 m and being mostly controlled by highly weathered pegmatite lineaments characterizing the study area.

Groundwater distribution pattern is constrained by geological structures as showed by weak correlation (R^2=0.53) between depth to groundwater level and topography. Theoretically, this implies that groundwater occurrence was dominated by compartmentalization through control of structural features, and that flow was controlled by geological structures. Transmissivity values ranged from $37m^2$/day to 63.53m2/day. The diagnostic and derivative curves, shown on log-log plots indicated that there are several changes in the flow-controlling mechanism suggesting a well-connected fracture network. Linear flow regime and wellbore storage effect alternate during early times of pumping while late time data showed half unit slope associated with linear flow conditions to a well in a channel aquifer. All boreholes showed a similar pattern except HO4-3125 which suggested boundary conditions associated with closed no flow boundary. Using hydrochemical data, results showed that Na-HCO3 was the dominant water composition for river water while Na-Cl was for groundwater. Environmental stable isotope data indicated river samples in areas with outcrops of geological structures having depleted δ18O (- 3.88 to - 5.12‰) and δ2H (-21.0 to -19.9‰) signatures similar to groundwater indicating a stable and continuous groundwater contribution to river flows. High evaporative enrichment of δ18O (0.87 to 2.93‰) and δ2H (11.6 to 1.5‰) was conceived in river samples from areas with no visible outcrops of dyke or pegmatite.

Geophysical, hydrogeological, hydrochemical and environmental stable isotope data were used to develop a conceptual hydrogeological model which explained site specific influence of geological structures on hydraulic parameters and Hout River flows. Results suggest that the ENE and E direction trending dolerite dykes and pegmatite within the study site act as conduit to groundwater flow thereby supplying water to the river. Deep aquifer system is marked by old groundwater as a result of prolonged residence and fluid rock interaction times in the subsurface area of discharge. The significant recharge is limited to high rainfall events hence managed aquifer recharge is recommended. The integration of several methods to explain site specific influence of geological structures on hydraulic parameters and Hout River flows provided baseline for future studies exploring other sites within the catchment.

Key words: aquifer hydraulic tests, aquifer-river interaction, conceptual model, groundwater, hydro-chemistry.

Research output

The following research output originates from this MSc thesis as contribution to the scientific community/body of knowledge:

Muchingami, I., Mkali, A., Vinqi, L., Pietersen, K., Xu, Y., Whitehead, R., Karsten, J., Villholth, K. and Kanyerere, T., 2021. Integration of hydrogeophysical and geological investigations in enhancing groundwater potential assessment in Houtriver gneiss crystalline basement formation of South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 123, p.103009.

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Chapter 1: General Introduction

1.1 Study overview

The overall target of this research is to evaluate hydrogeological characteristics of the study aquifer system with focus on identifying conditions for groundwater occurrence and its flow dynamics. The study also improves the understanding of the science of groundwater-surface water interaction processes using Hout River catchment as a case study. When there is a hydraulic connection between two systems, groundwater-surface water interaction occurs (Fleckenstein et al. 2006). The present study argues that unless the hydrogeological conditions of aquifers within ephemeral river systems are evaluated, the understanding of the influence of hydrogeological conditions on such systems may not be adequately established. The study would provide information to the research question: "What is the influence of site-specific hydrological conditions on groundwater processes and associated ephemeral river system?" To enable decision making and inform the intervention on abstraction or monitoring practices of groundwater and surface water, it is important to evaluate hydrogeological characteristics of the aquifer systems

1.2 Background to the study

Worldwide, water resources are under pressure due to escalating population and agricultural production. This is more evident in many developing countries where water scarcity is a well-known problem due to population growth, urbanisation, increasing irrigation demands and climate change (Cuthbert et al. 2016; Shanafield and Cook 2014; Senthilkhumar et al. 2015). Water resources within a country are available from two main reserves, namely surface water and groundwater. The surface water reserve is represented by the rainfall that is collected and stored above surface in the form of rivers, wetlands or dams, while the groundwater reserve is represented by water held below the surface (i.e. water table) and is only available through abstraction. The surface water reserve within the semi-arid to arid regions is dominated by ephemeral rivers while the groundwater reserve is mainly within crystalline basement rocks which are distributed extensively throughout Africa.

Sub- Saharan Africa is mainly underlain by crystalline basement rocks covering 40% of the region's 23.6 million square kilometres (MacDonald et al. 2001). This indicates the importance of crystalline basement aquifers in the livelihood of Africans as these aquifers are the major contribution to agricultural and rural domestic water supply (Witthuser et al. 2011; Holland, 2011). These aquifers are usually developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are mainly of Precambrian age and are, despite more often being described as strategic water supply, classified as low yielding (Wright, 1992). As such, groundwater exploration in such aquifers is often described as a more complex process since groundwater availability in such system is largely a consequence of the interaction of several processes related to recharge, underlying geological features and fracture connectivity of the aquifer rock matrix. Groundwater dependence from such aquifers makes proper understanding of these aquifers important in ensuring sustainable water supply given the scarcity of perennial drainage features (Datry et al. 2014).

Crystalline basement rock underlies large parts of the semi-arid Limpopo Province in South Africa. Within this region groundwater is the only dependable source of water for many users. This is evident in Hout River catchment where groundwater resources are largely contained within the Houtriver gneiss crystalline basement formation (Holland, 2011). Like most basement aquifers, this formation is characterised by high variability in terms of the recharge mechanisms, groundwater resource potential and the approximate depth to which yielding boreholes need to be drilled. Historically, groundwater exploration within such crystalline basement aquifers has been centered on identification of structural features and geological contacts at depth within the rock formation. This is because groundwater movement and storage in this formation has been described by previous researchers to occur via fractures, faults, weathered zones and other secondary features that enhance the aquifer potential only locally with a varying aquifer thickness ranging from depth extending from 12m to over 120m (Jolly, 1986; du Tout, 2001).

The Hout River catchment is the main region for agricultural production for South Africa, mainly potatoes that solely depend on groundwater (Vegter 2003). Besides agricultural purposes, groundwater within this region is used for domestic supplies and livestock watering. Due to the fact that groundwater is solely used for agricultural purposes within this region, there has been an increase in water demand due to rapid increase of irrigated area. Vegter (2003) also report that in some parts of the Hout River catchment groundwater levels declined below the pumping level due to over abstraction for irrigation. Recently in a quarterly status report on groundwater level trend for Limpopo region, the monitoring data revealed that there are stations distributed over the whole province where no recharge is notable. A7 region in which this current study is conducted marks the area in which a concentrated number of stations with no recharge occurs (Verster et al. 2017). Furthermore, monitoring data reveals impacts that results from poor management of groundwater as well as over abstraction. This is of concern because groundwater that is currently over exploited is the only reliable water resource in the study area, hence sound groundwater management in such areas is of importance.

Though the groundwater is replenishable due to rainfall, the imbalance between recharge and pumping is widening due to increasing population associated with high agricultural activity based on groundwater. Vegter (2003) noted that groundwater abstraction from the Doornlaagte catchment which is a sub-catchment of the Hout River catchment diminished the downstream groundwater flow due to declining groundwater levels resulted from abstraction leading to the dryness of the Hout River. The Hout River currently flows during torrential rainfall, other than that it is marked by pools of water in distinct locations. This indicates the interaction between an aquifer and the river affects the occurrence of flows, existence of static pools and amount of water stored beneath and adjacent to the river channel (Hughes, 2005). It is therefore fundamental to identify such areas within a river reach that interact with groundwater for better management and protection. Such study is of importance since within the Limpopo province favourable borehole locations are predicted along rivers and valleys from a topographical point of view (Holland, 2011).

There have been different studies in Limpopo basin focusing on characterisation of crystalline basement aquifers as they form major part of the rural water supply. However, most of such studies have focused on aquifer characterisation for the purpose of groundwater development and are conducted at regional scale (Vegter 2003; Witthuser et al. 2011; Holland 2011). Furthermore, little is known with regards to aquifer-river interaction as the province is mainly characterised by the ephemeral river systems and the focus has been on alluvial deposits along these ephemeral rivers as source of groundwater. However, no thorough investigation has been undertaken on them (Vegter 2003). This is due to insufficient direct data available to quantify almost all the individual processes from recharge to discharge at appropriate scales for water resources management. This issue is more common for Houtriver gneiss formation which is known to be highly heterogeneous and dominant in Hout River catchment (Holland, 2011). Another factor which limits the understanding of aquifer-river interaction is the insufficient site specific structural geological information which could assist in understanding likely dynamics of subsurface water movement within a catchment. The occurrence and movement of groundwater is controlled by various factors which includes geological features like lineaments and dykes, climate, geology and physiography (Senthilkumar et al, 2015). Improved structural geological information on groundwater recharge, discharge and flow is rarely available (Tanner and Hughes 2015) even though their influence on borehole productivity is understood and prioritised in some catchments like that of the current study (Holland et al. 2011, Holland and Witthuser 2011, Dippenaat and Van Rooy 2014). This means that research on site specific hydrogeological conditions to assess their influence on groundwater recharge, discharge and flow and ultimate impact on flows in ephemeral rivers continue to lag behind. This study therefore attempts to characterise and conceptualise site-specific hydrogeological conditions to demonstrate their influence on groundwater recharge, discharge, flow and associated ephemeral river system.

1.3 Problem statement

Lack of information on site-specific hydrogeological conditions to assess their influence on groundwater processes (recharge-flow-discharge) in relation to ephemeral river systems remains a challenge and such a situation needs to change. This means that site specific mechanisms controlling availability of water between underlying aquifer and associated ephemeral river remain to be poorly understood. This is a problem because not understanding site specific conditions in relation to groundwater processes and associated ephemeral river systems limits implementation of initiatives for groundwater abstraction that supports environment integrity and socio-economic activities. The main driver to the problem is the limited intensive site-specific studies with a comprehensive drilling program to ascertain the site-specific hydrogeological conditions in relation to recharge, flow and discharge. Furthermore, in Limpopo province studies focused on understanding the crystalline basement aquifer systems more in relation to groundwater exploitation at regional scale to meet the growing need of groundwater as many users are dependable on groundwater as the only source of water (Dziembowski, 1976; Jolly, 1986; Vegter, 2003; Pietersen et al. 2011; Holland, 2011). A detailed study focusing on site specific conditions to assess the influence on groundwater processes in relation to ephemeral river systems seems to be overlooked, hence the purpose of this study to provide such data.

1.4 Research question and thesis statement

To address the described research problem for this study, the main research question of the current study was formulated as follows: what is the influence of site-specific hydrogeological conditions on groundwater processes and associated ephemeral river?

The present study argues that thorough evaluation of hydrogeological characteristics of aquifers is essential to adequately establish the influence of hydrogeological conditions on groundwater occurrence, recharge, discharge and flow.

1.5 Study aim and objectives

The aim of this study is to develop a site-specific groundwater conceptual model for Hout River catchment in Limpopo, South Africa. This would improve understanding of the science of groundwater-surface water interaction processes thereby improving knowledge on recharge, discharge and flow processes. The knowledge gained will inform the basis for designing interventions on abstraction or monitoring practices of groundwater and surface water. To achieve this aim, this study formulated the following objectives:

1) Evaluate hydrogeological characteristics of the study aquifer system with a focus on identifying conditions for groundwater occurrences and its flow dynamics (hydraulics)
2) Characterise the spatial variation in aquifer-river interaction
3) Conceptualise the influence of site-specific hydrogeological conditions to groundwater processes and associated river.

1.6 Significance of the study

The study areas being in semi-arid environment where groundwater remains the most important sources of water for various uses, the importance of the present study is in many ways. For example, the present study continues to show that, although crystalline basement rocks have low yields and shallow aquifer systems, groundwater in such environment is available in varying quantities to support the environment and socioeconomic activities of people. Such availability of groundwater depends upon the hydrogeological characteristics of the underlying aquifer (Holland, 2011), hence the focus in the current study on local hydrogeological conditions. Secondly, although such environment are semi-arid with sporadic rainfall which lead to highly variable recharge mechanisms, the presence of faults, weathered zones and other secondary features in the study area provide potential for local aquifer occurrence with depths ranging from 12m to over 120m. Such information remains vital for planning interventions to abstract and monitor water levels for sustainability. Understanding the role of local hydrogeological conditions in the study area provides a practical recognition on the influence of site-specific hydrogeology on groundwater occurrences and flow dynamics and support to the nearby river system. Such improved understanding informs the basis for interventions that can sustain groundwater resource in the area thereby sustaining ecosystems and socio-economic initiatives for people's livelihoods.

The planned paper that will be published from the proposed study will provide the insight in the field of groundwater-surface water interactions for environmental integrity [ecosystem support i.e. river and socioeconomic development [food production] thereby providing novelty on role of site-specific hydrogeological conditions for supporting the ecosystem and peoples livelihood in the drought prone areas. Globally agreed challenges of climate change must be addressed with scientific information at local scale or site specific area where abstraction or use and monitoring of water resource takes place. Water is managed i.e. abstracted and monitored at local scale or site specific area. Therefore, case study approach provides a practical context for a plausible assessment for replication is similar areas.

Thirdly, the focus on conceptual modelling to explain influence of site-specific hydrogeological controls to groundwater processes and river system is important because such a focus encourages analytical and critical review of existing regional and catchment models developed earlier on the same theme. Such a review provided a basis for gap analysis and thereby provided a basis for generating data to validate the developed site-specific conceptual model. The development of site-specific models encourages the use of derivative analysis to amplify the groundwater flow regimes in a system thereby enabling refinement of conceptual model. Such approach is new as it provides a new methodological approach in refining groundwater conceptual models, hence the novelty of the current study.

1.7 Scope and nature of the study.

In terms of the scope, the field of hydrogeology is a broad concept that covers aspects like physical and environmental hydrogeology. It highlights the interrelation of geological processes with water. The current study mostly falls on the physical hydrogeology aspect, where the focus is on establishing the influence that local hydrogeology has on groundwater occurrence, recharge, flow and discharge. Aquifer parameters are estimated (transmissivity and storativity). Portion of environmental hydrology is included within the study to understand sources of water and ultimately assess aquifer-river interaction.

In terms of the nature of the current study, qualitative and quantitative methods were adopted in this study where experimental fieldwork and desktop design were utilized to address the research question. The experimental design, in this case involved geophysical surveys, drilling of boreholes and installation of data loggers which were used for collection of water levels and characterise the aquifer system. Hydrochemical data and environmental isotope data was also collected to characterise the spatial variation in aquifer-river interaction. The desktop design includes collection of secondary data on: water levels, recharge estimates, geology, hydrogeology, chemistry and isotopic data to conceptualise the influence of local hydrogeological characteristics on groundwater processes and river flows.

1.8 Conceptualization of the current research project

The current study is part of the Danida project entitled "Enhancing sustainable groundwater use in South Africa (ESGUSA)". The Danida project is a three-year project (2018-2020) and it is being implemented by University of Copenhagen, Department of Water and Sanitation (DWS), EkoSource-South Africa, International Water Management Institute (IWMI) South Africa and the University of the Western Cape (UWC). The objectives of the Danida Project are:

- Establish research partnerships between RSA and Denmark
- Improve the understanding of hydrogeological conditions in typical geological settings and farming communities in RSA, exemplified by the Hout /Sand river catchment in Limpopo.
- Development of modelling and resource indicator tools for integrated groundwater management.
- Stakeholder involvement in development and promotion of sustainable groundwater management options.
- Increasing research capacity in RSA within integrated groundwater resource assessment and management.

With regards to the Danish project, the current study aimed at contributing towards improving the understanding of hydrogeological conditions in typical geological settings and farming communities in the Hout /Sand River catchment in the Limpopo province in South

Africa. Therefore, the scientific research problem, research question and the hypothesis of the current study were conceived within the framework of the larger Danida project.

1.9 Thesis outline

Chapter 1 provides a brief background to the topic and outlines the research problem, research question, thesis statement, objectives, significance and scope and nature of the study. Chapter 2 provided a review of literature on hydrogeological characterisation. This chapter also looks into how other studies used hydrogeological characteristics to understand recharge, discharge and flow of groundwater and this is looked into relation to surface water. The theoretical framework which provides the principles and theories guiding the current study are also included. Chapter 3 presents general setting and location of the study area and experimental study sites. This chapter focuses on describing climate, topography, geology and hydrogeology of the study area. The research design and data collection and analysis methods are presented in Chapter 4. Chapter 5 demonstrates the use of aquifer characteristics in understanding their influence on groundwater processes and how such aquifer characteristics influences river flows in ephemeral river system. Chapter 6 demonstrate the use of hydrochemistry and environmental stable isotopes in assessing and characterising the interaction between aquifers and rivers in order to determine discharge sites along the river. Finally, Chapter 7 provides a summary of major findings and a conceptualization of the site-specific hydrogeological conditions which are used to explain groundwater processes in relation to ephemeral river flows.

Chapter 2 : Literature review

2.1 Introduction

The previous chapter provided the general introduction of the study. This chapter starts with providing a brief review of previous studies done relating to the hydrogeological characteristics of hard rock aquifers across the world and within the study area. The chapter then reviews the different methods for evaluating aquifer characteristics, methods for characterising aquifer-river interaction and finally the aspects to consider when developing hydrogeological conceptual model. These reviews were conducted with intention to identify gaps in literature and understanding of these components is essential to comprehend groundwater processes in relation to ephemeral rivers. A theoretical and conceptual framework which guide this research work is discussed in this chapter.

2.2 Previous studies on hydrogeological characteristics

Hydrogeological characteristics have been studied extensively from different aquifers and in different parts of the world. Most of the time hydrogeological characteristics are investigated for sitting productive boreholes for human use, for establishing key wells for monitoring purposes, exploratory drilling to establish aquifer geometry, estimate aquifer hydraulic parameters and water quality assessment. The current study investigates hydrogeological characteristics to understand local groundwater controls with respect to recharge of the underlying aquifer, discharge of groundwater to the associated ephemeral river and groundwater flow mechanism (groundwater processes)of the Hout River catchment.

In a highly fractured and hydrothermally altered crystalline bedrock with a pyrite deposit in an alpine environmental in the USA, Kahn et al. (2007) estimated basic hydrologic properties of a shallow aquifer system and developed a water budget. Using infiltration tests in surficial materials, injection and pumping tests, numerical modelling (MODFLOW) of aquifer test results, discharge estimates, and construction of watershed-scale numerical model were utilized to characterize the shallow aquifer system. Results from a study by Kahn et al. (2007) showed that surficial infiltration rates ranged from 0.1-6.2x10^{5} m/s while discharge was estimated at 1.28x10^{3} km^{3}. Numerical modelling analysis of single-well aquifer test predicted lower specific storage in crystalline bedrock than in ferricrete and colluvial material (6.7x10^{-5}-2.0x10^{-4} l/m). Similarly, the hydraulic conductivity in crystalline bedrock was lower than in colluvial and alluvial material (4.3x10^{-9}-2.0x10^{-4} m/s) (Kahn et al.2007). The hydrograph results on Kahn et al. (2007) suggested that the stream was mostly controlled by groundwater flow rather than runoff. Kahn et al. (2007) addresses objective 1 of the study as well as objective 2 of the study, however, current study uses conceptual model to estimate T and S whereas Kahn et al. (2007) focused more on numerical modelling. The current study however expected that the stream is mostly controlled by groundwater flow rather than runoff especially during dry periods.

In a fractured bedrock aquifer flow into a well is controlled by structural permeability than porosity. Abija et al. (2019) used field methods such as geological, hydrogeological and electrical resistivity depth sounding coupled with remote sensing methods for lineament extraction to understand the subsurface layering, rock types, layer thickness, their hydraulic characteristics, depth of abstraction and vulnerability to contamination of crystalline rocks. These crystalline rocks such as granites, dolerites and consolidated sandstone underlie 90% of the Cross River State, Nigeria. The interpretation inferred five geoelectric layer subsurface in a lithological sequence of top lateritic soil, a weathered overburden, silt or sand and in some instances mudstone unit, shale and crystalline rocks. The dominant joints orientation was the NE-SW direction with few fractures trending N-S and NW-SE. Aquifer hydraulic conductivity varied from 4.65 x 10^{-6} cm/sec to 7.58 x 10^{-6} cm/sec in the sandstones, 2.20 x 10^{-6} cm/sec to 7.72 x 10^{-6} cm/sec in the weathered regoliths and 7.74 x 10^{-6} cm/sec in shales. The transmissivity of the sandstones range from 4.017 x 10^{-3} to 6.54912 x 10^{-2} m^2/day, fractured saprolite from 1.9008 x 10^{-3} m^2/day to 6.7219 x 10^{-3} m^2/day and shale was 6.668 x 10^{-3} m^2/day. The study concluded that groundwater potential was poor to fair within the investigated region. Abija et al. (2019) addresses objective 1 of the study focusing on evaluating hydrogeological characteristics of the aquifer system and demonstrated possible methods to be used when characterizing crystalline basement environments which has always been challenging. However, the study estimated K and T, whereas the current study focused more on S and T which were chosen because they give indication of storage and discharge rates of the aquifer and that information is crucial when understanding groundwater processes.

Many developing countries of sub-Sahara Africa are characterized by complex crystalline basement bedrocks, hence detailed evaluation and understanding of the associated aquifers is of importance. With this regard, Tijani et al. (2010) characterized the influence of three bedrock types namely: banded gneiss, augen gneiss and quartz-schist on hydraulic properties and implications for groundwater recharge in Nigeria. The study utilized existing borehole data and pumping/sludge test data to estimate hydraulic properties of the weathered regolith/fractured crystalline aquifer. Results revealed that the weathered regolith thickness varies across the studied bedrock types and that the observed average discharge is generally low about 80.8 m^3 /day. Using Cooper Jacob (1946) method, transmissivity was estimated by Tijani et al. (2010). A mean value of 7.3m^2/day for augen gneiss, mean value of 2.8m^2/day for banded gneiss and mean value of 2.7 m^2/day for quartz-schist were obtained. Hydraulic conductivity was then estimated from the evaluated transmissivity and saturated thickness of the aquifer with values of 0.1-0.18m/day for both the banded gneiss and quartz-schist while for augen gneiss a value of 0.2-0.5m/day was estimated. Based on the pumping test result curves by Tijani et al. (2010), the recharge boundary, impermeable boundary condition and situation where discharge rate is proportional to in-flow into the well. The study by Tijani et al. (2010) concluded that the bedrock type and geological structure influence regolith aquifer recharge and yield positively while regolith thickness and saturated thickness have no significant influence. The study by Tijani et al. (2010) address objective 1 of the current study which focuses on groundwater occurrence and hydraulics, however the current study estimates transmissivity and storativity whereas Tijani et al. (2010) estimated transmissivity as well as hydraulic conductivity. The current study, however, expects to encounter same boundary conditions with those of Tijani et al. (2010).

Pumping tests are important tools that provide information on the hydraulic behaviour of borehole, the reservoir and the reservoir boundaries. In South Africa pumping tests are performed mainly to determine the long-term sustainable yield of a borehole and estimate aquifer parameters (Van Tonder et al. 2002). Based on this, a manual to analyse pumping test in fractured-rock aquifers has been developed by Van Tonder et al. (2002). This manual emphasises the use of analytical procedures to analyse pumping test data even though theoretically, a three dimensional numerical flow model is best to use for fractured rock aquifers however, the data required is usually not available. The single fracture model and double porosity model are mainly applied in fractured rock aquifers in South Africa (Van Tonder et al. 2002). Thies and Cooper- Jacob are also applied in fractured aquifer only for radial flow (Van Tonder et al. 2002). Van Tonder et al. (2002) also addresses objective 1 of the current study where aquifer parameters are estimated and gave guidelines on how to conduct and analyse pumping test within fractured rock aquifer system.

Throughout Africa, crystalline basement rocks are extensively distributed and underlies large parts of the semi-arid Limpopo Province in South Africa. Crystalline basement rocks (bedrock) are composed of hard, crystalline or re-crystallized rocks of igneous or metamorphic origin, such as granites, basalts, metaquartzites or gneisses with negligible primary porosity and permeability (Clark, 1985; Gustafson and Krásný, 1994). The Houtriver gneiss basement aquifer covers significant portion within the Limpopo Mobile Belt (LMB) and act as a main supply of water in most of the rural and farming communities within the Limpopo province. Hence, there are several studies that have been reported on groundwater resource occurrence and dynamics within the Houtriver gneiss formation.

Among such studies is the study by Jolly (1986) in which extraction of groundwater from the weathered and fractured portions of the crystalline bedrock is reported, where high yielding fractured aquifers were observed at depths between 80 to 120 m. Furthermore, Jolly (1986) reported the storage co-efficient of the upper weathered and fractured zones of the composite aquifer to be 0.01 and 0.0025, respectively. Pietersen et al. (2011) reported that low borehole yields with mean yield of 1L/s for the weathered zones due to its low permeability while reporting borehole yields reaching 40L/s for the fractured zone. The understanding obtained from these studies was utilised to discuss results obtained from the current study.

The Houtriver gneissic formation is intruded by dykes with rocks belonging to the Bandelierkop Complex that predominantly trends northwest and northeast (Du Toit and Sonnekus, 2014), occurring as highly deformed keels within the formation. These intrusive dykes, mostly with a varying thickness from 7 to 20m (Jolly, 1986) are assumed to influence groundwater flow patterns within the formation. A correlation of the trend of dykes and borehole productivity by Holland (2011) showed that high mean transmissivities are related to NE, ENE and WNW trending dykes and lower transmissivities in the NW and NNE trending dykes. Furthermore Holland (2011) reported transmissivity values ranging from 4m^2/day to 40m^2/day with high values around the Mogwadi area. The current study expected transmissivity estimates which corroborate with those of Holland (2011).

With regard to hydrochemistry within the Houtriver gneiss, Abiye at al. (2020) conducted a study within Hout River catchment and showed that southern and central part of the catchment contain old groundwater with high salinity due to long residence. Regionally Holland (2011) classified dominant groundwater types in Limpopo Plateau to vary from a

Na-HCO_3 to a Na-Mg-HCO_3 and Na-Cl while rainwater is of Ca-HCO_3. Groundwater generally in Limpopo province is characterised by the wide spread occurrence of high nitrate concentrations and normally thought to be of anthropogenic origin. Verhagen et al. (2009) conducted multi tracer study in Bochum District of Limpopo Province to understand origins, systematics and hydrological linkages of high nitrate concentrations in groundwater. Authors concluded that high nitrate concentrations are not only of anthropogenic component but also of the natural, tree-root driven process. Although the current study is not investing high levels of nitrate, it is taken into consideration when calculating Cation-Anion balance to evaluate the reliability of the dataset.

From the previous studies summarised above, it is evident that there are various applications in which information on hydrogeological characteristics is used. These include groundwater resource development and management, groundwater flow conceptualization and aquifer-river interaction. However, limited studies have focused on evaluating hydrogeological characteristics for aquifer-river interaction.

2.3 Evaluation of hydrogeological characteristics of the crystalline basement aquifer.

2.3.1 Conceptual framework

Crystalline basement rocks are composed of hard rock, crystalline rocks of igneous or metamorphic origin, such as granites, basalts gneisses or metaquartz with negligible primary porosity and permeability (Jolly, 1986; Wright, 1992). These aquifers as graphically shown in Figure 2.1 are usually developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are mainly of Precambrian age and are, despite more often being described as strategic water supply, classified as low yielding (Wright, 1992). Crystalline basement aquifers are different from each other due to the thickness of weathered material and whether saturated or not as well as the extent of fracturing (Holland, 2011). At regional and local scale these components are depended on a number of independent and interrelated factors. For instead Holland (2011) showed that borehole productivity relies on the presence of weathered material overlying the fractured rock and enhanced where there is an alternate source of recharge such as river or associated alluvium. It is therefore important to understand how groundwater occurs in the area and the different hydrogeological conditions on the occurrence of groundwater because these structures control the movement and localization of groundwater.

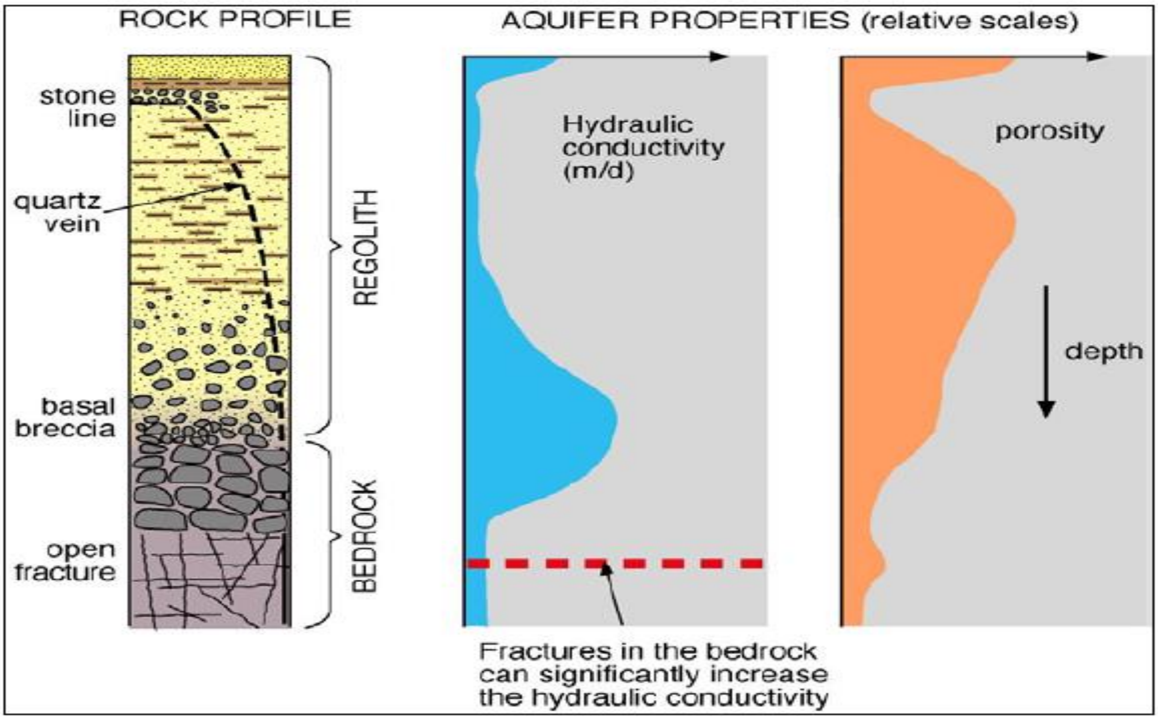

Figure 2.1 Permeability and porosity of basement rock (Chilton and foster, 1995)

Regarding crystalline basement aquifers, flow is complex and governed by the hydraulic potential gradient and hydraulic conductivities in the regolith and underlying fractured bedrock. Generally, the flow behaviour of crystalline bedrock aquifers is shallow, focused in weathered and fractured zone, however Toth (1963) indicated that local, intermediate, and regional flow systems could be superimposed on one another within the groundwater basin. Furthermore, regional flow occurs within the major interconnected fracture systems, while main groundwater flow systems are relatively localised to the zones between recharge on watersheds to discharge by run-off or evaporation at valley bottoms (Holland, 2011). Understanding groundwater occurrence within a system is crucial to adequately characterise the aquifer.

2.3.2 Aquifer characterisation

Aquifer characterisation is described as the evaluation of three-dimensional structure, the hydraulic and transport properties and chemistry of aquifers (Maliva, 2016). Commonly, aquifer characterisation is referred as groundwater exploration in which subsurface formations are investigated to understand the subsurface hydrogeologic characteristics of aquifers. Within the crystalline basement aquifers, groundwater exploration has been centred on identification of structural features and geological contacts at depth with the rock formation. Different methods including geological mapping, borehole drilling and pumping tests and geophysics have been employed to generate hydrogeological information. The current study applied these methods to understand the subsurface variation, aquifer hydraulic properties and to identify structural features that controls groundwater occurrence, flow, recharge, and discharge in the study catchment, the Hout River catchment.

2.3.2.1 Geological mapping

Geological mapping involves gathering and evaluating geological information to enhance understanding of the subsurface material in which groundwater occurs by conducting field survey. This is a fundamental tool for a comprehensive understanding of site conditions which controls groundwater availability. Jolly (1986) describes groundwater movement and storage within the Houtriver gneiss to occur via fractures, faults, weathered zones and other secondary features that enhance the aquifer potential. Proper geological frame of an area is important to visualise the groundwater flow system. The current study explored similar features during field survey as those reported by Jolly (1986).

2.3.2.2 Geophysical studies

The assessment of the groundwater potential and borehole siting in typical crystalline formation aquifers has often presented challenges and more often drilling of numerous dry and seasonal boreholes has been reported for poorly sited wells across the formation. This is despite the fact that a combination of hydrogeophysical and geological methods has over the years been successfully applied in some crystalline basement aquifers to increase borehole success rates through inferring the subsurface distribution of groundwater controlling structures 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 (e.g. in Zody (1969); Martinelli and Hubert 1985; Metwaly (2009); Chuma et al. 2013). The current section demonstrates the effectiveness of applying integrated geophysical methods to infer subsurface features useful in identifying potential drill targets

Among most geophysical techniques used for groundwater exploration the electrical and electromagnetic methods are frequently included in the investigation. Aizebeokhai and Oyeyemi (2017) combined the Vertical Electrical Sounding (VES) with 2D geoelectrical resistivity imaging to characterise the weathered and fractured zones in a crystalline basement complex terrain in southwest Nigeria. This was conducted to delineate the weathered overburden and fracture zones within the study site with intention of assessing groundwater potential and be able to site productive boreholes. Results by Aizebeokhai and Oyeyemi (2017) indicated the effectiveness of integrating techniques when characterising the aquifer. The study delineated the overburden thickness, weathered and fractured zones, fractures, vertical contacts and fresh basement. Aizebeokhai and Oyeyemi (2017) addresses part of objective1 for the current study, however, the current study combined VES with 1D magnetic profiling and horizontal Frequency Domain Electro-Magnetic (FDEM).

Vereecken et al. (2005) recommended that at least two of the geophysical exploration techniques should be used when characterising an aquifer. Example of the multi-technique approach include Adadzi et al. (2018) where a VES was coupled with resistivity profiling within an area of flat topography in Elem community in Ghana. Adadzi et al. (2018) results showed three sub-surface geological formations with varying resistivity. Based on the analysis of the results from both methods, the authors concluded that the Elem community is underlain by gneisses and schists with thick clay and sand overburden. Furthermore, the formation has undergone varying degrees of weathering which control groundwater occurrence and accumulation. The current study used horizontal FDEM along with the magnetic method in order to produce an improved selections of the VES points along all transect lines.

Integration of methods provide better and more concise understanding of the subsurface structural setting of the area of interest. This is fundamental in basement terrains as these aquifers are usually developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are mainly of Precambrian age and are, despite more often being described as strategic water supply, classified as low yielding (Wright, 1992). As such, groundwater exploration in such aquifers is often described as a more complex process since groundwater availability in such system is largely a consequence of the interaction of several processes related to recharge, underlying geological features and fracture connectivity of the aquifer rock matrix. Akinlalu et al. (2016) mapped the subsurface geologic structures of Precambrian basement complex of Iwaraja in Nigeria in terms of trend, extent and depth to fracture zone using combined geophysics approach of ground magnetic and 2-D resistivity method. Batte et al. (2008) improved the success rate of boreholes in Kamuli District in Uganda through the use of resistivity profiling and VES. VES was performed at spots with negative anomalies having resistivity ranging between 50-250 Ohms (Batte et al. 2008).

Groundwater dynamics within basement aquifer is further complicated by the presence of lineaments such as rivers, streams, buried channels, quartz and pegmatite veins and dolerite dykes. Geophysical characterization only helps in understanding about the potentiality of the system (Chandra et al. 2006), hence, there is a need to validate characterized features for groundwater potentiality. Chandra et al. (2010) conducted an integrated study consisting topographical mapping of quartz reef sites, forward 2D resistivity modelling, Electrical Resistivity Tomography (ERT) survey, drilling of experimental bore wells, lithology collection, yield measurements, and electrical resistivity logging. Results from Chandra et al. (2010) were concluded to be in agreement with each other. Olorunfemi and Oni (2019) showed the effectiveness of integrated geophysical methods by drilling two boreholes in which the predicted fractured basement zones was encountered and the borehole logs correlated well with the interpretation models of the drilled VES locations. This shows the importance of integrating techniques when characterizing the aquifer system so that productive boreholes can be sited.

2.3.2.3 Borehole drilling and lithological logs

Most of aquifer characterisation techniques are validated through drilling, these include geophysics, geological mapping, and aquifer tests. Three types of boreholes are often drilled when characterising the aquifer system, these are monitoring, exploratory and production wells (Maliva, 2016). The monitoring wells are constructed for monitoring the water levels and samples for water chemistry analysis. The production boreholes are constructed to evaluate well yield while the exploratory wells are used for collecting hydraulic and lithologic data and water samples. These lithological logs are then used to delineate the subsurface layers and used to identify aquifer types. Groundwater Resource Information Project (GRIP) Limpopo database of the South African Department of Water Affairs is example of the database containing information obtained from the drilling process. This helps in determining the depth and thickness of aquifer units in different geological units.

2.3.2.4 Aquifer hydraulics

Aquifer hydraulic tests forms part of the tools used for aquifer characterisation as the merit of aquifer as a potential source of water is dependent mainly on its ability to transmit water (transmissivity, T) and its ability to store water (storage coefficient, S). Cook (2003) considers crystalline basement aquifers to fall between porous media and conduit system. The weathered material can be represented by a porous medium and fractured material can be regarded as fractured porous medium with groundwater flowing in a conduit network of fractures and stored between the conduits. To understand the ability of the aquifer to transmit and store water, often aquifer test is conducted.

Aquifer test is defined as controlled field experiment to determine the hydraulic properties of water bearing and associated rocks. Through a variety of methods which include bail tests, slug test and pumping test water level in a borehole is changed and the drawdown and/or recovery of the water level is measured against time and/or space. For this dissertation, the emphasis is solely on the pumping test. This is because the pumping test can provide measurements of aquifer hydraulic parameters that are representative of the large volume of aquifer as compared to slug test which provides values of hydraulic conductivity representative of a small area around the vicinity of the piezometer. There are three basic common types of pumping tests, the step drawdown test, constant discharge test and recovery test (Van Tonder et al. 2002). The step drawdown test is performed after the determination of the blow yield to assess the performance of the borehole and determine the discharge rate for the constant discharge test. Meanwhile the constant discharge test determines the long-term yield of the borehole, the transmissivity, and the storage capacity of the aquifer. Aquifer parameters give a good indication of the physical environment of groundwater flow, which plays an important role in the quality of the groundwater.

Behavior of an aquifer is studied by analyzing the pumping test data, however there is a challenge of choosing appropriate model that represents the reality (Holland, 2011). Diagnostic plots (Table 2.1) which include log-log plots of the drawdown versus the time, semi-log plots of drawdown versus time are commonly used to overcome the challenge of choosing appropriate conceptual model (Sun *et al.* 2015). These plots aid in identification of the dominant flow regime and are commonly used in conjunction with the derivative plots which assist in identification of flow phase and more specifically the fracture intersections (Figure 2.2). In South Africa Van Tonder *et al*, (2002) developed Flow Characteristics Excelprogrammed code which included the use of derivatives to characterize drawdown behavior. The program provides powerful tools for the detailed diagnostic and analysis of step, constant and recovery drawdown data. The current study however, applied Aqtesolv to analyze the pumping test dataset.

Table 2.1: Diagnostic tools for groundwater flow characterisation

Plot	Slope/feature of the derivative	Time	Flow Characteristics	Fracture setting
Log-log	1	Early time	Wellbore storage (WBS)	Drawdown is from the storage volume of the well not the reservoir.
	0.5		Linear flow	Linear flow conditions to a single fracture with infinite conductivity or uniform flux along the fracture
	0.25		Bilinear flow	Flow is from both the fracture and the formation, indicative of a good fracture network with matrix contribution.
	0.5	Late time	2 parallel no-flow boundaries, or 3 equidistant no floe boundaries.	Limited fracture extent
	1		Four closed boundaries	A geological boundary of lower permeability surrounding the borehole is reached by the cone of depression,
Semi-log	Straight line	Middle to late	Radial acting flow (RAF)	Occurs when a fracture reservoir is considered to be a continuum, when the aquifer is considered homogeneous. It occurs in well-connected fracture network.

	Doubling slope	After RAF	One no flow boundary	Fracture is limited
	Quadrupling slope	After RAF	Two perpendicular no flow boundaries	No-flow boundaries are perpendicular to the fracture
Derivative	Dip in the derivative	Early time (after WBS)	Double porosity aquifer type	Groundwater is from the fracture and matrix, flow regime changes from linear to bilinear
	Downward trend	Late time	Recharge boundary	Aquifer is receiving recharge during test, can be induced from surface water bodies.
	Downward then upward	Depends on fracture depth and Q	Position of a fracture is reached and followed by dewatering of the fracture	Limited fracture extent
	Horizontal line	Middle to late	Radial flow	Occurs when a fracture reservoir is considered to be a continuum, when the aquifer is considered homogeneous. It occurs in well-connected fracture network.
	Doubling of slope	After RAF	1 no flow boundary	Fracture/s have a limited extent
	Slope of 1	Late time	Closed boundary	

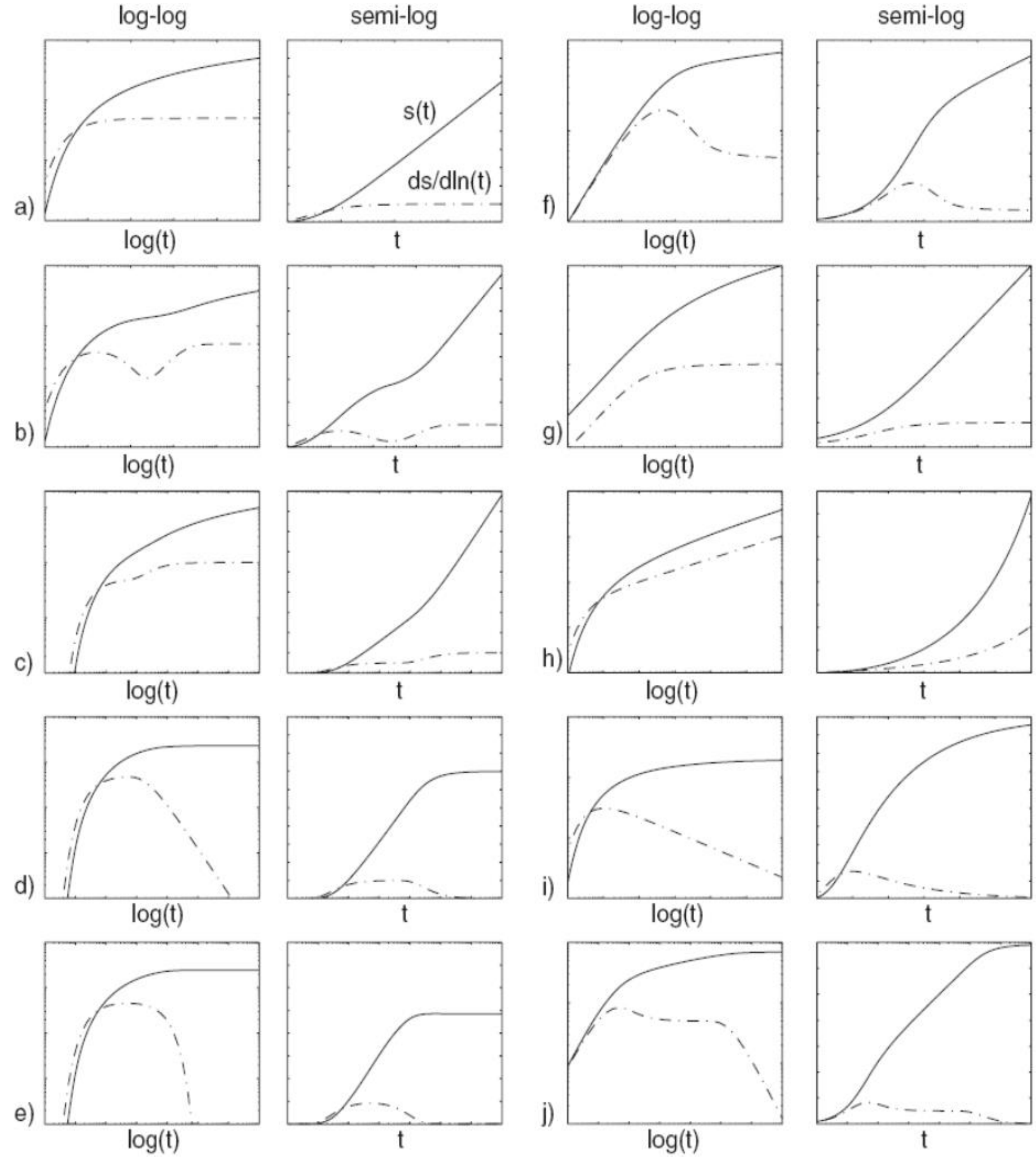

Figure 2.2 Typical diagnostic plots plots a) Theis model infinite two-dimensional confined aquifer; b) double porosity or unconfined aquifer; c) infinite linear no-flow boundary; d) infinite linear constant head boundary; e) leaky aquifer; f) wellbore storage and skin effect; g) infinite conductivity 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 (Renard *et al*, 2009

Crystalline basement aquifers are heterogeneous hence there has been a continuous development of analytical models and well-testing procedures that are applicable to weathered-fractured media. These models include leakage from an adjacent aquifer (Hantush and Jacob 1955; Moench, 1985), partially penetrating well (Hantush, 1961), large diameter well (Papadopulos and Cooper, 1967), flow in an anisotropic unconfined aquifer with delayed gravity response (Neuman, 1974; Moench, 1997), dense network of fractures in a porous matrix (Moench, 1984; Barker, 1988), and single fracture intersecting the well (Gringarten *et al.* 1974; Gingarten and Ramey, 1973). Diagnostic plots allow for identification of certain flow regimes and facilitates the selection of an appropriate model. Combination of pumping test solutions that govern vertical leakage such as the classical leaky-aquifer model or unconfined condition with delayed gravity response, while considering the double-porosity behavior of the underlying bedrock are normally applied in basement aquifers. This is because crystalline basement rocks are semi-confined (Fractured bedrock) with unconfined weathered media (Jolly, 1986). These two components are hydraulically interconnected and must be treated as such.

It is remarkable and recommended to use a series of methods to obtain information on hydrogeological characteristics. Such integrated approaches are useful for proper characterization of aquifers since each method has some limitations. For instance, Tijani et al. (2010) combined borehole data and pumping test data to evaluate hydraulic properties of the weathered regolith/fracture crystalline aquifer. Meanwhile Hammond and Field (2014) integrated geophysical logging and aquifer tests while showcasing the importance of derivative analysis and diagnostic plots over the conventional method of manual type-curve analysis. Proper evaluation of hydrogeological characteristics is necessary for identifying hydrogeological conditions for groundwater occurrence and its flow dynamics.

2.4 Characterising aquifer-river interaction

Understanding and managing groundwater resources in arid to semi-arid regions is a challenging task that is globally important (Cuthbert et al. 2016). Groundwater sustains both ecosystems and human communities in such regions. Groundwater interacts with surface water bodies such as rivers, wetlands and lakes hence, the dominant process for semi-arid groundwater recharge is thought to be as focused, indirect recharge from ephemeral stream losses (Cuthbert et al. 2016). These interactions often result in groundwater altering the quality and quantity of surface water in surface water bodies and also surface water altering the quality of groundwater in aquifers (Sophocleous, 2002). It is therefore crucial to understand these interactions for effective management of water resources.

Banks et al. (2011) characterise aquifer river interaction as connected and disconnected systems. When a river is gaining water from or losing water to a local groundwater system, it is referred to as connected system while the disconnected system is defined by an unsaturated zone which prevents active interaction between the surface water system and the aquifer (Banks et al. 2011). To assess the interaction between aquifers and rivers, Brodie et al. (2007) documented wide range of methods which include field observations, ecological indicators, hydrogeological mapping, geophysics and remote sensing, hydrometric analysis, hydrochemistry, hydrographic analysis and environmental tracers, artificial tracers, seepage measurements, temperature studies, and water budget. For this dissertation, the emphasis is on environmental tracers and hydrochemistry. Application of multi-tracer approaches have proven invaluable in constraining contributing sources of solutes, preferential flow pathways and residence times within hard rock aquifers

In most hydrogeological studies, environmental isotope techniques have become the routine to provide insights into storage properties of the hydrogeological systems. These are commonly referred to as environmental tracers which provides valuable information with regards to aquifer characteristics and groundwater flow paths (Verhagen et al. 2009). Clark and Fritz (1997) provide detailed discussion on the application of the environmental isotopes in hydrogeology. The current study focuses more on stable isotopes of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) to characterise aquifer-river interaction.

Oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) are the commonly used stable isotopes in water studies. During phase changes of water between liquid and gas, the heavier water molecules tend to concentrate in the liquid phase, which fractionates the hydrogen and oxygen isotopes. Precipitation is isotopically heavier and water that evaporates from the ocean is isotopically lighter than the water remaining behind. These isotopic ratios from an environmental sample can be compared with the isotopic ratio of standard mean ocean water (SMOW) (Hiscock, 2005). When $\delta^{2}H$ is plotted as a function of $\delta^{18}O$ for water found in continental precipitation, an experimental linear relationship is found that can be described by the equation (Craig, 1961):

$\delta^{2}H = \delta^{18}O + 10$

This is known as the Global Meteoric Water Line (GMWL) in which the climatological conditions (temperature, latitude, altitude, and rainfall amount effects) influence the position of any pair of δ^2H and δ^{18}O on this line for rainwater worldwide. Groundwater isotopic condition is altered by physical processes after the infiltration of precipitation. These processes include diffusion, dispersion, mixing, and evaporation. Local Meteoric Water Line (LMWL) is used to locally determine the origin of water such that samples plotting on the LMWL are considered to be of meteoric origin whereas samples deviating from the LMWL could originate from other sources (Varsanyi et al. 2015). Therefore, a difference in the isotopic composition of groundwater and river water would be expected. Meanwhile, isotopically depleted waters are associated with cold regions while enriched waters are found in warm regions (Clark and Fritz, 1997) (Figure 2.3). This may relate that depleted waters (more negative isotope value) infiltrated in the colder period while enriched waters may have infiltrated in warmer period (Figure 2.3). These characteristics can be used to explain the recharge-discharge processes, origin of water and the possibility of the two water bodies interacting.

Durowoju et al. (2019) generated a LMWL for Thohoyandou in Limpopo Province which is defined by $\delta^2H = 7.56\ \delta^{18}O + 10.64$, its intercept is slightly higher than that of GMWL. This reflects an additional supply of recycled moisture across the Thohoyandou region. The Pretoria LMWL is defined by $\delta^2H = 6.7\ \delta^{18}O + 7.2$ in which the intercept is lower than that of the GMWL indicating relatively low humidity condition and signature of secondary evaporation in the area (Abiye et al. 2011). Another possible LMWL is that of the Taaibosch area which is defined by $\delta^2H = 8.17\ \delta^{18}O + 13$. Thohoyandou LMWL is generated from the data of one hydrological year of which it is recommended that at least minimum of three years data is needed. For representative results, the current study employs the Taaibosch LMWL and Pretoria LMWL as reference.

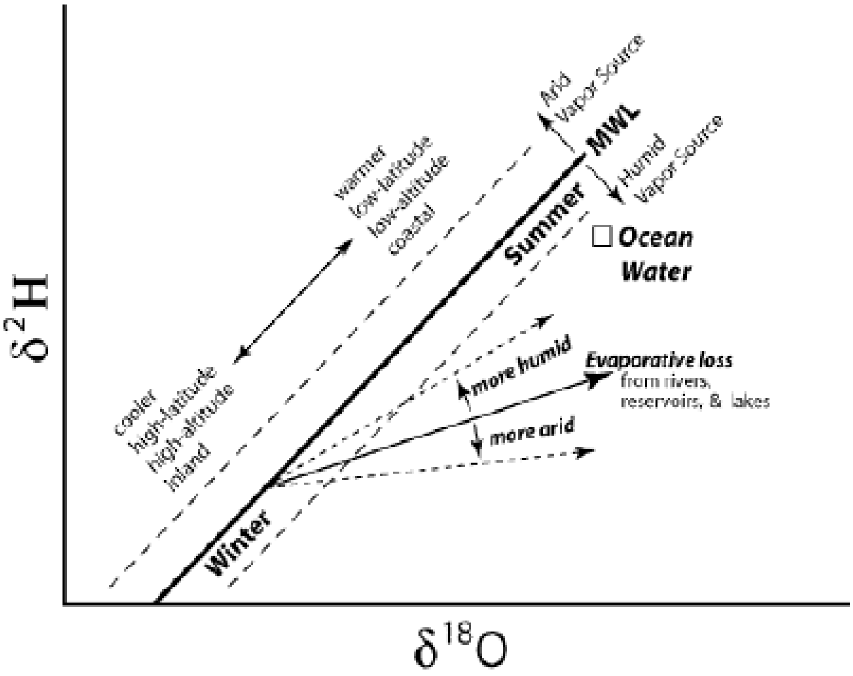

Figure2.3: Summarised stable composition from precipitation to percolation (Holland 2011).

Stable isotopes are frequently used in conjunction with hydrochemistry to further confirm any possible interaction between two sources. Groundwater is expected to have higher concentrations of dissolved constituents than surface water since groundwater chemical composition is influenced by its origin, rock type hosting water (Todd and Mays, 2005). This is however valid only if surface water is not contaminated from any anthropogenic activities. The difference between surface water and groundwater concentrations is used as an indicator of groundwater discharge or recharge. Kalbus et al. (2006) argue that the difference must be sufficiently large to confidently conclude that groundwater and surface possible interact.

As recommended, researchers have used a combination of the methods to characterise the groundwater surface water interaction. Banks et al. (2009) conducted a hydraulic, hydrochemical, and tracer-based study to investigate the role of the saprolite-fractured bedrock aquifer system on groundwater surface water interaction. Girmay *et al*, (2015) concluded that groundwater contributes to the baseflow of semi-perennial streams and rivers in the studied region while isotopic signatures in some wells indicated that river water and seepage from micro-dams locally feed the adjacent aquifers. This was concluded based on the use of environmental isotopes of hydrogen and oxygen and hydrochemistry. Preferential recharge areas, flow path, and changes in the relationship between groundwater and surface water were accurately identified using a combination of hydrological, hydrochemical and isotopic methods in unconfined aquifers (Londono et al. 2008).

2.5 Hydrogeological conceptual model

Groundwater related investigations are complicated and usually difficult to thoroughly understand. Conceptual model therefore serves to simplify the field conditions and organise the various flow processes so that the hydrologic system can be analysed with ease. Assumptions are often made to summarise the understanding of how water flows within the aquifer system, enter and leaves the aquifer system. Conceptual model can therefore be regarded as a theoretical form of the water mass balance calculation. Banks et al. (2009) provided three types of conceptual models (Figure 2.4) in which at least one of them is applied when studying groundwater-surface water interaction under gaining-stream conditions. Within hard rock aquifers it is important to understand subsurface flow activity on both the weathered and deeper bedrock compartments as a basis for developing reliable conceptual models of these systems.

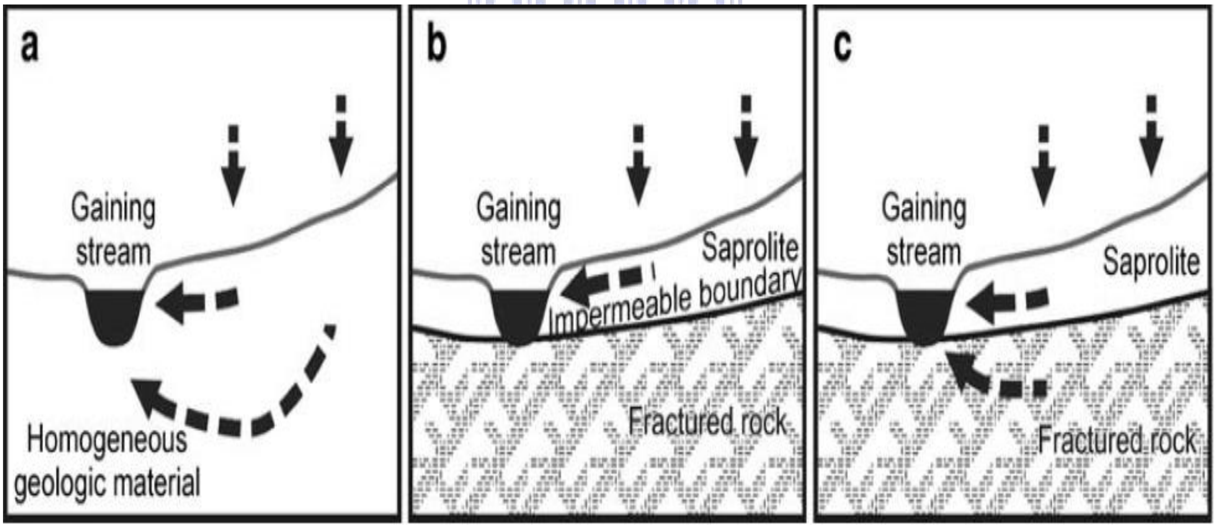

Figure 2.4: Groundwater-surface water interaction conceptual models under gaining stream conditions in a complex hard rock aquifer system: a homogeneous system b subsurface flow within the weathered zone only, and c subsurface flow occurring in both weathered and deeper fractured aquifer (Banks et al. 2009).

There two modelling approaches used in hydrogeology, the fixed modelling and flexible modelling approach. Esse et al. (2013) differentiate between the two, where the fixed modelling approach assumes that a single model structure can be developed to apply in many contexts and conditions. On the other hand, the flexible approach calls for multiple working hypotheses to be considered. Fenicia et al. (2011) emphasise the use of the flexible framework to allow the hydrologist to hypothesize, build, and test different structure models. At a catchment scale the limitation in process understanding and data availability remain major research and operational challenge hence "one-size-fits-all" model structure is not ideal. In this study, the flexible approach was followed to conceptualise the recharge-flow-discharge system and to demonstrate how such a process support the nearby river life.

In every developed conceptual model in hydrogeology, geological framework forms the basis for the development. Geological maps, borehole logs, geophysics and field mapping are used to produce the geological framework. The development of hydrologic framework follows in which it is produced from groundwater levels, aquifer hydraulic properties, hydrochemistry and isotopes. Banks et al. (2012) used conceptual modelling to demonstrate how hydrogeological and hydroclimatic controls influence the state of connection in a pristine catchment and the complexities of fractured rock environments. The authors integrated hydraulic, hydrochemical and tracer-based techniques to determine source and loss terms of the river and groundwater system. Regionally, Holland (2011) integrated hydraulic characterisation, recharge investigation, isotope and hydrochemical analysis as the basis of the conceptual hydrological model of the Limpopo basement aquifers. Recently Abiye et al. (2020) conceptualised the hydrogeological setting on catchment scale as compared to Holland (2011). Conceptual hydrogeological model is important step in managing an aquifer and its development should be iterative process, meaning that even though there are available models within Hout River catchment, they must be updated as new data becomes available or as the understanding of the system gets improved. Based on the Holland (2011) and Abiye et al. (2020) studies, the current study developed a conceptual model to explain the influence of site-specific hydrogeological controls to groundwater processes and river.

2.6 Theoretical and Conceptual framework

2.6.1 Theoretical framework of the study

Darcy's Law, an empirical law that suitably addresses and approximate groundwater movement was employed as the theoretical framework for this study. The law states that the fluid flow through the porous bed medium shows direct proportionality to the differences in heights of fluid between the two ends of the filter bed, and inversely proportional to the length of flow path (Freeze & Cherry 1979). It also states that the flow quantity is also directly proportional to the coefficient K which is dependent upon the nature of the porous medium. Darcy's Law has several assumptions: (i) flow will not occur if there is no pressure gradient over a distance (ii) if there is a pressure gradient flow will occur from high pressure towards low pressure (iii) the greater the pressure gradient through the same material, the greater the discharge rate (iv) the discharge rate will be different through different formations even if the pressure gradient is the same in such differing formations (Freeze and Cherry, 1979). In fractured rock aquifers, Freeze and Cherry (1979) argued that Darcy Law is only 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. The theory of Darcy's law is used in understanding groundwater flow system and interpret data pertaining to pumping test.

The concept of hydrogeological characterization is employed for the current study as it involves evaluating various characteristics of the aquifer using different forms of data. This include evaluating the structure (geology), hydraulic properties and the chemistry of aquifers. The aquifer structure is evaluated to understand groundwater occurrence while the aquifer hydraulic parameters are evaluated to understand storage capacity and flow dynamics. Analyses of water chemistry was conducted to aid decision relating to quality of water for various uses as well as understanding of groundwater flow mechanisms. In general, hydrogeological characterization may be carried out to help inform the sustainable use and management of aquifers and their interaction with other water bodies. This study used the concept of hydrogeological characterization to answer the research question "What is the influence of site-specific hydrogeological conditions on groundwater processes and associated ephemeral river?"

Chapter 3 : Description of the study area

3.1 Introduction

This chapter describes the study area. A detailed description of the study area is essential because it informs site selection, applicable methods to collect and analyse the data. Attention is given to rainfall as the source of groundwater recharge in the area, geology as a host media of the recharge water, hydrology (surface water bodies) as a potential source of focused recharge. Such features have potential to facilitate or slow down the recharge, flow and discharge of groundwater and surface water in the study area.

3.2 Location of the study area

The Hout River Catchment (HRC) occupies an area of 2,478 km^2 in the Limpopo River Basin system in South Africa. The HRC is composed of three quaternary catchments namely A71E, A71F and A71G (Figure 3.1). A quaternary catchment is a fourth order catchment in a hierarchal classification system (Ebrahim et al. 2019). The catchment elevation ranges from 840 m to 1,739 m above mean sea level (mamsl). Mogwadi previously called Dendron is the main urban and commercial farming centre situated 60 km northwest of the city of Polokwane, Limpopo. The Mogwadi region is the main source of agricultural production mainly potatoes for the Southern African region (Verster, 2003). Groundwater is largely used in this region for agricultural production since the 1950s making its management a priority facilitated by sound understanding of the groundwater processes.

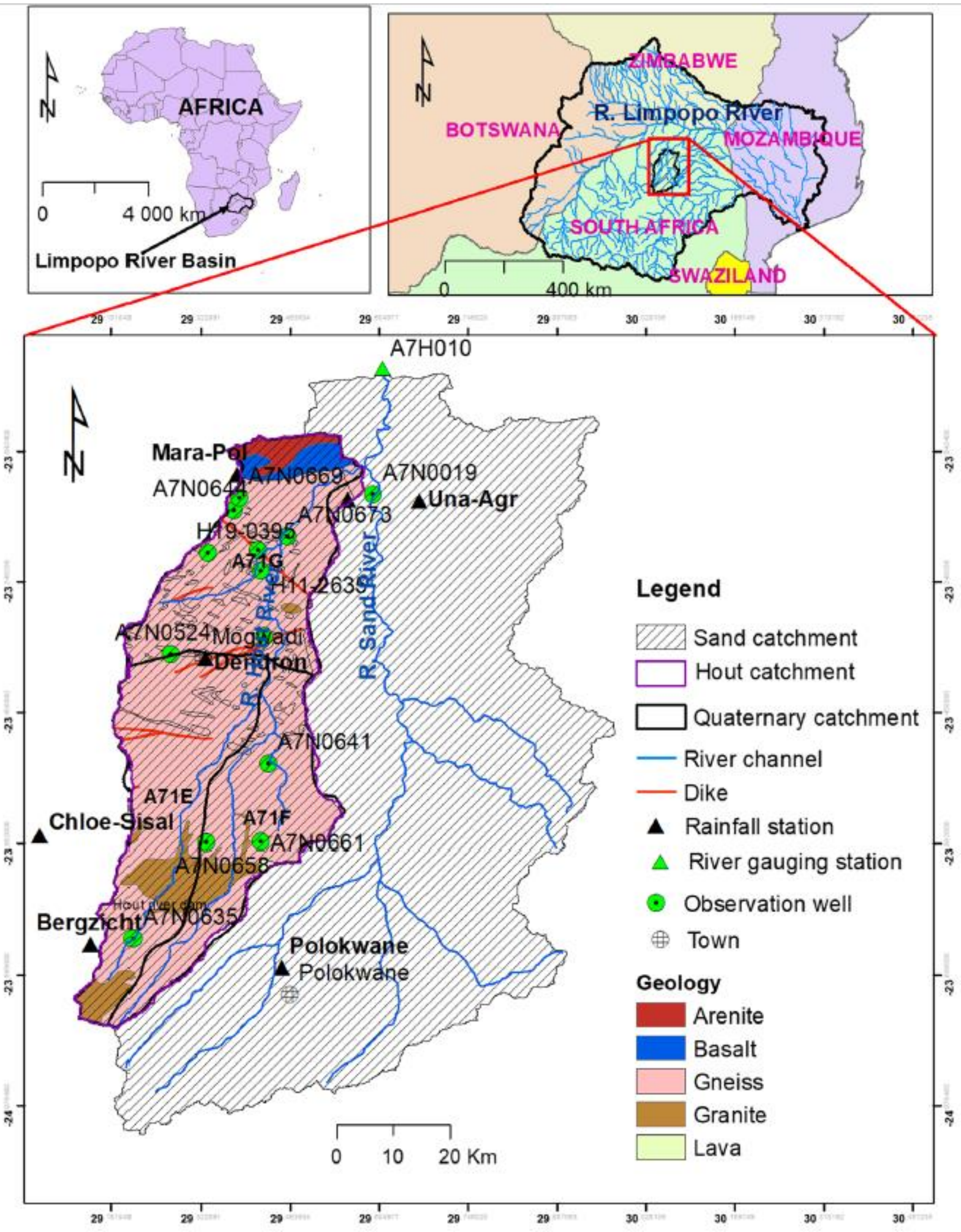

Figure 3.1: Location of the study area with respect to South Africa (Ebrahim et al. 2019)

3.3 Climate of the study area

Climate refers to the long-term change in weather conditions of an area. In this context, climate variables include rainfall, temperature and evaporation. The Hout catchment falls within semi-arid climate with an increasing rainfall trend towards the north. Annual long-term mean precipitation ranges from 300mm/year towards the south and increases up to 700mm/year towards the north where the Soutpansberg Mountains are situated (Lombaard et al, 2015). Data from the Dendron climate station (1972-2015) suggest annual long-term precipitation of 407mm/year (Ebrahim et al. 2019). The catchment experiences most of its rainfall between November and March/April (Figure 3.2) (Masiyandima et al. 2002; Holland, 2011). It is therefore expected that groundwater levels would rise during these rainfall months as a results of rainfall recharge and that the Hout River would experience flows during this time of every hydrological year.

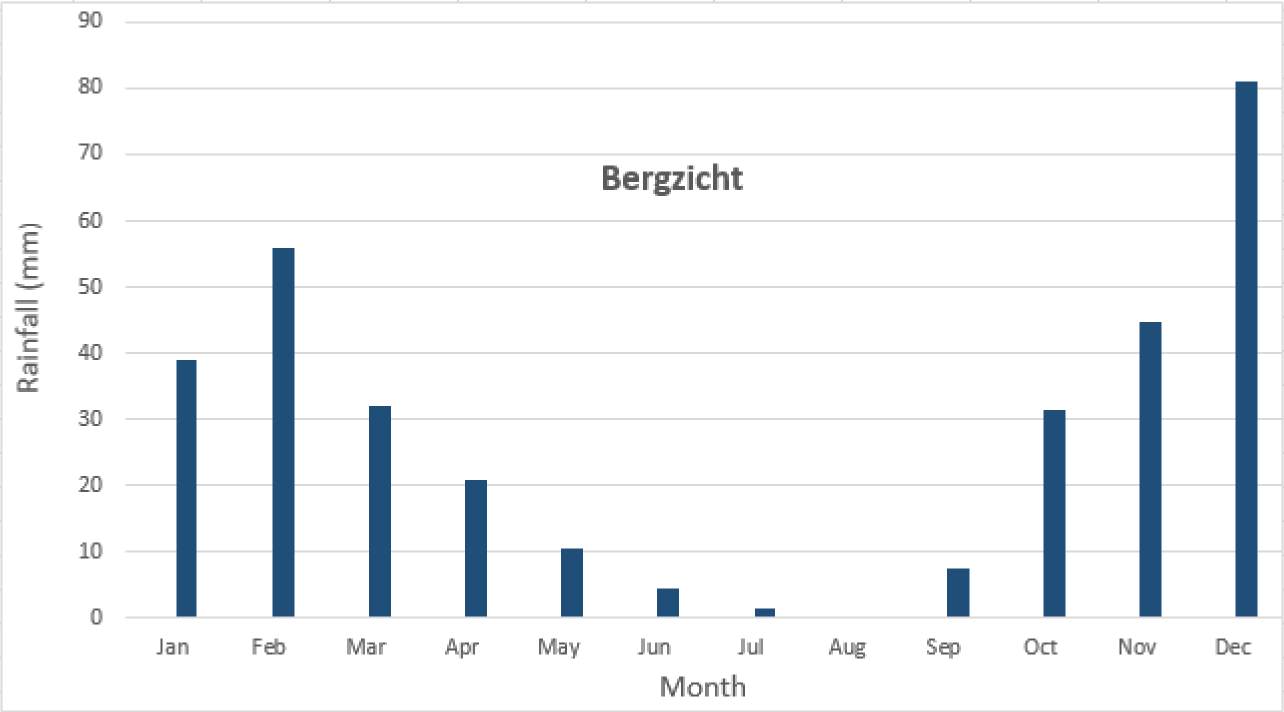

Figure 3.2: Average rainfall for Bergzicht from 2015-2018 (Data source: South African Weather Services SAWS)

The catchment experiences temperatures range from 16°C-30°C in summer to 4°C-22°C in winter (Abiye et al. 2020). Holland (2011) reported that the highest mean temperature recorded is in January and minimum temperatures occur on average in July. Evaporation and evapotranspiration may vary during these months and this may have implication on stream flow as the catchment has rivers that sustain flow only during the wet season (November to March).

3.4 Hydrology

The Hout catchment hosts the Hout River which is ephemeral, flowing intermittently following large and intense precipitation events during the wet season. This River is a tributary to Sand River which drains into the Limpopo River. Hout River Dam is constructed within the Hout River to supply water for the community (Verster, 2003). Alluvium deposits along the Hout River were spotted during field investigation and they ranged between 15-20m. Fallon et al. (2019) analysed the water level data for well A7N0019 which was adjacent to the river. The analyses showed quicker and more pronounced response to rainfall event and maybe influenced by its proximity to the river, probably involving additional focused recharge from the River (Fallon et al. 2019). Also it is noted from field inspection that river ecology is affected in areas with large groundwater abstraction for irrigation as compared communal land (South side of the catchment) (Vegter, 2003). It is therefore important to know the surface water bodies in the study catchment as these features may act as an additional source of focused recharge and at times a groundwater discharging point. It is expected that Hout River may be subjected to naturally high flow variability due to the nature of climate experienced in the study area. During dry periods the river will have sections that have either permanent flows, isolated pools or sometimes completely dry.

3.5 Hydrogeology of the study area

The study area is comprised of three aquifers: a weathered gneiss aquifer (12–50m below the ground), a fractured gneiss aquifer below the weathered zone that extends up to 120 m below the ground and the alluvial aquifer (Dziembowski, 1976; Jolly, 1986; Vegter, 2003; Pietersen et al. 2011; Holland 2011). The weathered aquifer is characterised by weathered zones underlain by fractured basement rocks and is unconfined to semi-confined. On the other hand, the fractured rock aquifer consists of the interconnected network of fractures and is confined while the alluvial aquifer deposits occur along the Hout River (Pietersen et al. 2011). The fractured lower aquifer is known as high yielding due to fractures collecting water, and the upper weathered aquifer is low yielding (Jolly,1986). Screen zone for most of production wells in the area is within the fractured aquifer as the water table is deeper than the weathered zone in most cases (Holland, 2011). According to Jolly (1986) the storage coefficient of the upper and lower units of the aquifer are 0.01 and 0.0025, respectively.

Borehole yield reaching 40*l*/s for the fractured zone have been reported by Pietersen et al. (2011) with low borehole yield (mean yield of 1*l*/s) for the weathered zone due to its low permeability. In the Southern side of the catchment where the Houtriver gneiss overlie the younger granites, the depth of weathering and fracturing is higher. Though in the Northern side of the catchment alluvial or weathered zone is important as its thickness is higher and there is possible episodic recharge from the river itself (Abiye et al. 2020).

In a study by Holland (2011) it is reported that high mean transmissivities are associated with NE, ENE and WNW trending dykes and lower transmissivities are associated with NW and NNE trending dykes. Transmissivities of the aquifer vary between 4m^2/d to 40m^2/d for Limpopo Plateau (Witthuser et al. 2011) in which the current study area falls into. Groundwater recharge within this catchment is highly variable as different authors suggested different estimate, these include Vegter (1992) who estimated recharge as 23.6mm/year in Mogwadi region, in 1995 Vegter estimated a recharge of 8mm/ year in Alldays, a town close to Mogwadi. Masiyandima et al. (2002) estimated a long term annual recharge of 3.8% total annual rainfall while Holland (2011) estimated recharge of 2mm/year in Mogwadi using the chloride mass balance method. Recently Ebrahim et al. (2019) estimated diffused recharge to vary from 1.3 to 44.5 mm/year. Groundwater is solely used for irrigation within the HRC and irrigation areas are increasing putting more pressure to the resource hence understanding recharge processes are of importance to provide baseline information for sustainable groundwater management.

3.6 Geology of the study area

Holland (2011) defined the geology of the HRC as being characterised by the crystalline (granite) complex of the Houtriver gneiss. The Houtriver granitic gneiss is pinkish-grey, pegmatoidal and highly fractured and weathered. Open fractures in the lower zone act as main collectors or conduits of water flow (Fallon et al. 2019). One main structural feature is the Houtriver Shear Zone (HRSZ) cross cutting the catchment in the E-W direction (Figure3.3). The aeromagnetic map exhibit both positive and negative anomalies which are largely influenced by geological structures such as faults and dykes (Figure3.4). The aeromagnetic interpretation showed that positive magnetic anomalies coincide with dolerite dykes trending NE-SW direction, granites, Greenstone remnants and Soutpansberg Group rocks. This area could influence groundwater flow and its spatial occurrence while the areas with negative anomalies like highly weathered zones could be considered as sites with high groundwater potential. Based on the aeromagnetic map it is visible that some dykes may not be magnetic as not all dykes and lineaments in the aeromagnetic map coincide with high magnetic anomalies.

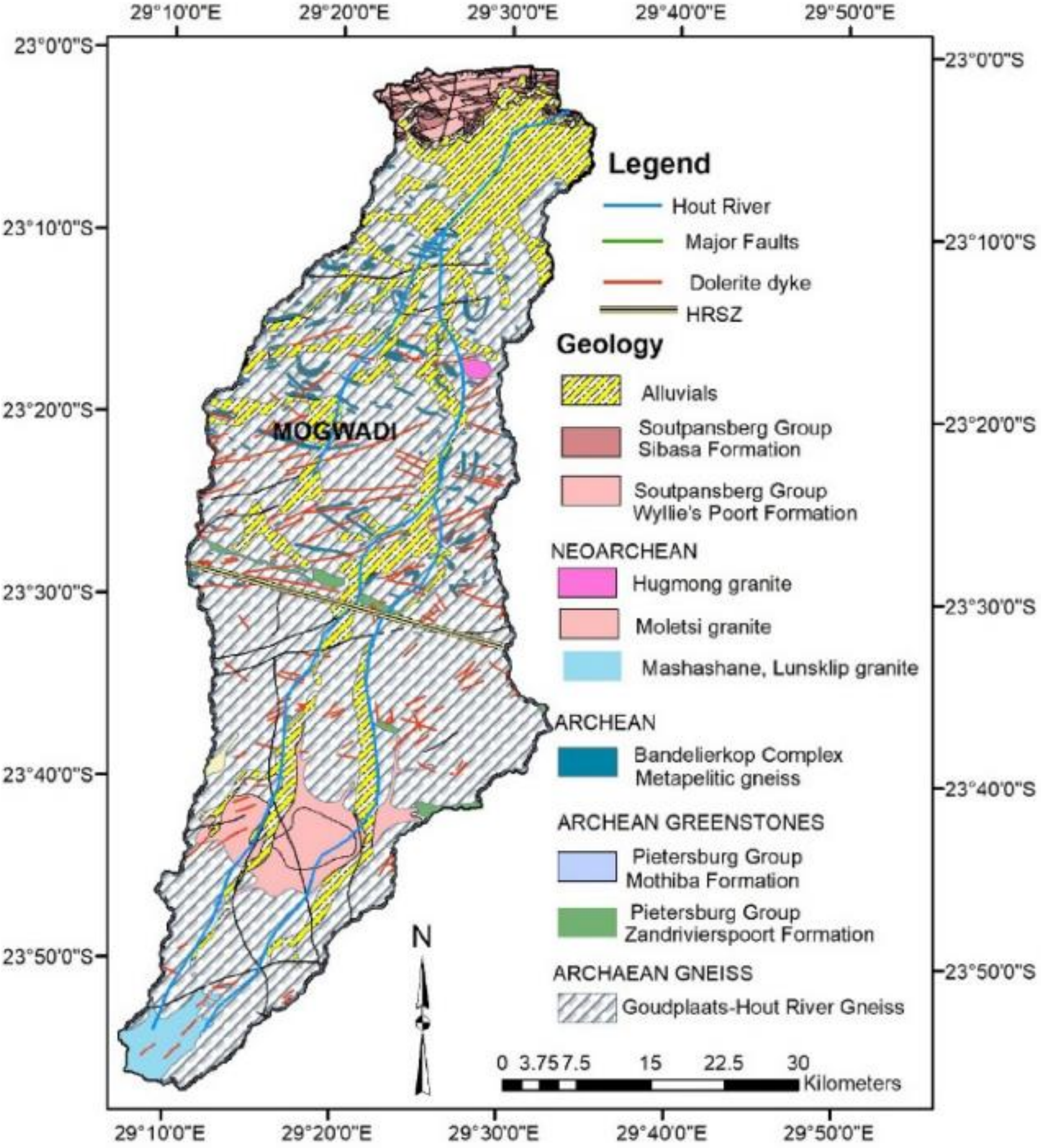

Figure 3.3: Geological map of the HRC with the HRSZ cutting the catchment in the E-W direction with almost equal portion. (Data source: Council for Geoscience, map adapted from Abiye et al. 2020)

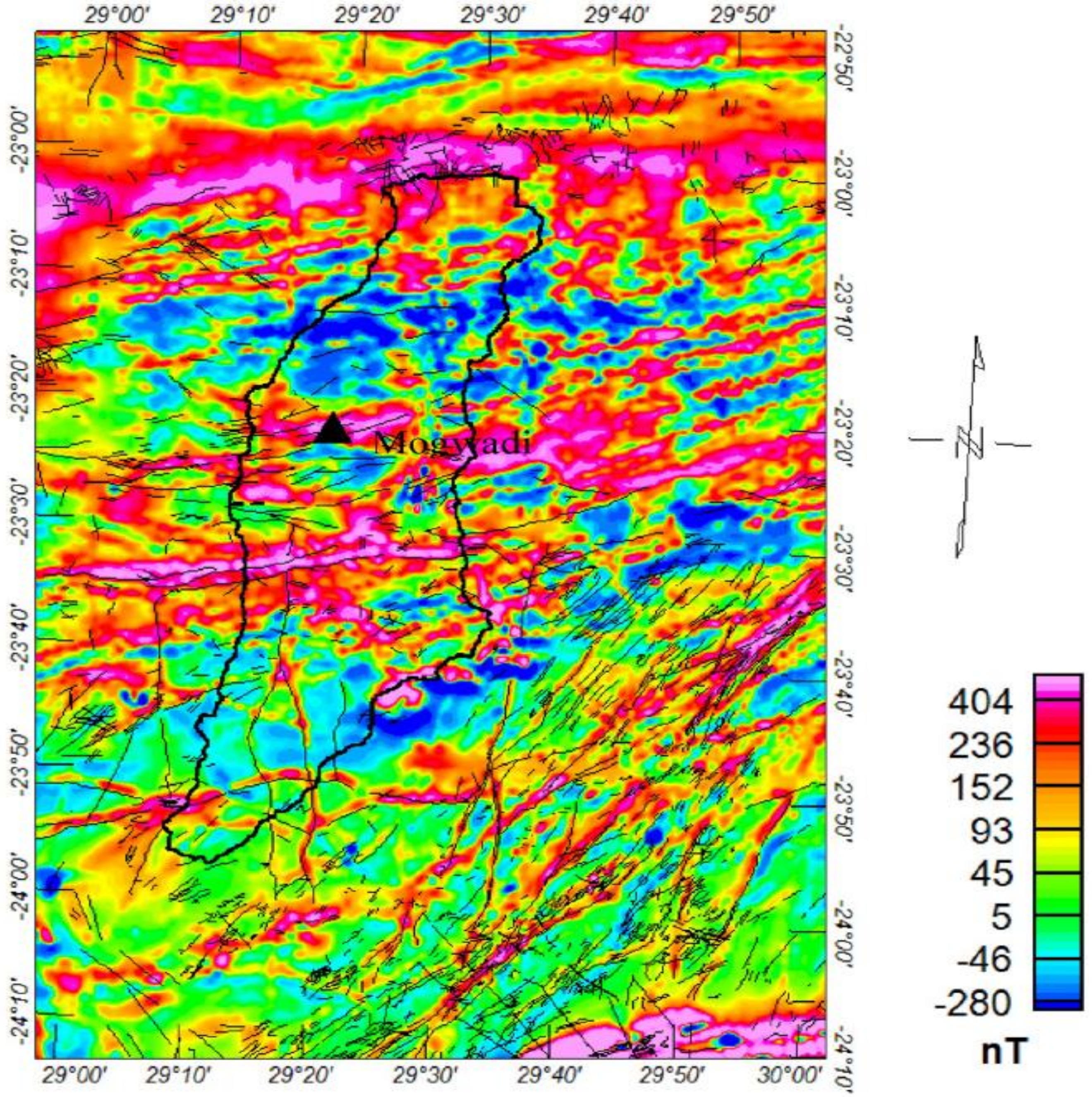

Figure 3.4: Aeromagnetic map with superimposed geological structures in HRC (Data source: Council for Geoscience, map adapted from Abiye et al. 2020)

The formation is predominantly exposed in the regions where ephemeral streams occur, with its occurrence being most prevalent in the region extending from Polokwane - in the south, up to the Soutpansberg in the north. The gneissic formation is intruded by dykes (Figure3.5) with rocks belonging to the Bandelierkop Complex that predominantly trends northwest and northeast (Du Toit and Sonnekus, 2014), occurring as highly deformed keels within the formation. Two major igneous events account for most of the dykes occurring within the study area. The younger doleritic dykes are of the Karoo age while the older Diabase dykes are generally considered to be from the Bushveld complex. These intrusive dykes, mostly with a varying thickness from 7 to 20m (Jolly, 1986) are assumed to influence groundwater flow patterns within the study area.

Figure 3.5: Intrusive diabase dykes cutting through pink gneiss formation.

These different geological formations would influence the extent of aquifer-river connectivity affecting both quantity and quality of exchanged water. Furthermore, it is evident from the field work that areas that have a dyke cutting through the river channel have moist zones to permanent pools (Figure 3.6).

Figure 3.6: Contrasting images of the river bed at Mamadila experimental site taken during the field visit showing a dry river bed with moist zones found where the dyke is cutting through the river channel.

3.7 Selection of study site

Four potential experimental sites (Figure 3.7) within the HRC were identified based on geological and hydrogeological criteria in order to select one site which will be suitable to answer the research question of current study. The regional geology and description were inferred from the 1:250 000 map of the study area. Based on the above-mentioned criteria, each site was evaluated: Site 1: Situated within Hout River Flood plain, in addition the geological setting falling within a region that has several faults and dykes' structures inferred with noticeable change in lithological contact. In addition, visible surface water pools were observed along the river channel. Site 2: Dense network of dykes and noticeable changes in lithological contact are situated within alluvial flood plain of the Hout River. Site 3: Situated within alluvial flood plain with an existing surface water feature in the form of a focused recharge dam and has a dense network of dykes. There are noticeable changes in geological contacts within the area in addition to groundwater being pumped in a farm dam. Site 4**:** Situated in the headwaters of Hout River and within the vicinity of the Hout River dam comprising the alluvial aquifer. Visible surface water pools were observed along the river channel.

Several methodologies were implemented to select the optimal experimental site, these included a review of the geological setting of the underlying aquifer system; sentinel 2 time series analysis of using rainfall data for 2016 & 2017; distribution of average static groundwater level in relation to topography and aeromagnetic geophysics assessment. Based on these methodologies site 4 was chosen as the experimental site because of the un impacted river system, before the dam, high fracture network within the parent rock, existence of visible dykes on the river segment which control river aquifer interaction, visible surface water features at points where dykes are cutting the river (Figure 3.8), nearness to community for citizen science (contributed to data monitoring). Site1 and 2 had no river flow and visible features for monitoring and hence not ideal sites while site 3 had interesting features like site 4 however, it is situated in a disturbed hydrological environment with much pumping of groundwater.

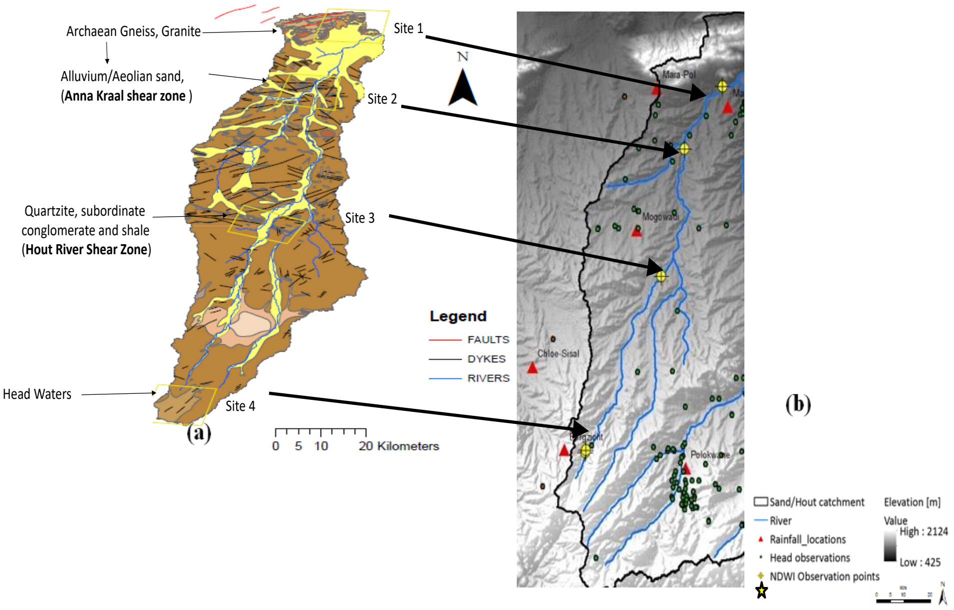

Figure 3.7: (a) Geological Map and (b) satellite topographic imagery of the Hout River Catchment indicating the four potential experimental sites for the project.

Figure3.8: Isolated perennial water pools at the dyke features, suggesting that the dykes control groundwater flow within the Houtriver gneiss formation.

Chapter 4 : Research design and methodology

4.1 Introduction

The current chapter explains methods that were used to collect and analyse data for the study including the research design, research integrity and quality assurance aspects that were followed in carrying out the study. All these aspects enabled the researcher to answer the research question and achieved objectives outlined in chapter 1. This chapter is divided into three sections as follows: a] research design, b] research methods and c] quality assurance where issues of reliability, validity, research ethics and study limitations are discussed.

4.2 Research design

4.2.1 Research design approach

The study was designed to follow an integrated approach by assessing different characteristics influencing groundwater flow, hydrochemistry and interaction between the aquifer and ephemeral river. A field experimental study type was followed in which four boreholes were drilled in the Mamadila site along the river and measurements were conducted along the river. This approach was used to allow quantitative and qualitative assessments to be done.

4.2.2 Sampling design

There are different sampling design and approaches that could be used in research. These include purposive, reliance, cluster and random sampling design amongst others. The current study used a purposive sampling design in which the units to be observed were selected on the basis of researcher's judgement. Purposive sampling design was used based on the study objectives to characterise and explain possibility of the aquifer discharging to the river or river recharging the aquifer. The samples were therefore collected along the river reach and from boreholes close to the river.

4.2.3 Unit of analysis

For the first objective of this study which focuses on evaluation of hydrogeological characteristics of the study aquifer, the unit of analysis was the aquifer hydraulic parameters and properties. For establishing groundwater contribution to the river system and vice versa using hydrochemical and environmental isotope analysis, the unit of analysis was the major cations and stable isotopes such as ^{18}O and ^{2}H from both groundwater points and surface water points under study.

4.3 Research methodology

The methodologies for a research study included quantitative, qualitative, mixed (quantitative and qualitative) and participatory. Quantitative research, which was employed in this study, is an approach for testing objective theories by quantifying variables and examining the relationships between variables. In this study, numerical data were collected and analysed on groundwater levels, aquifer hydraulic parameters, hydrochemical and isotopic composition as well as other components of the groundwater balance were made.

4.4 Data collection and analysis methods

4.4.1 Evaluation of hydrogeological characteristics of the crystalline basement aquifer.

The first objective of this study was to evaluate hydrogeological characteristics the aquifer system in which geophysical methods were applied in inferring potential drill targets within the Houtriver gneiss crystalline basement aquifer system as well as identify conditions for groundwater occurrence. These boreholes were drilled to conduct pumping test and finally determine aquifer hydraulic parameters (T and S). In addition to aquifer parameters groundwater levels were analysed to give indication of groundwater flow and borehole logs were analysed to show the geology encountered at depths within each borehole. Transmissivity is a hydraulic parameter which explained groundwater flow.

Regarding site selection for borehole drilling, geophysical methods were used, these included 1D ground magnetics in which a proton magnetometer was used followed by frequency domain electromagnetic exploration methods using EM34 unit as a horizontal profiling method to identify points of potential interest along the line. Lastly, vertical electrical sounding (VES) using the wenner electrode configuration was used on selected potential sites to infer the variation and thickness of the underlying layers at selected anomalous regions (Figure 4.1). In this electrode array survey, the distance between the current electrodes is always equal to three times of the potential electrodes with all the electrodes being after each measurement (Wenner, 1916). The choice of the Wenner array was informed by its ability to resolve a multiple layered system because of its high vertical resolution) suitable for a multilayered formation (like the Houtriver gneiss formation described in Jolly (1986)), (Wenner, 1916; Zody et al. 1974).

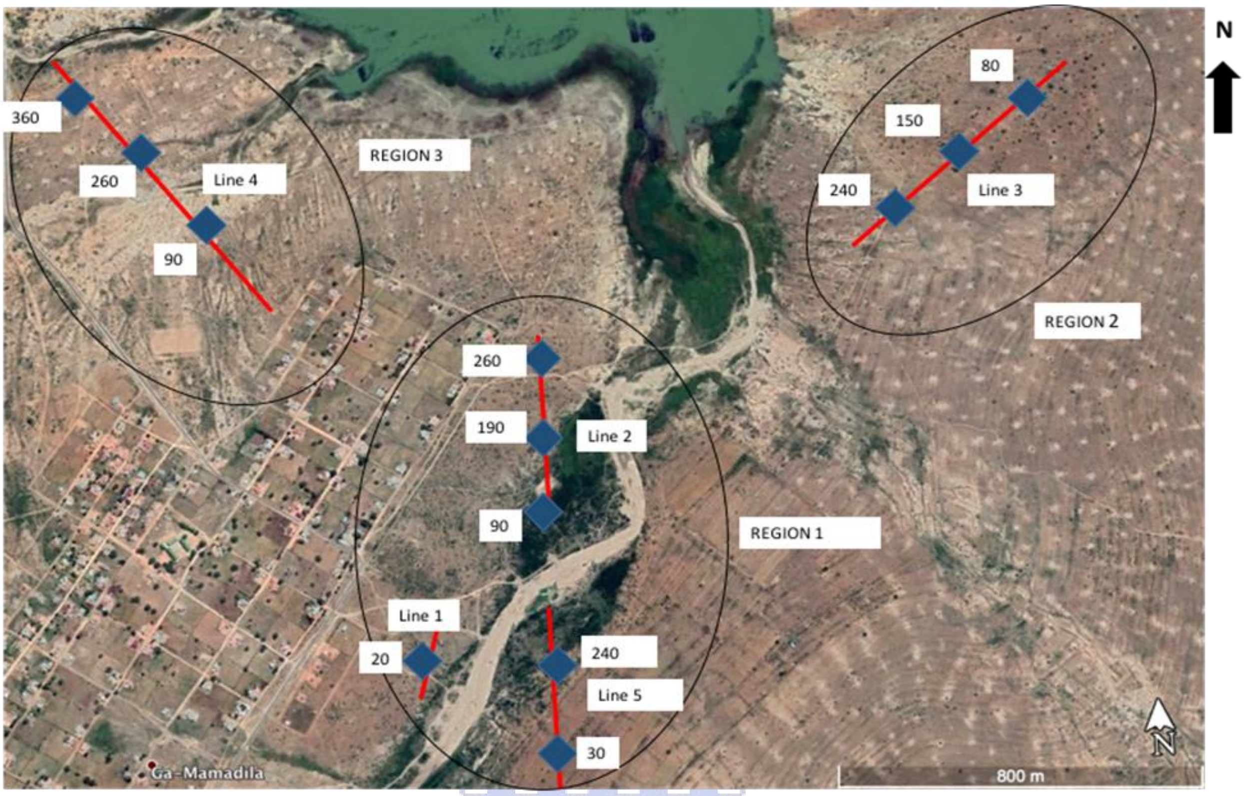

Figure 4.1: Google earth images of the study area showing the horizontal profile lines and positions for vertical electrical sounding sites (in m) for survey regions 1-3.

Data collection procedure

During magnetic surveys, firstly the geological strike and the regional trend of faults and dykes in the region of interest were determined so that the survey is planned such that the lines are perpendicular to geological strike, faults and dykes since they are clearly visible in survey when approached at 90^0 to strike. Along all geophysical survey lines data were collected at 10 metre intervals within each line using proton procession magnetometer. A total magnetic profile was produced and points with contrasting magnetic susceptibilities were identified. As a complimentary profiling tool, the frequency domain electro-magnetic (FDEM) method was used to come up with improved selection of VES points along all transect lines. Lastly vertical electrical resistivity sounding was done to investigate the vertical layering in the formation and in assessing the groundwater potential of selected sites. Magnetic surveys were successfully used to obtain information pertinent to the presence of indirect groundwater features such as the presence of faults, lineaments and dykes that form aquifer boundaries or act as controls to subsurface flow in crystalline basement aquifers.

To determine aquifer hydraulic parameters, aquifer tests were conducted in four boreholes that were drilled during the course of this study. Pumping test was conducted using BP 40-mono pump. To determine the appropriate discharge rate for constant test, a step test was conducted for about 6hrs 30minutes with maximum discharge rate of 8.12L/sec. Based on the results from the step test, borehole HO4-3126 was pumped at 4.20 L/sec while borehole HO4-3127 was pumped at 5.88 L/sec for the duration of 48hrs. This duration was chosen based on the fact that heterogeneous and discontinuous nature of crystalline basement aquifers requires generally long term testing. Drawdown was measured by subtracting all subsequent depth to groundwater levels from the initial static water level.

Different researchers in Limpopo crystalline basement aquifers, analysed pumping test data using classical analytical models such as Theis (1935) and the Jacob's approximation (Cooper and Jacob, 1946) method. These methods in additions to methods such as Barker (1988) are collated together with graphical plots (i.e. semi-log, log-log & derivatives) into the Flow Characteristic (FC) excel spreadsheet developed by the Institute for Groundwater studies in South Africa (Van Tonder et al. 2002). The analysis of the aquifer test data of the current study however were done according to the type of the aquifer system, borehole characteristics. The data were analysed with the software package AQTESOLV Pro version 4.5 using automatic curve fitting or manual fitting of late time data with the appropriate analytical solution/conceptual model (i.e. confined, unconfined, leaky and fractured aquifers). The software also allows for a visual and automatic curve matching to solution type curves.

4.4.2 *Characterising spatial variation in aquifer river interaction*

There are various methods that can be used to assess aquifer-river interaction. Some are suitable for perennial river systems while others are suitable for non-perennial river systems. Because of the nature of study, only methods that were suitable for non-perennial river systems were given attention. These can be grouped into field-based measurements and desktop methods. Field based methods include hydrometric analysis, hydrochemical analysis, environmental tracers, stable isotope analysis, remote sensing, geophysical and field indicators. Hydrogeological mapping, modelling and hydrographical analysis can be of desktop methods. Each method has its own advantages and disadvantages, and they differ in terms of their application procedure and scale to be applied at. To achieve objective two of the study which is focusing on aquifer-river interaction, confirmatory methods like hydrochemistry and environmental isotopes were chosen to confirm the possible interaction in the chosen sites. Assessing possible interaction provides better understanding of groundwater recharge, discharge and flow processes

Environmental isotope analysis

For environmental isotope analysis, field sampling was carried out during dry season which is represented by sampling period of June 2019. Further isotopic data were obtained from the following source, Abiye et al. (2020), which included stable isotopes (^{2}H, ^{18}O and ^{13}C) and radiogenic isotope (^{14}C). As part of this investigation, grab sampling technique was adopted during the sampling for environmental isotope (^{2}H and ^{18}O) analysis. This technique was applied for sampling in the river while borehole samples were collected during pumping test at discharge point at a specific depth ensuring that representative sample is collected from around the borehole screen area. Plastic isotopic bottles with tight fitting caps were used to collect the samples. Prior collection of samples these bottles were thoroughly rinsed and ensured that during filling they were filled to the top and were tightly closed to prevented evaporation which is one factor to be prevented when sampling for isotopic analysis. Isotopic ratios might be altered if evaporation takes place. Correct labelling of the sampling was done and care in transportation and packaging was of priority to prevent any spillage and misinterpretation of laboratory results which might results from wrong labelling. Furthermore, cooler box was used to preserve the samples while keeping the temperature standards to further prevent evaporation.

To analyse the isotopic samples that were collected, LGR DTL-100 Liquid Water Isotope Analyzer (Model 908-008-2010) manufactured by Los Gatos Research Inc was used following the standard method. The results were represented as deviation from Vienna and given in delta notation from the equation:

$$\delta^{18}O\ (\delta^{2}H) = \left(\frac{R\_sample}{R\_standard} - 1\right) \times 1000$$

R is the isotope ratio of the heavy to the light isotope ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) in both the sample and the standard. The standard is called the Vienna Standard Meteoric Ocean Water (VSMOW) (Craig, 1961). Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) are conservative in nature and have been used to trace flow paths and sources of rainfall and groundwater within a hydrogeological system. Variations in atomic mass of elements results into different reaction rates causing fractionation (Clack and Fitz, 1997). For referencing purposes, the resulting stable isotope data were plotted along with the Local Meteoric Water Line (LMWL) and global meteoric water line (GMWL). GMWL was derived from the Craig (1961) equation: $\delta D = \delta^{18}O + 10$ while LMWL is found from a best line fit of locally derived rainfall samples. Pretoria LWML was used.

Hydrochemical analysis

For hydrochemical analysis, field sampling was carried out during dry season which is represented by sampling period of June 2019. Secondary datasets were also collected from the review of records to strengthen the database. Grab sampling technique was used to sample river water while groundwater samples were collected during pumping test conducted. Plastic bottles were used to collect the samples, depending on the availability of water along the river reach, the depth where the samples were collected varied. Grab sampling technique involves inserting a plastic bottle directly into the river water vertically ensuring that the opening is facing down until desired depth then the bottle is turned upwards allowing the sample to flow into the bottle. Temperature, pH value, dissolved oxygen and electrical conductivity were measured in-situ using a HachTM HQ40D portable multi-parameter probes since these parameters do change once the water samples are exposed to ambient conditions and during storage and laboratory analysis. The parameters were only recorded when the meter had stabilized. The probe was calibrated before field trip using standardized solutions within the EC and pH ranges in the study area. Correct labelling of the sampling was done and care in transportation and packaging was of priority to prevent any spillage and misinterpretation of laboratory results which might results from wrong labelling.

All water samples were analysed for major ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO^{3-}), sulfate ($SO4^{2-}$) and chloride (Cl^{-}) since these ions comprise over 90% of all dissolved solids in groundwater regardless of whether the water is fresh or saline (Freeze and Cherry, 1979). Major ion results were presented in a Piper diagram. Piper diagrams consists of two trilinear diagrams (plots with three axes) and one diamond shaped mixed field. The trilinear diagram on the left-hand side represents the cation concentration while anion concentrations is represented on the right-hand side. Piper diagrams can plot numerous water samples onto a single diagram and classify waters according to their chemical characteristics. The diamond shaped mixing field between the two trilinear diagrams allows the graphical interpretation of the mixing of two or more end member waters. Due to that similarities and differences between separate water analyses can be spotted, therefore, it is suitable for analysing spatial variations in interactions.

4.4.3 Development of groundwater process conceptual model

Record review and field measurements are two methods that were used to collect dataset that were used to develop site specific hydrogeological model to assess aquifer-river interaction in relation to groundwater recharge and discharge process. To collect existing dataset such as geological, hydrological, climatological and geographical datasets record review was used. These are collected because they are required when setting up a model. Geological dataset collected included borehole logs, geological map and geological cross sections of the study area. Climatological dataset included precipitation data and distribution of that data to correlate with groundwater levels. Hydrological data included water levels from monitoring wells and previous investigations on the aquifer and the river or any surface water body in the vicinity. Geographical dataset included soil maps, land use maps, aerial photographs and topographical maps. These records were obtained from government agencies, local and private organizations. Field measurements included water level monitoring along selected boreholes and along the river.

Once all the necessary data was collected, hydrogeological conceptual model that explains aquifer-river interaction was be developed. This model explaining groundwater contribution on the river system of the study area was produced using Surfer 11 software. Abiye et al. (2020) produced the groundwater level contour map to infer potential groundwater flow direction for the catchment.

4.5 Quality assurance and quality control

All water samples were analysed at an accredited laboratory which is accordance with the international standards. Bottles that were used for storage of the samples were pre-rinsed at least three times before sampling and to ensure that same site is sampled for each sampling day, GPS was used to locate the site. Field water quality parameters which changes during transportation were measured during the field work on site. This was done to get representative samples of the site and calibration of the multi-parameter probe was done on each day of the field work. Before any use of the hydrochemical data, cation-anion balance was calculated for each sample so that only suitable samples were included in the analysis.

Younger (2007) stated that only samples that are below 5% can be used and those in range of 10-15% they should be used with caution. Samples with cation anion balance above 15% should be discarded. This was done to follow the principle of electroneutrality which states that water cannot carry the net electrical charge but must always be electrical neutral. The results from this study were compared to those that are conducted in the same setting as the study area.

4.6 Research integrity

This study involved different parties and because of that there were legal considerations to adhere to. These included meeting held with the community of Mamadila where this experimental study 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” (ESGUSA) 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 them. Permission to use data from the South African Weather Service was obtained through an agreement between the researcher and the institution and non-disclosure form was signed. Furthermore, all the data requiring confidentiality were kept under such way and were not shared among other third parties neither used for other purposes apart from this research.

4.7 Limitations of the study

Various challenges were encountered during the implementation of the current study as follows: The first limitation was that there was no adequate time to collect all the required data sets within the experimental site to clearly observe the trends over the longer term. This limited the understanding of changes in parameters being analysed. To overcome this lack of change detection analysis on primary data sets, secondary data were collected and used for trend analysis to infer the patterns. The second challenge was the nonexistence of the river flows to give us primary data on river recharge or river discharge and lack of secondary data on river flows that could give an indication of time when the river flowed or flows. This limited the understanding for field observation on the focused recharge in the in-stream of the river. To overcome this limitation sampling was conducted where there were pools along the river reach to check whether such water was from dykes discharging onto river bed or river water recharging subsurface system.

Chapter 5 : Evaluation of hydrogeological characteristics of the aquifer system.

5.1 Introduction

This chapter presents and discusses results of the evaluation of hydrogeological characteristics of the aquifer system of the study area, which forms the first objective of the current study. Firstly, results and interpretation on geophysics data sets and borehole logs are provided to show that groundwater occurrence within Houtriver gneiss formation is described by a heterogeneous multiple-layered and fractured aquifer system. Secondly, results and interpretation on nature of groundwater levels and aquifer tests are provided to show that groundwater flow properties are influenced by the subsurface heterogeneities. Based on the above description, this chapter argues that in order to determine the aquifer influence in Hout River it is necessary to understand the hydrogeological controls to groundwater flows such that under natural conditions the exchange fluxes between the aquifer and the river would largely depend on the groundwater level hydraulic gradient and the aquifer hydraulic properties.

5.2 Geophysics results and interpretation

Interpretation of results for this section was based on plots of both profiling (magnetic and Electro-Magnetic (EM)) and Vertical Electrical Sounding (VES) field measurements. The interpretation was done according to region 1, 2 and 3 (Figure 4.1) where each region consists of profile lines. In each region, geological contacts or structures likely to control groundwater occurrence were identified using results of the lateral profiling obtained using magnetic and electromagnetic methods. These are presented first followed by the probable depth layering and the possible distribution of various litho-stratigraphic sections that could influence the groundwater potential of the area as indicated by arrows. Position of the anomaly was obtained by electrical resistivity sounding done on anomalous zones.

5.2.1 Region 1

Profile 1 and 2 were carried out during the field survey. To investigate the variations in horizontal geologic structures that likely influence groundwater dynamics within the study area, 1D magnetics survey, horizontal and vertical electromagnetics were done on profile line 1 (Figure 5.1a). At 20m point along the line, two profiling methods managed to pick an anomalous region. Another potential geological contact at 50m was suggested based on detected magnetic anomaly. However, it was inferred as a dry geological contact as this magnetic anomaly is not well complemented with significant changes in electrical conductivity from both vertical and horizontal FDEM results. Only the anomalous region at 20m was further investigated for depth variation using the electrical resistivity sounding method. Field electrical resistivity measurements suggested a single fractured region between depths 24 m to 54 m from the ground surface (Figure5.1b). Profile line 2 had three main anomalous zones identified using the magnetic profiling and electromagnetic methods (both horizontal and vertical), (Figure5.2a) and VES profiling was done at 90m, 190m and 260m (Figure5.2b). On the southern side of the riverbank, an additional profile line (named line5) was done to infer potential groundwater targets. Anomalous zones at 30m and 240m were observed using Magnetic and EM profiling on the southern bank (Figure5.3a). Vertical electrical resistivity sounding investigations were further conducted on the three identified sites and the results suggest a predominantly multiple layered formation (Figure5.3b). The results suggest that these sections have a varying thickness in which weathered zone and fractured region have a high groundwater bearing potential (suggested by reduced measured apparent electrical resistivity values) and the inferred thickness of these layers in region 1 makes the area potentially high groundwater yielding.

5.2.2 Region 2

Profile line 3 was done in this region, which was cutting through a pegmatitic lineament and with an orientation towards the East-West direction. 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 (Figure5.4a). The cross-sections inferred from the vertical electrical resistivity sounding suggest highly weathered zone and several fractured sections (Figure5.4b). Multiple fractured layers being suggested from the resistivity cross sections suggest a high groundwater potential within the site.

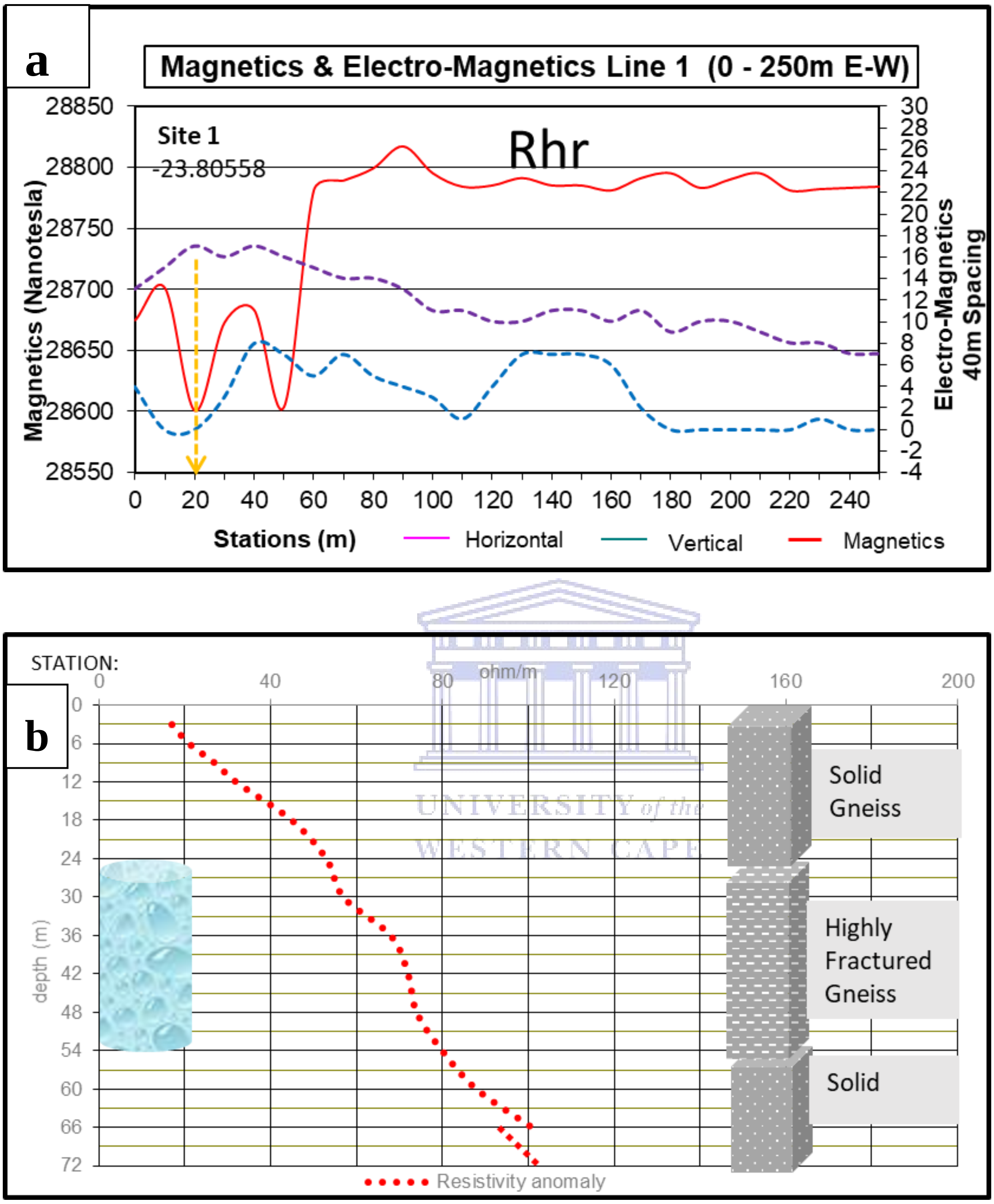

Figure 5.1: (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 1 showing an anomaly at 20m and (b) The corresponding vertical electrical resistivity section together with the inferred depth variation profile from the interpretation of field electrical resistivity results.

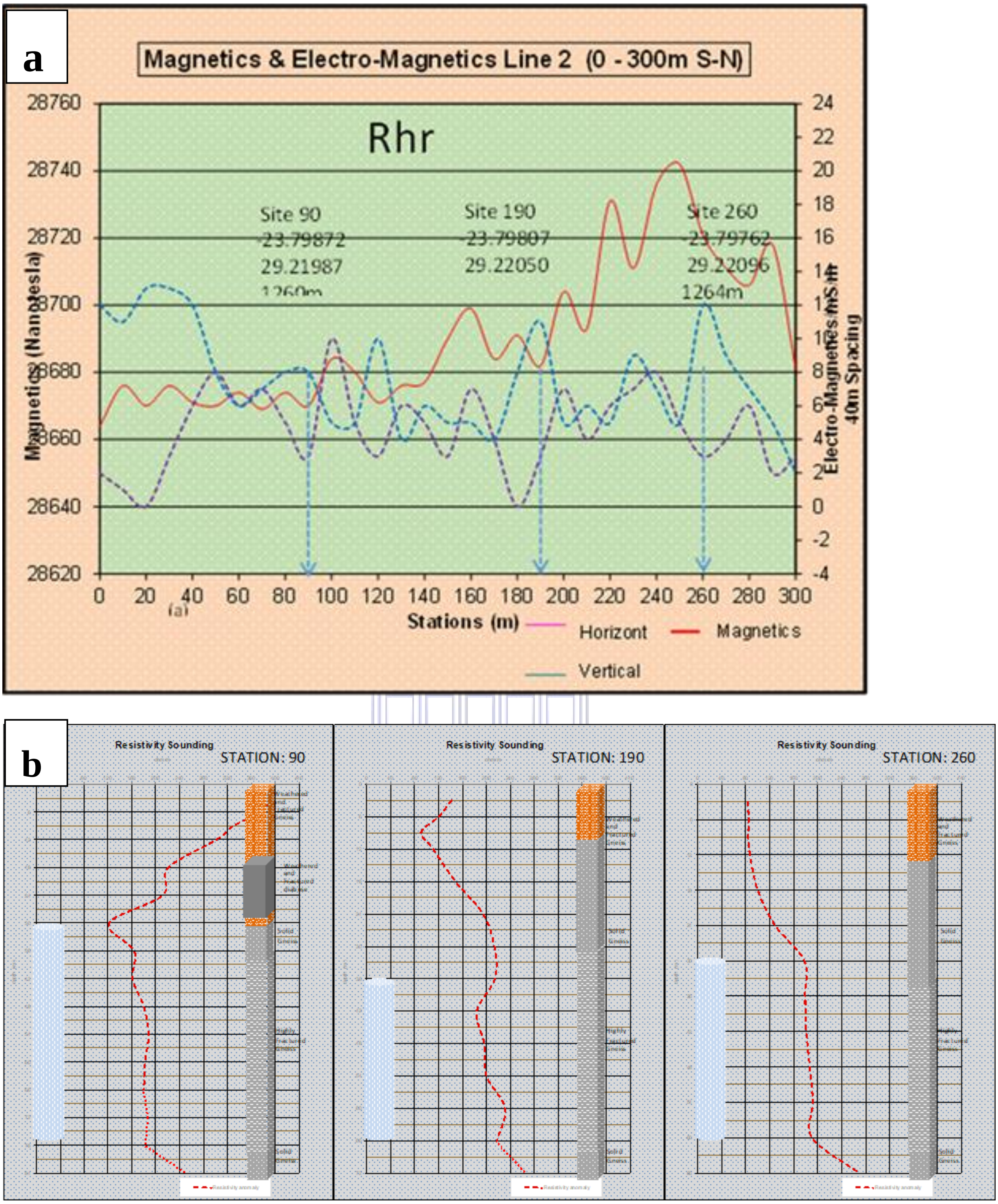

Figure 5.2: (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 2 showing potential groundwater anomalies at 90m, 190m and 260m and (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from the interpretation of field electrical resistivity results.

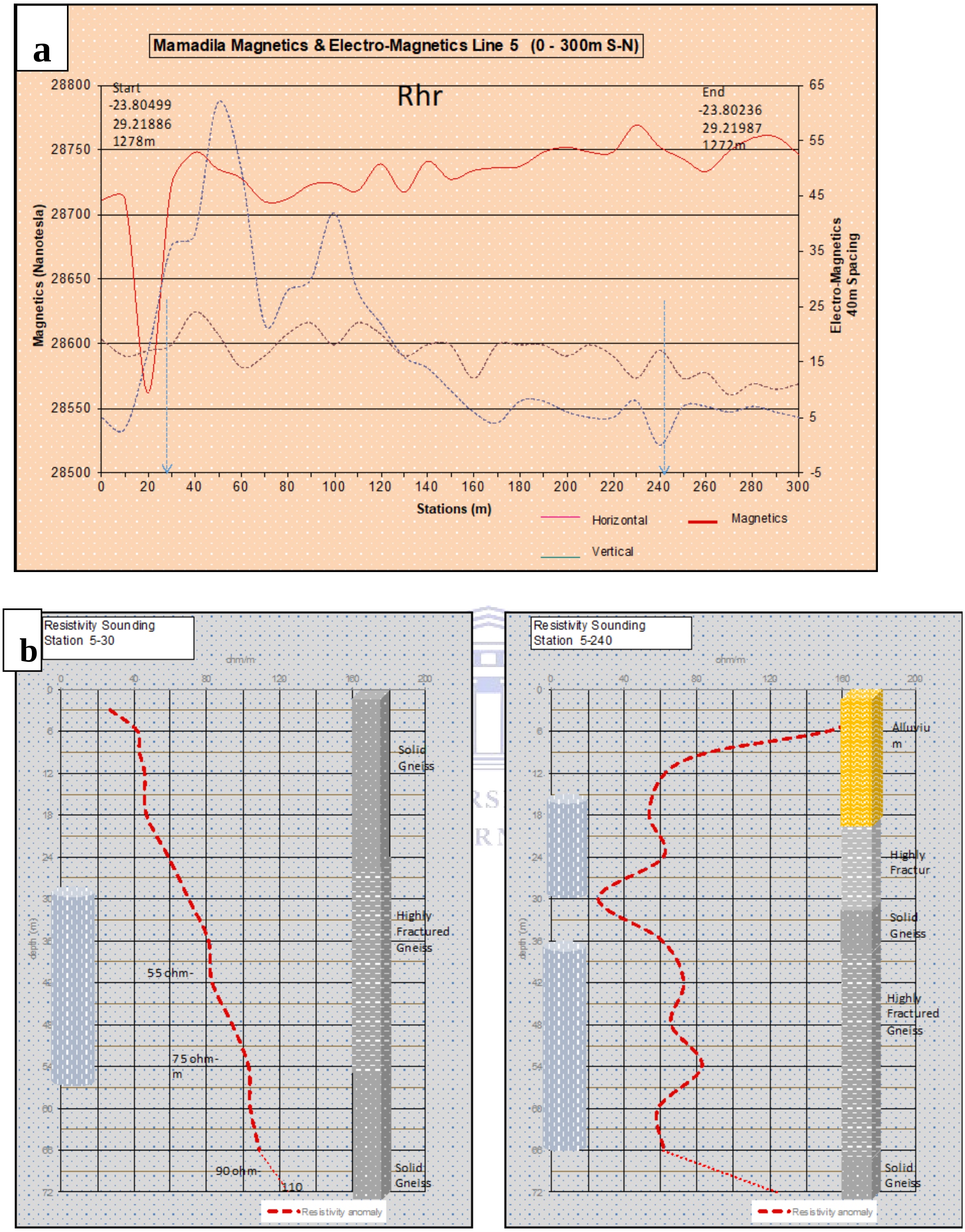

Figure 5.3 5: (a)Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 5 showing potential groundwater anomalies at 30m, and 240m and (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from the interpretation of field electrical resistivity result

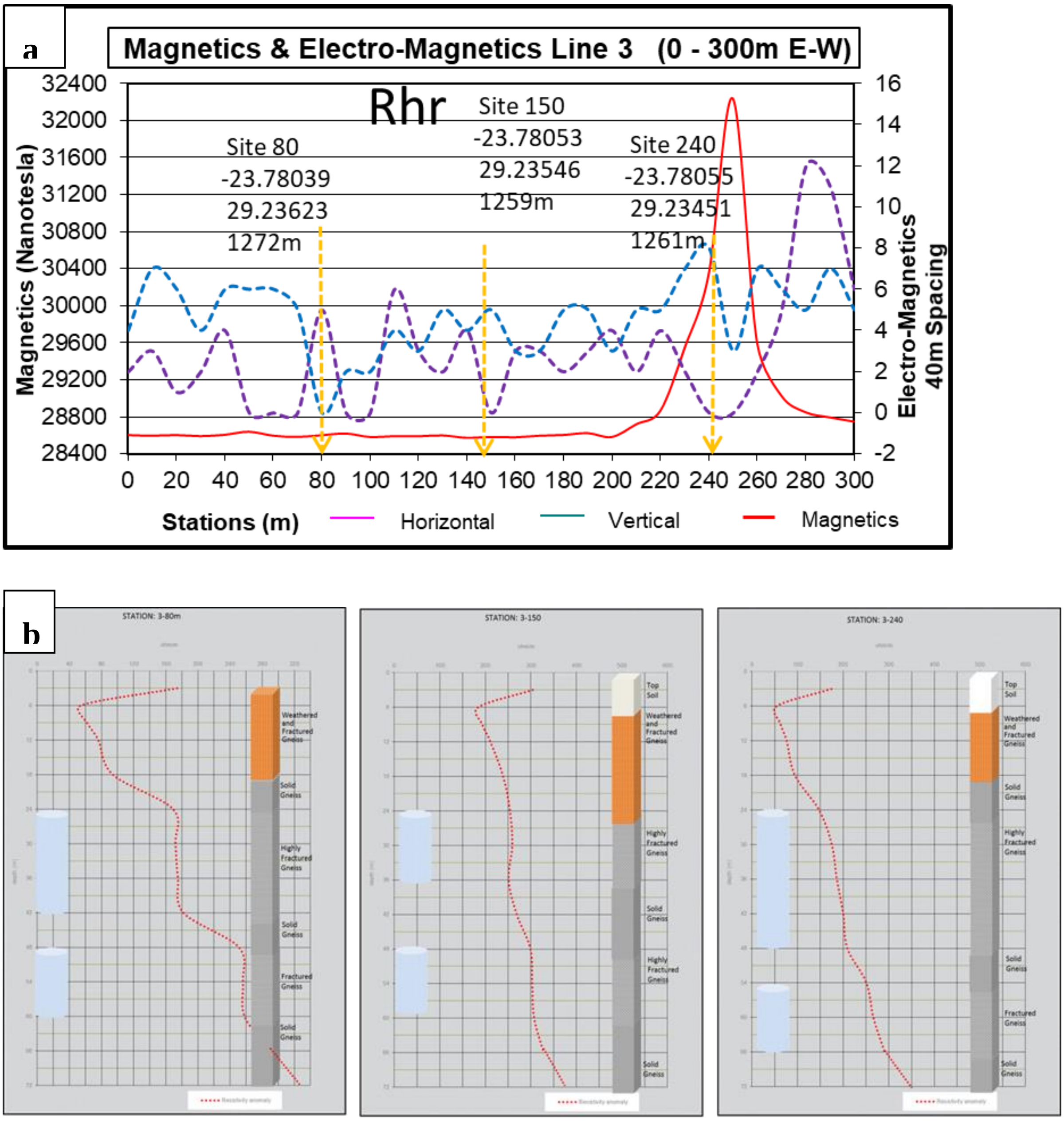

Figure 5.4:(a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 3 showing potential groundwater anomalies at 80m, 150m and 240m and (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from the interpretation of field electrical resistivity results.

5.2.3 Region 3

Profile line 4 was done in this region with total length of 400m and a North South orientation (Figure4.1). Anomalous regions at 90m, 260m and 360m were obtained when using magnetics and electromagnetic survey results (Figure5.5a). All these regions were subjected to further investigation using 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 (Figure5.5b).

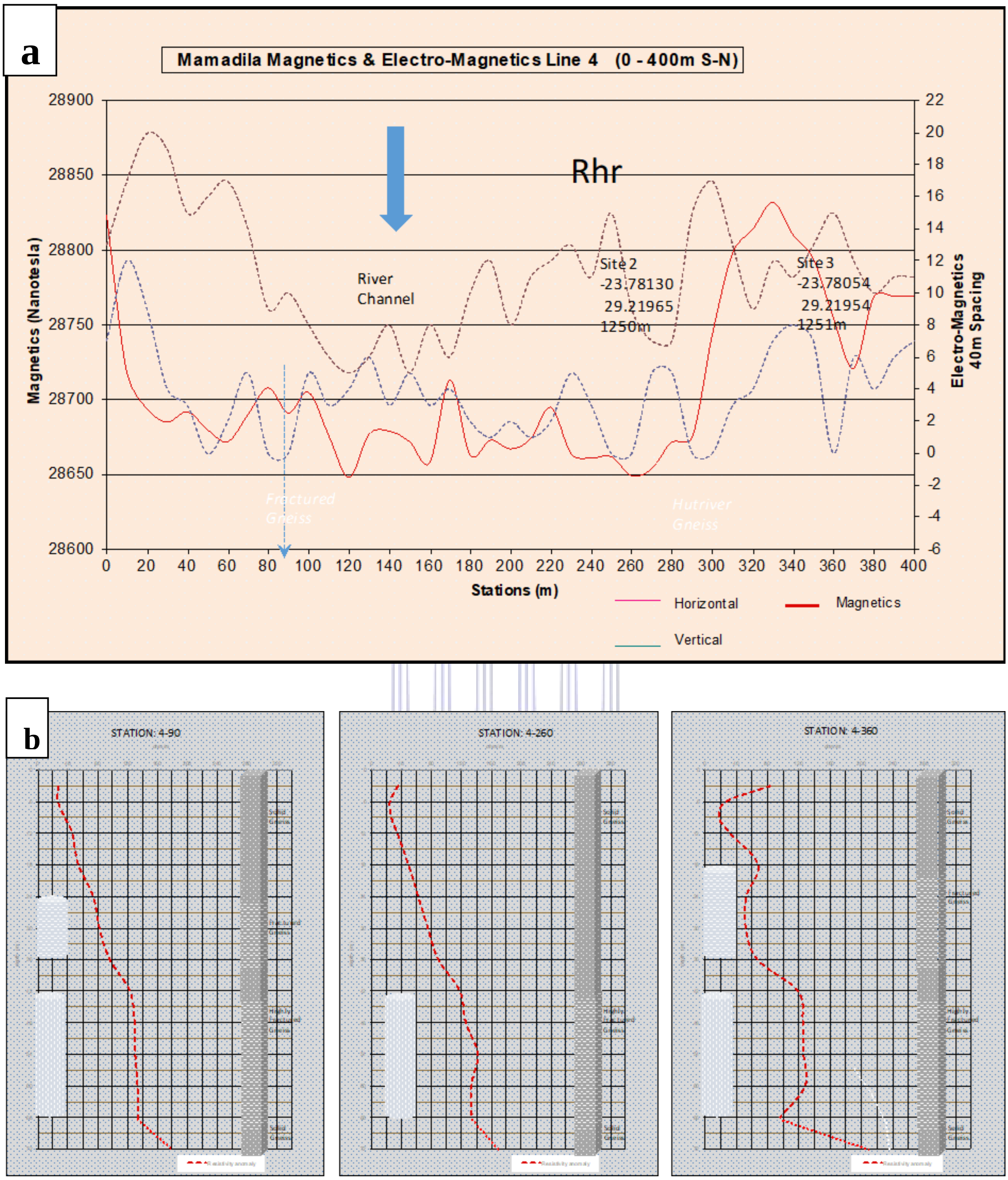

Figure 5.5: (a) Variation of magnetic susceptibility, the horizontal and vertical FDEM results along profile line 4 showing potential groundwater anomalies at 90m, 260m and 360m and (b) The corresponding vertical electrical resistivity sections together with the inferred depth variation profile from the interpretation of field electrical resistivity results.

5.3 Borehole drilling results and interpretation

Groundwater exploration within crystalline basement aquifer is often described as a more complex process since groundwater availability in such system is largely a consequence of the interaction of several processes related to recharge, underlying geological features and fracture connectivity of the aquifer rock matrix. Due to the above, four boreholes were drilled within the Mamadila site. These boreholes were drilled to verify and improve geophysical results and conduct pumping test. DTH air rotary percussion method, which uses compressed air and a rotating bit to cause vibration and break rocks was used to drill the boreholes. Drilled boreholes consisted of two shallow boreholes namely HO4-3125 (60m) and HO4-3128 (48) and two deep boreholes (HO4-3126 (84m) and HO4-3127 (120m) Table5.1 provides summary of these boreholes while appendix 1 provides the typical drill logs.

Table 5.1: Summary of successfully drilled boreholes.

Borehole ID	**Depth(m)**	**Rest water level(mbcl)**	**Blow yield (l/s)**	**Summary**
HO4-3125	60	5.49	0.3	Drilled into the shallow alluvial layer and shallow weathered regolith of the aquifer underlain by a solid diabase dyke
HO4-3126	84	12.45	5	Cutting across different bands of solid Hout River gneiss and highly weathered and potentially water bearing weathered pegmatite lineament.
HO4-3127	120	14.23	5.6	Cutting through a highly fractured pegmatite layers and weathered Diabase dyke
HO4-3128	48	9.83	8.4	Cutting through highly pegmatite layers and at the edge of a Diabase dyke

mbgl = metres below groundwater level, mbcl = metres below borehole collar level, mamsl = metres above mean sea level

Lithological cross-section was developed from drill log samples collected during drilling of the test boreholes (Figure 5.6). The borehole drill summary presented in Table 5.1 and developed lithological cross-section confirms the complexity that is associated with the typical Houtriver gneiss formation as had been inferred from the geophysical profiling, which had predicted that the groundwater occurrence is being controlled by many structures inclusive of diabase dykes, pegmatite lineaments and varying degrees in weathering and fracturing in different sections of the parent gneiss. According to Macdonald et al. (2005), the average yield in most crystalline basement aquifers in Southern African basement aquifers are in range of 0.1–1 l/s. The boreholes in this study had average borehole yield which was way greater than what was reported by Macdonald et al. (2005).

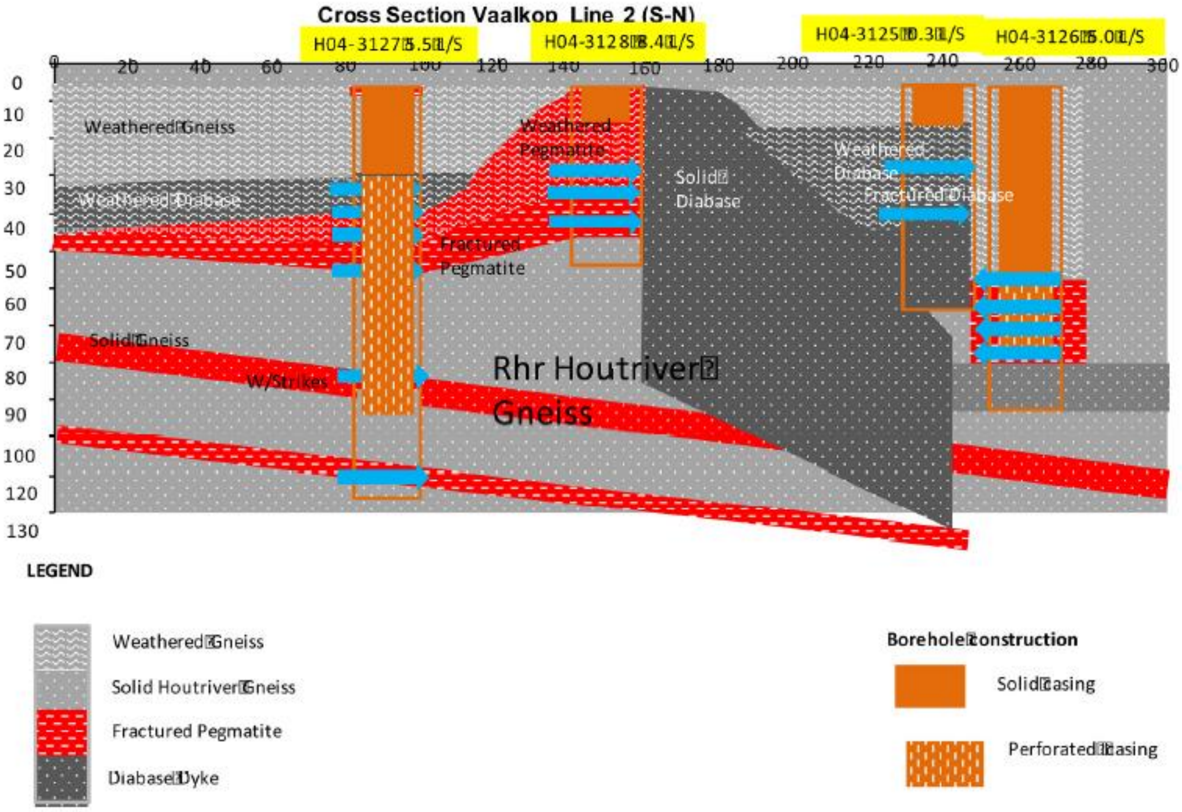

Figure 5.6: Inferred lithological cross-section developed from boreholes drilled within Houtriver gneiss aquifer formation. The blue arrows indicate zones of water strikes.

The above results showed useful information regarding the geologically complex Houtriver gneiss crystalline basement formation. Drastic lateral variations in the aquifer are suggested by the results from magnetic and electromagnetic investigations. Such lateral heterogeneities are interpreted to be influenced by existence of structures such as lineaments, dykes and fault zones, which ultimately control groundwater dynamics within the formation. Taylor (1999) suggested that groundwater occurrence within metamorphosed systems is controlled by existence of secondary porosity like joints and fractures. This was confirmed by the VES results presented from the study and that secondary porosity nature resulted into vertical heterogeneities with alternate wet and dry zones within the formation. It was therefore relatively easier to infer sections of localized occurrence of groundwater in the Houtriver gneiss hard-rock formation using electrical resistivity owing to the lower resistivities of these water-rich zones compared with typical high resistivities of crystalline rocks. Owen et al. (2005) reported resistivity values in range of 20-100Ωm for typical basement aquifers in Zimbabwe. The current study suggested potential groundwater bearing regolith to have resistivity values less than 120Ωm based on inferred depth of influence and vertical stratigraphy of the formation from the VES. These values are within the range reported by Owen et al. (2005). It is also suggested by the VES results that the deeper groundwater bearing sections of the crystalline basement formation are controlled by the fracturing. This is suggested based on resistivity values in excess of 300Ωm in depths below 30m from the ground surface, these sections are also characterised by reduced resistivity values which are inferred as fractured zones (and potential groundwater strikes) occurring within the solid bedrock. Lithological cross section constructed from drill logs samples collected during drilling of the test boreholes confirms the heterogeneity and layering within the formation as was inferred from the hydrogeophysical results.

5.4 Nature and trends of groundwater levels

Many researchers have tried to identify the most important factor(s) in controlling groundwater occurrence in typical crystalline terrain like Houtriver gneiss formation (Holland, 2011; Dippenaar and Van Rooy 2014; Holland and Witthuser 2011). Amongst these factors, the influence of topography on groundwater level was shown to be one of the factors that explains the nature of the underlying aquifer system as it controls the movement of groundwater as well as the interaction of groundwater and surface water bodies. When conceptualizing groundwater flow systems and assessing the relationship between aquifers, rivers and its associated ecosystems, it is necessary to consider how the surface topography relates to the occurrence of the water table. A plot of average groundwater level data with topography is characterized by a relatively weaker correlation ($R^2 = 0.53$) (Figure5.7). This is an indication that groundwater occurrence within the study area is dominated by compartmentalization through control of structural features, and that flow is controlled by geological structures. These results are similar to those obtained by Abiye et al. (2020) suggesting that groundwater levels are higher where structures are densely concentrated and deep groundwater levels occur in areas with less occurrence of structural discontinuities. This means that groundwater flow within the Hout River catchment is dictated by the local faults and dykes and that groundwater occurrence within the catchment is structurally controlled. Abiye et al. (2020) suggested a groundwater flow direction to N-NE (Figure 5.8).

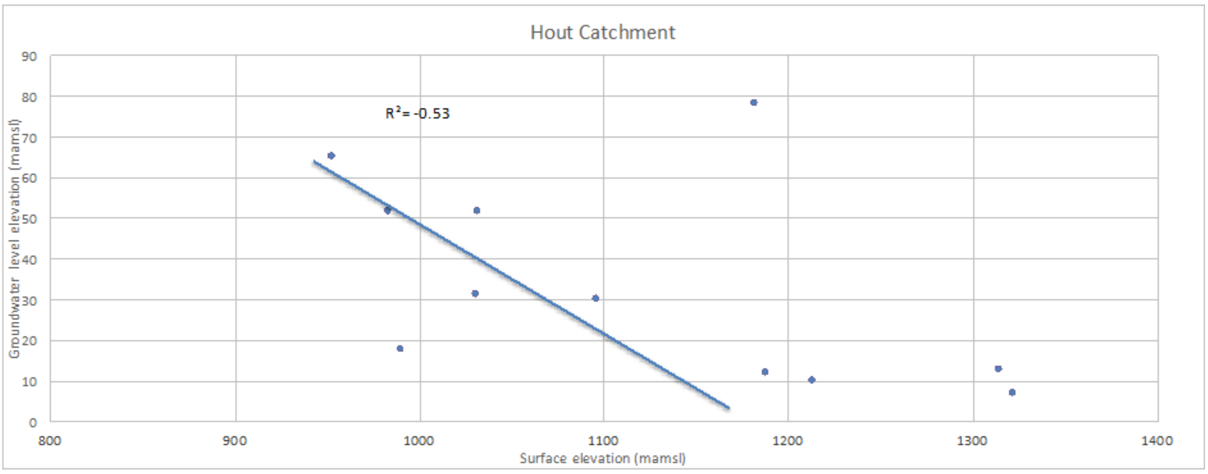

Figure 5.7: A plot of depth to groundwater level vs topography suggesting a weak correlation

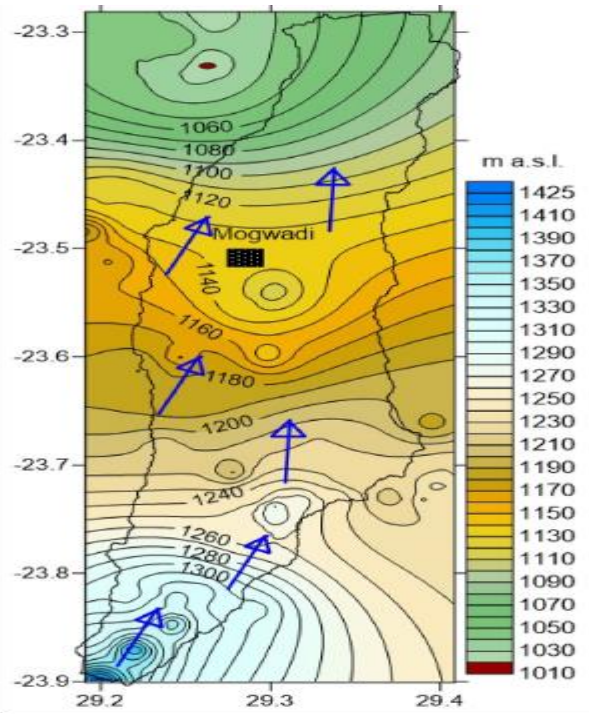

Figure 5.8: Groundwater flow pattern within HRC with flow direction to N-NE (Abiye et al. 2020).

Boreholes within the study site were equipped with data loggers after completion of borehole development. Groundwater levels are also compared in shallow and deep boreholes for period of the rainy season from October 2019 to January 2020. Generally, results show similar trend between boreholes over time (Figure 5.9). This suggests that there is connectivity between the shallow and deeper boreholes, however, HO4-3125 had missing data due to missing monitoring instrument. This is a most likely case of vandalism as the borehole is located close to a foot path.

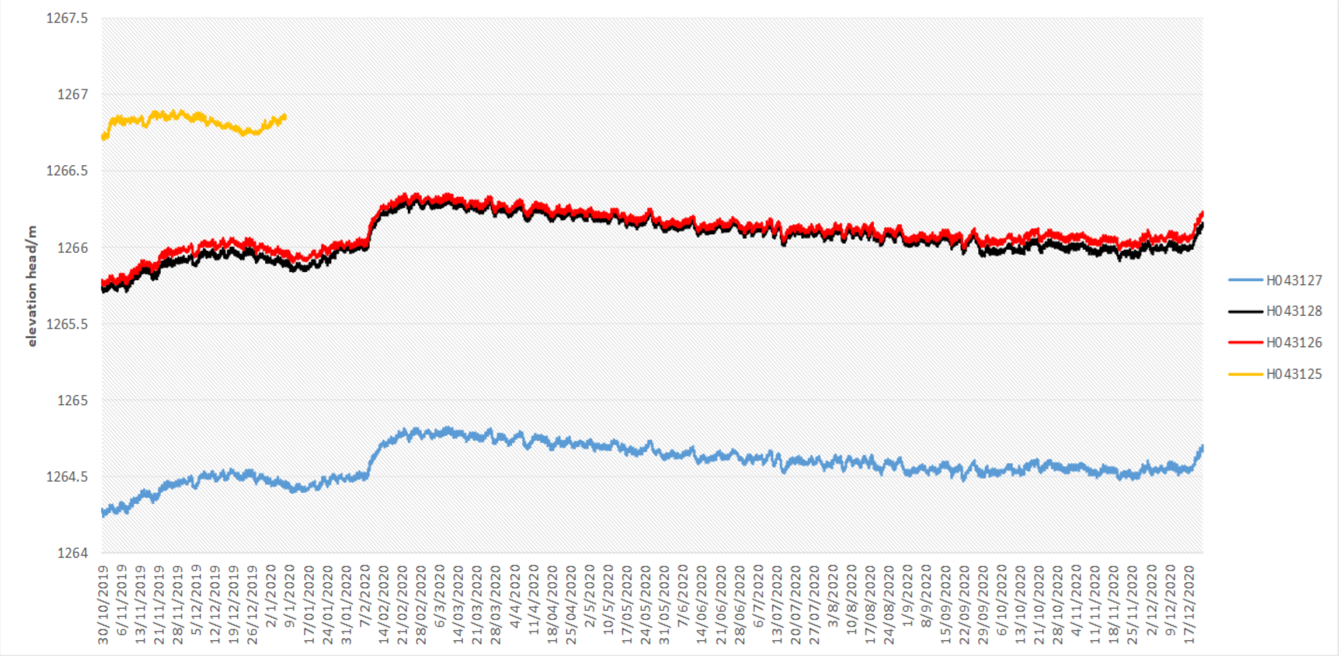

Figure 5.9: Groundwater level trends during the study period

5.5 Aquifer tests

Aquifer tests are conducted with an objective to understand the aquifer's ability to store and transmit water, aquifer extent, presence of boundary conditions and hydraulic connection to surface water. Well-test interpretations have improved with the arrival of inverse analysis, derivative analysis and diagnostic plots. Three types of pumping tests were carried out: step drawdown test (SDT); constant discharge test (CDT); and recovery test (RT). The Aqtesolv test Pro software package was used for the generation and analysis of the graphs. Each borehole was analysed individually, and observation boreholes were used to infer connectivity as well as to determine storativity. The plots used to analyse each borehole are discussed in the subsections below.

Step drawdown test: HO4-3127

H04-3127 was drilled to a depth of 120m with three major water strikes encountered at varying depths: 33m with blow yield of 1L/s, 43m with blow yield of 3.5L/s and 114m with blow yield of 1L/s. Final blow yield was 5.5L/s. A SDT was conducted on HO4-3127 where BP 40-mono pump was installed at a depth of 84 mbgl and the rest water level (RWL) was

14.83 mbgl. The SDT was carried out with four steps of increasing discharge: 2.18L/s, 4.16L/s, 6.02L/s and 8.10L/s, each planned for 120 minutes in duration except the last step which was only 60 minutes before reaching available drawdown of 68.66 m. In this regard the SDT was mainly carried out to estimate the greatest flow rate that may be sustained by the pump well for the duration of the discharge. A constant discharge rate of 5.88L/s was selected to sufficiently stress the borehole. It is a good idea to obtain preliminary estimates of aquifer properties using simpler solutions. Hence, an initial transmissivity of 42.61m^2 /day was estimated from the SDT using the Theis (1935) solution for a confined aquifer.

Constant discharge test: HO4-3127

The CDT was conducted at a rate of 5.88 L/s for the duration of 48hrs. Three observation wells: HO4-3128 (84.26m away), HO4-3126 (194.70m away) and HO4-3125 (204.61m away) are monitored. 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 (Figure5.10). 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 there 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.

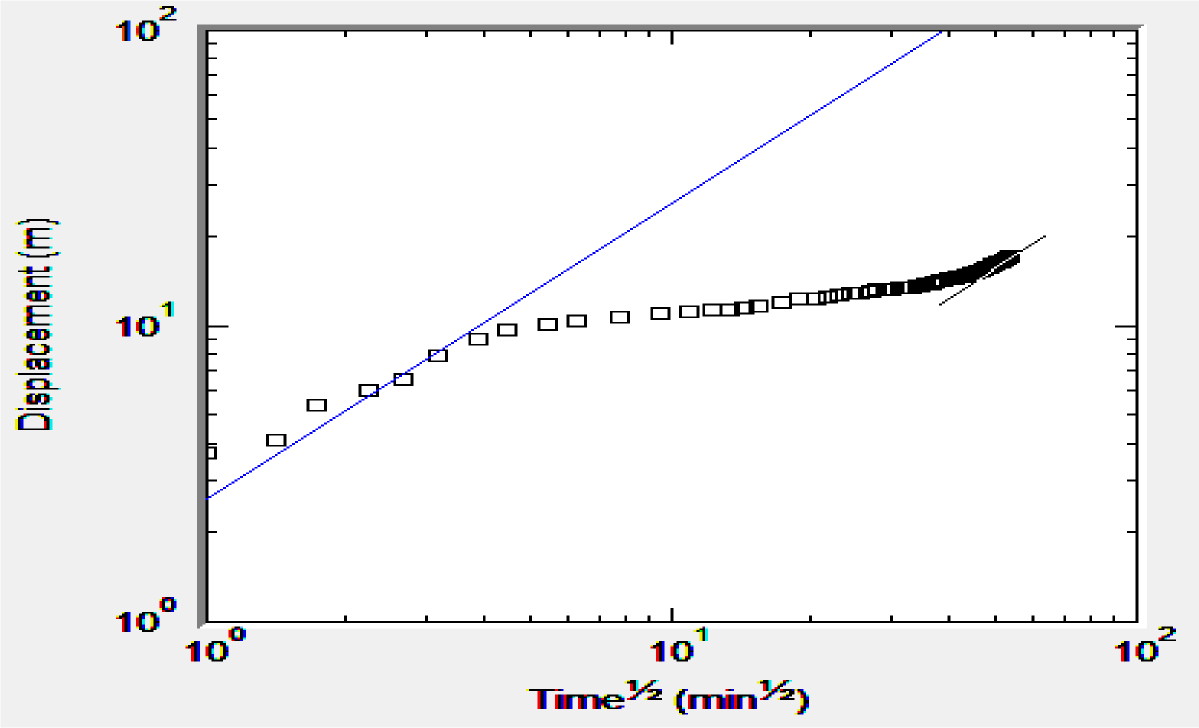

Figure 5.10: Linear flow plot to evaluate borehole flow conditions.

The Cooper-Jacob method for confined aquifer fitted the intermediate segment of the data estimating transmissivity of 41.82m^2 /day (Figure 5.11) while Theis solution of confined aquifer estimated transmissivity of 57.83m^2 /day when estimated together with all observation boreholes.

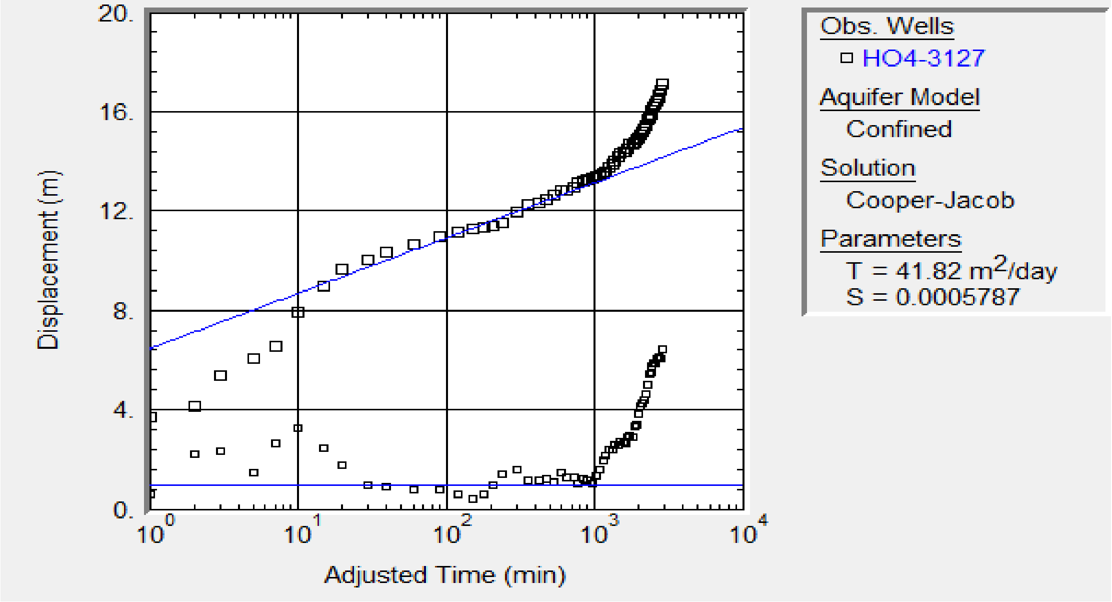

Figure 5.11: Diagnostic plot (semi- log) fitted with a Cooper-Jacob model of pumping borehole (HO4-3127).

The recovery data is analysed using the Theis recovery method. A transmissivity value of 32.33 m^2 /day was estimated using the recovery data. Given the above, an average transmissivity for the pumped borehole was calculated as 43.99 m^2 /day which correlates well to the transmissivity of 42.61 m^2 /day estimated using the SDT data. These results correlate well with those of Holland (2011) for boreholes drilled in pegmatite within the Limpopo Province. Therefore, the transmissivity obtained during this test confirms the presence pegmatite encountered during the drilling of borehole H04-3127 (Figure 5.6) and its control of groundwater flow.

Observation boreholes and Storativity

HO4-3128, HO4-3126 and HO4-3125 were selected as observation boreholes to determine connectivity or lack of connectivity as well as understanding the influence of geological structures on groundwater flow. Due to the nature of study it is important to understand how each observation borehole responds to the pumping so that influence of geological structures can be articulated. HO4-3125 is 204.61m away from the pumped borehole, this observation borehole was drilled at a depth of 60m with two water strikes at 25m with blow yield of 0.1L/s and at 45m with blow yield of 0.2L/s. Final blow yield is 0.3L/s with RWL of 6.36 mbdl. The diagnostic and derivative curves, shown on a log-log plot (Figure 5.12), from observation well HO4-3125 indicates that there are several changes in the flow -controlling mechanism, while pumping well is pumped at 5.88L/s. Before 120 minutes, both curves exhibit typical response associated with wellbore storage effects in which the drawdown and its derivative exhibit unit slope at early time. Second segment of the data, the derivative stabilises indicating infinite acting radial flow. The start of radial flow indicates the time at which the fractured reservoir behaves as homogenous. The third segment (730-1620 min) is characterised by bilinear flow with a slope of 0.25. Later in the segment (1620-1980 min) a constant drawdown occurred while derivative has a dip which indicates dewatering of a fracture zone at *s* between 2.81 and 2.85m. Last segment of the drawdown curve has a unit slope of 1 which indicates closed no flow boundary aquifer.

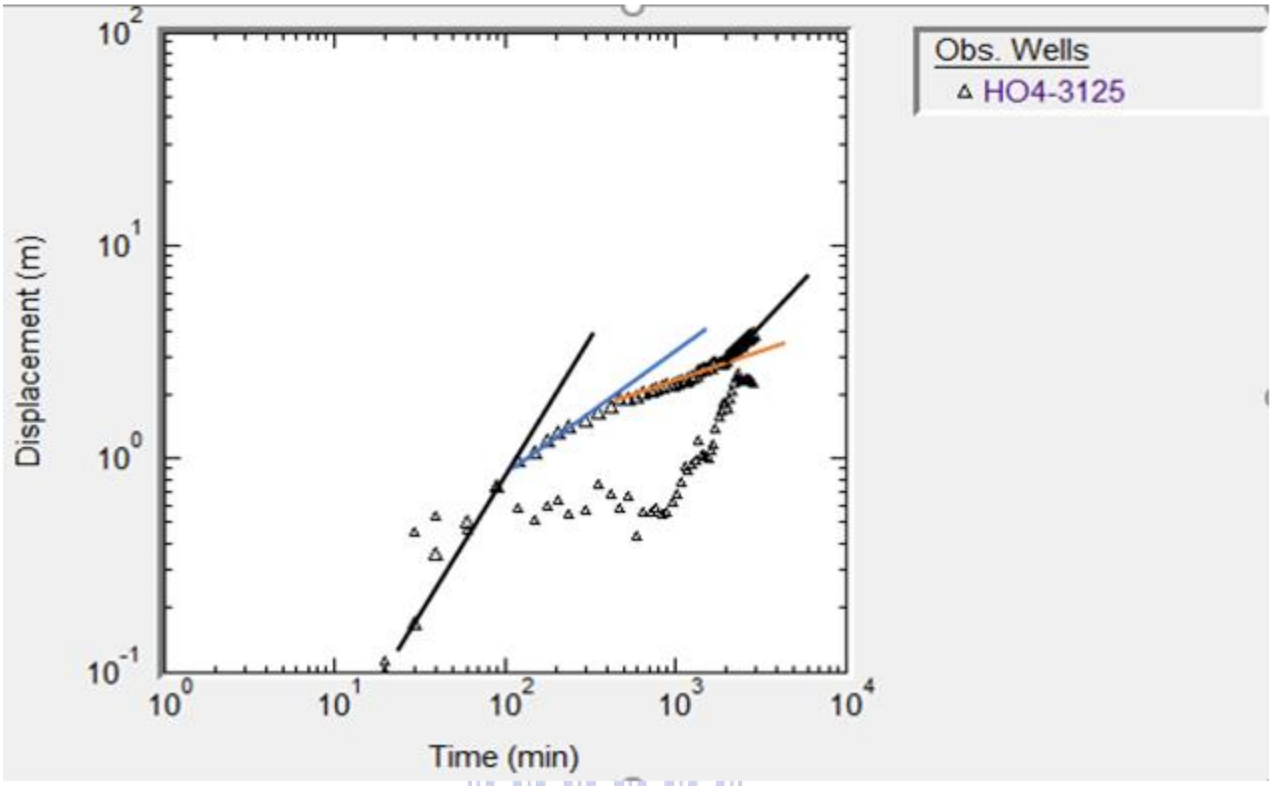

Figure5.12: Diagnostic plot (log- log) showing difference flow regimes encountered while observing at HO4-3125 and pumping at HO4-3127.

The Moench leaky aquifer model (Case 2) was used producing a transmissivity of 63.46m^{2} /day and storativity of 4.35×10^{-6} is estimated. Moench leaky aquifer model has three cases considering effects of wellbore storage: Case1 assumes overlying and underlying constant head sources, while Case 3 replaces the underlying source with an impermeable boundary (Van Tonder et al. 2002). Case 2 on the other hand assumes no flow aquitard boundary condition (Van Tonder et al. 2002). Papadopulos-Cooper model (T= 62.14 m^{2} /day and storativity of 6.85×10^{-6}) was also applied as it accounts for wellbore storage effects. The recovery data is important as it may provide valuable additional information in cases where the drawdown-curve was disturbed maybe by variations in the pumping rate. The drawdown curve fitted with Theis recovery method confirms the homogenous behaviour identified in the drawdown-curve (Figure5.12). A T value of 65m^{2} /day was estimated and it correlates well with the transmissivity value obtained while pumping and observing at HO4-3125. This indicated that the natural inflow during recovery is representative of the ARF segment identified in Figure 5.12.

HO4-3126 is 194.70m away from the pumped borehole, this observation borehole is drilled at a depth of 78m with three water strikes at 49m with blow yield of 1L/s, at 65m with blow yield of 2L/s and at 69m with blow yield of 2L/s. Final blow yield is 5L/s with RWL of 12.45 mbdl. The diagnostic and derivative curves, shown on a log-log plot (Figure5.13), from observation well HO4-3126 indicates that there are several changes in the flow -controlling mechanism, while pumping well at 5.88L/s.

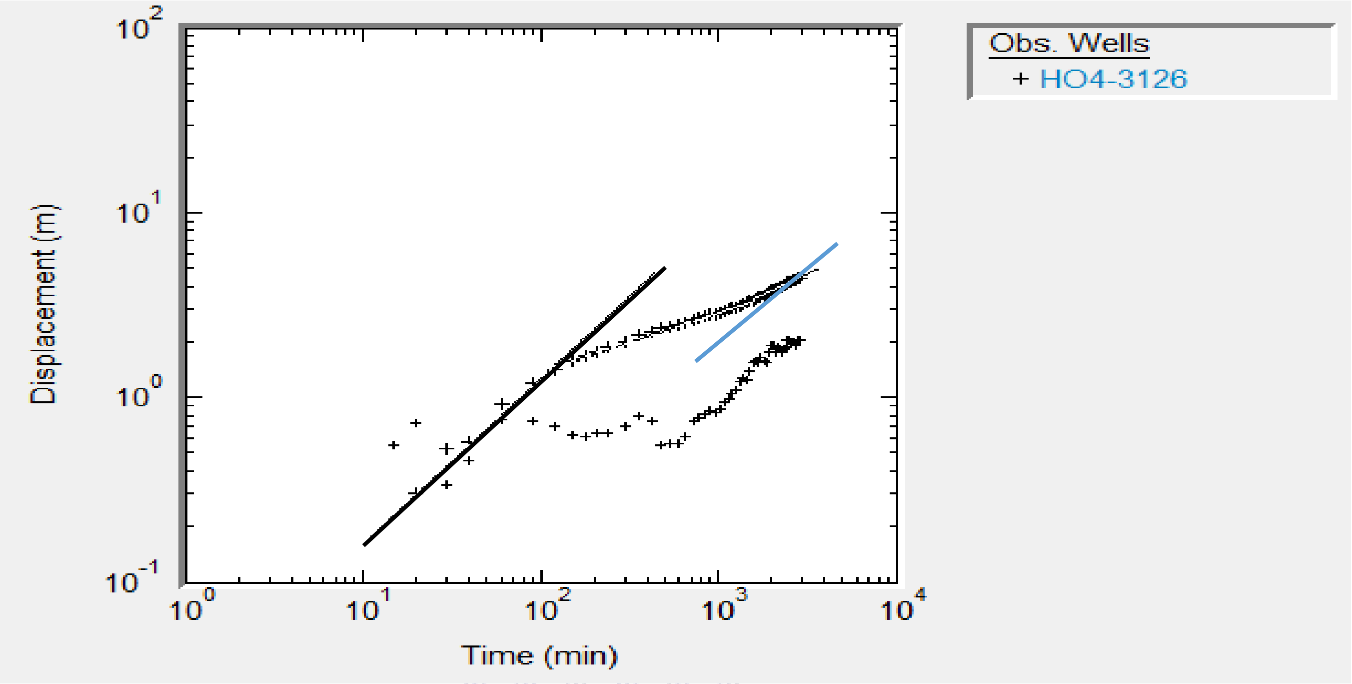

Figure5.13: Diagnostic plots (log- log) for observation HO4-3126 showing different flow regimes.

Before 100 minutes, both curves exhibit typical response associated with wellbore storage effects in which the drawdown and its derivative exhibit unit slope at early time. The second segment of this data on linear log plot (not shown) shows flattened derivative data suggesting IARF while the last segment of the drawdown curve has a unit slope of 0.5 which indicates channel strip aquifer. Using Moench double porosity model to estimate transmissivity since the derivative has a dip following effects of wellbore storage. An estimate of 44.28m^{2} /day (Aquifer thickness of 120m) was obtained with storativity value of 4.343×10^{-7}. The recovery data presented on Figure5.14 estimated transmissivity of 46m^{2} /day. The recovery plot showed that at late times the cone of depression reached a recharge boundary (constant-head). This suggested a transmissive fracture system within bedrock units and was confirmed by the constructed lithological cross-section (Figure 5.6) which clearly indicates water strikes within a fractured pegmatite. Tijani et al. (2010) also encountered recharge boundary and impermeable boundary for Precambrian basement complex of South-western Nigeria and concluded that these boundary conditions are not bedrock dependent but can be attributed to structural heterogeneity.

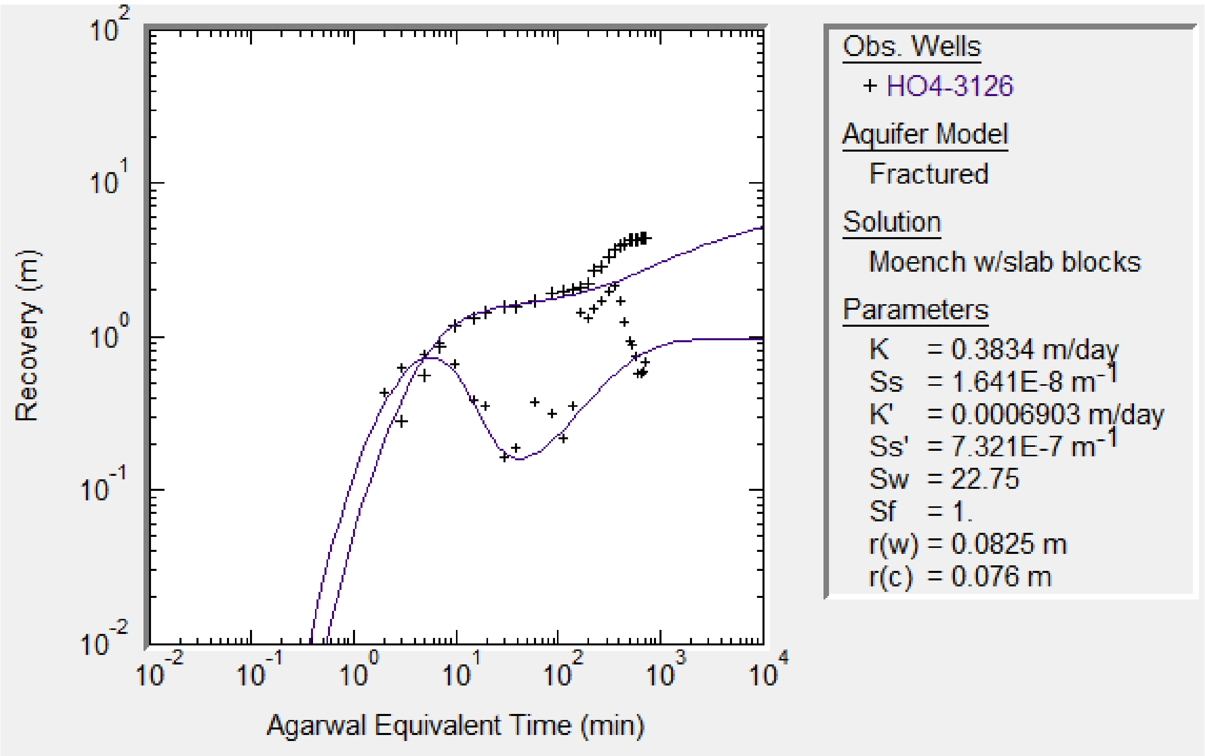

Figure 5.14: Diagnostic plots (log- log) for observation HO4-3126 fitted with Moech model

HO4-3128 is 84.26m away from the pumped borehole, this observation borehole is drilled at a depth of 48m with three water strikes at 30m with blow yield of 2L/s, at 32m with blow yield of 4.4L/s and at 37m with blow yield of 2L/s. Final blow yield is 8.4L/s with RWL of 10.58 mbdl. The diagnostic and derivative curves, shown on a log-log plot (Figure5.15), from observation well HO4-3128 indicated that early 30 minutes of data, both curves exhibit typical response associated with wellbore storage effects in which the drawdown and its derivative exhibit unit slope at early time. This effect is followed by a dip in a derivative indicating double porosity. The drawdown data stabilises while derivative has a dip indicating fracture dewatering. Late time draw down exhibit half unit slope indicating linear flow conditions to a well in a channel strip aquifer. Drawdown data illustrated in Figure 5.15 was highly disturbed (due to the dewatering of fractures) and that makes the evaluation complicated and often parts of the curve can be modelled. Due to the above Moench double porosity model was used to estimate transmissivity using recovery methods as they provide an alternative approach where drawdown curve has been affected by fracture dewatering (Figure 5.16). An estimate of 41.35m^2 /day (Aquifer thickness of 120m) was obtained with storativity value of 1.023×10^{-6}. This storativity value falls in the upper range of characteristic values (3.3E-06 to 6.9E-05 m-1) for fissured rock (Batu, 1998).

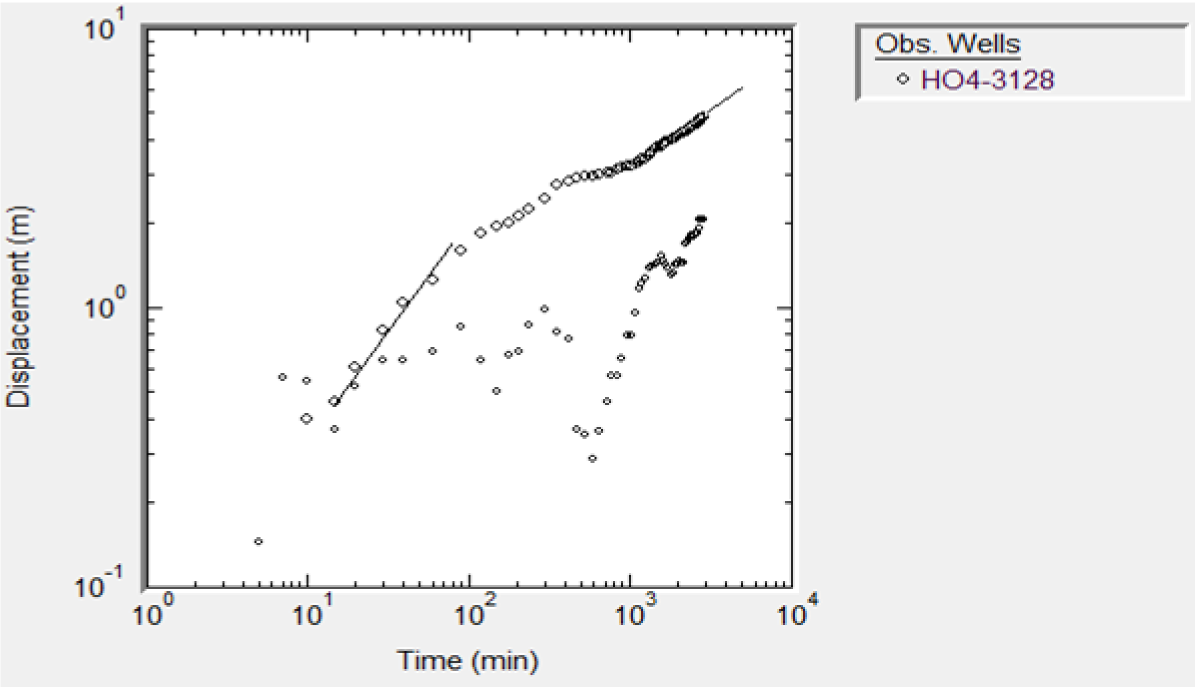

Figure5.15: Diagnostic plots (log- log) for observation HO4-3128 showing different flow regimes.

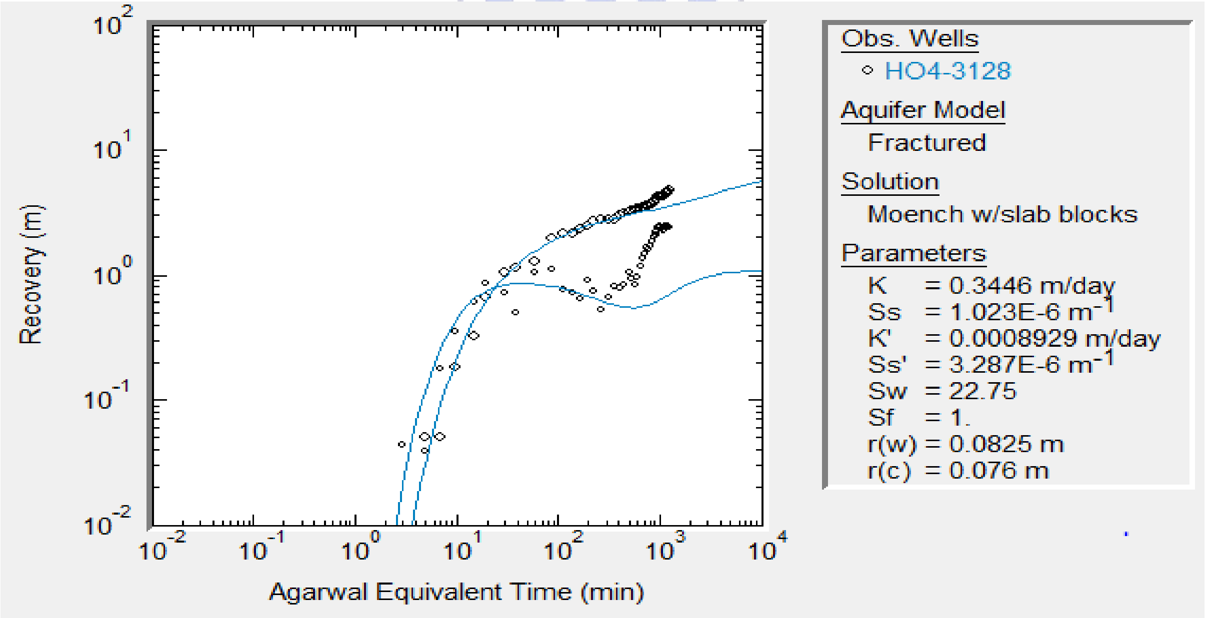

Figure5.16: Diagnostic plots (log- log) for observation HO4-3128 fitted with Moech model

Step Drawdown test: HO4-3126

H04-3126 was drilled to a depth drilled of 78m with three water strikes at 49m with blow yield of 1L/s, at 65m with blow yield of 2L/s and at 69m with blow yield of 2L/s. Final blow yield is 5L/s A SDT was conducted on HO4-3126 where BP 40-mono pump was installed at a depth of 62 mbgl and RWL was 10.38 mbgl. The SDT was carried out with four steps of increasing discharge: 2.49L/s, 4.23L/s, 6.17L/s and 8.12L/s, each planned for 120 minutes in duration except the last step which was only 15 minutes before reaching available drawdown of 54.24m. The SDT was mainly carried out to determine the borehole performance and the abstraction rate for CDT. A constant discharge rate of 4.20L/s was selected to sufficiently stress the borehole.

Constant discharge test: HO4-3126

The CDT was conducted at a rate of 4.20L/s for the duration of 48hrs. Three observation wells: HO4-3125 (60.14m away), HO4-3128 (97m away) and HO4-3127 (190m away) were monitored. 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. Before 10 minutes, the drawdown exhibits the typical response associated with infinite conductivity fracture in which the drawdown exhibits half unit slope. At intermediate times the drawdown and its derivative shows that several discrete fractures were evidently dewatered. 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 suggested well-connected fracture network. The nature of the curves results in complicated evaluation and only parts of the curve can be modelled hence recovery curve was used as an alternative approach. An estimate of 37.46m ^{2} /day for T was obtained using Theis recovery plot.

Observation boreholes and Storativity

HO4-3125, HO4-3128 and HO4-3127 were selected as observation boreholes to determine connectivity or lack of connectivity as well as understanding the influence of geological structures on groundwater flow when pumping partial penetrating borehole. Due to the nature of study it is important to understand how each observation borehole response to the pumping so that influence of geological structures can be articulated. HO4-3125 is 60.14m away from the pumped borehole. The diagnostic and derivative curves, shown on a log-log plot (Figure5.17), from observation well HO4-3125 indicated that there are several changes in the flow -controlling mechanism, while pumping well is pumped at 4.20 l/s. Before 240 minutes, drawdown curve exhibit typical response associated with linear flow having 0.5 gradient. Intermediate time the derivative stabilises indicating radial acting flow (RAF) while the late time data (1740min till end of the test) exhibit half unit slope associated with linear flow conditions to a well in a channel aquifer. Using Cooper-Jacob, T value of 50.02 m^2 /day with Storativity of 1.145×10^{-4} was obtained. A similar transmissivity was obtained by Tessema et al. (2014) using Cooper Jacob method as well and estimated T value of 53.4m^2/d for crystalline basement rocks of the North West Province. The recovery data estimated a T value of 40.68m^2 /day with storativity of 1.145×10^{-4} using Theis method. This correlates well with the storativity value obtained using drawdown data of this observation borehole.

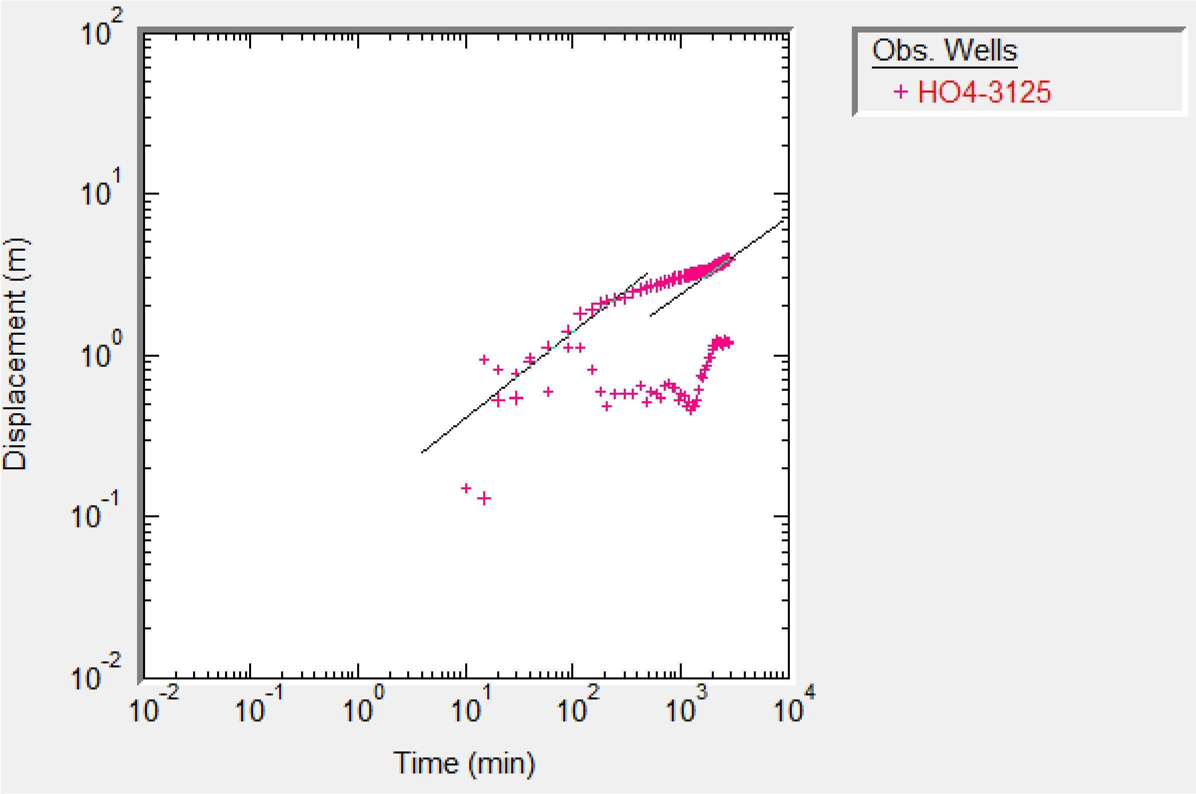

Figure5.17: Diagnostic plots (log- log) for pumping well HO4-3125 showing different flow regimes.

HO4-3128 is 97 m away from the pumped borehole with RWL of 9.83 mbdl while **HO4-3127** is 190 m away from the pumping borehole with RWL of 14.23 mbdl. HO4-3128 and HO4-3127 exhibit the same flow regimes hence analysed together. The diagnostic and derivative curves, shown on a log-log plot (Figure5.18), indicates that there were several changes in the flow -controlling mechanism, while pumping well is pumped at 4.20L/s. Early time data exhibit half unit slope while the intermediate region indicates RAF. The late time data exhibit half unit slope associated with linear flow conditions to a well in a channel strip aquifer. Using Theis method, T was estimated to be 46.75m^2/d. The recovery data was also piloted using Theis method, a T value of 35.4m^2 /day (HO4-3128) and 34.04m^2 /day (HO4-3127) with storativity of 1.632×10^{-04} (HO4-3128) and 1.327×10^{-04} (HO4-3127)was estimated. Based on the above calculated storativity value range of 2.8×10^{-06} – 1.4 ×10^{-04} which is less than that of basement aquifers of Limpopo (7×10^{-03} - 5×10^{-02}) as reported in Witthuser et al. (2011). This indicates that the Houtriver formation has less storativity within the matrix than the fractures which have similar T ranges to that of basement aquifers of Limpopo in literature.

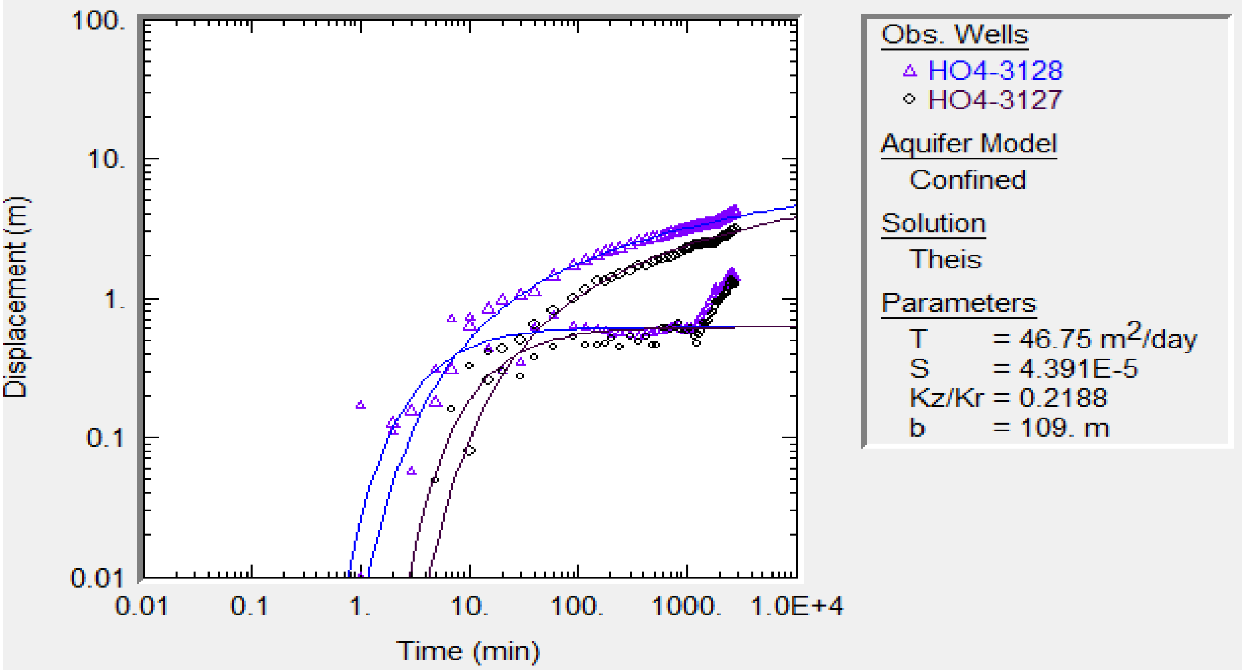

Figure5.18: Diagnostic plots (log- log) for observation HO4-3127 and HO4-3128 fitted with Theis model

Results from the study evidently show that the groundwater occurrence and its flow dynamics are structurally controlled. The shallow groundwater levels observed throughout the study area suggests the presence of localised groundwater flow system with short flow paths. The nature of groundwater flow within the study area is controlled by geological structures. This has an influence on the extent of aquifer-river interaction as the nature of groundwater flow influences the volume of groundwater contribution to rivers and the stability of flow conditions along the river itself. An area receiving a regional groundwater flows would have a relatively stable river flows compared to the river which is contributed from local groundwater flows. Due to localised groundwater flow system the Hout River is characterised by pools in river sections with visible outcrop of dyke or pegmatite (Figure 3.6).

5.6 Summary

This chapter combined different techniques to evaluate hydrogeological characteristics of the study aquifer system with focus on identifying conditions for groundwater occurrence and its flow dynamics. These techniques included hydrogeophysical, geological and aquifer testing approach. The chapter argued that in order to determine the aquifer influence in Hout River it is necessary to understand the hydrogeological controls to groundwater flows. From magnetic and electromagnetic investigations results, Houtriver gneiss crystalline basement aquifer system is characterized by drastic lateral variations. Such lateral heterogeneities are interpreted to be influenced by existence of structures such as lineaments, dykes and fault zones, which ultimately control groundwater dynamics within the formation. VES results also confirms the control of secondary porosity (joints and fractures) to groundwater occurrence, resulting in vertical heterogeneities with alternate wet and dry zones within the formation. 30m below the ground surface marks the end of the regolith zones and the beginning of the unweathered zone with fractured zones occurring within the solid bedrock. Drill logs collected confirms the heterogeneity and layering within the formation as was inferred from the hydrogeophysical results. Transmissivity values determined from the constant pumping tests range from $37m^2$ /day to $65m^2$ /day while storativity values range from 2.8×10^{-06} – 1.4×10^{-04}. The next chapter presents and discusses the results of the hydrochemical and isotopic analysis which were done to assess aquifer-river interaction.

Chapter 6 : Characterising spatial variation in aquifer-river interaction

6.1 Introduction

This chapter presents and discusses results regarding hydrochemistry and environmental stable isotope compositions of groundwater and surface water in order to assess and characterise interaction between groundwater and surface water and ultimately determining groundwater discharge sites along the Hout River. Hydrochemical and isotopic analyses are frequently used to confirm the interrelations between groundwater and surface water in arid to semi-arid environments. In this study water sampling was conducted in June 2019 representing dry hydrologic period. This period was purposely chosen in order to understand other sources of water to the Hout River except rainfall. Key results obtained are described, interpreted and compared to other findings obtained from semi-arid environments. These results only provide qualitative understanding of aquifer-river interaction in terms of location and mechanism of interaction.

6.2 Electrical conductivity

Electrical conductivity (EC) values are mainly used as a proxy of salinity and the degree of mineralization to describe the hydrochemical characteristics. To show the extent of salinization using the classification by Freeze and Cherry (1979), total dissolved solids (TDS) are calculated from EC values using the relationship TDS (mg/l) = 0.64*EC (μS/cm) (Hiscock and Bense, 2014). TDS values are used to show the extent of salinization using the classification of Freeze and Cherry (1979) as provided in Table 6.1. Based on the above mentioned salinity classification, this study consist of fresh groundwater. Two boreholes (HO4-3126 and HO4-3127) sampled are the closest groundwater wells and are assumed to be representative of the groundwater in the vicinity of surface pools. Departmental existing monitoring wells are all located outside the acceptable distance of this study.

Table6.1: Simplified classification of groundwater salinization (Freeze and Cherry, 1979)

Groundwater class	**TDS (mg/l)**
Fresh water	0-1 000
Brackish water	1 000-10 000
Saline water	10 000-100 000
Brine water	Higher than 100 000

Table 6.2: EC values for surface water during sampling period June

Site	**EC(µS/cm)**	**TDS(mg/l)**
StationA	189.2	122.98
StationB	449.6	292.24
StationC	248	161.2
StationD	247.7	161.005
StationE	309	200.85
StationF	430	279.5
Dam	370	240.5
HO4-3126	634	412.1
HO4-3127	632	410.8

Groundwater samples were characterised by fresh waters with the highest EC of 634 µS/cm and TDS of less than 1000 mg/l (Table 6.2). The lower EC maybe be attributed to high velocity of groundwater and low mineralisation. These findings align with results from Abiye et al. (2020) which was done within the Hout River catchment as a whole while this current study only focused on the Southern part of this catchment. The study looked at characterisation of the crystalline aquifer at a catchment scale level and the results showed that the southern part of the catchment has EC values ranging between 473.0 µS/cm and 1228.0 µS/cm while EC increases moving central to northern part of the catchment. In addition, samples from the Hout River were taken at 7 points along the river. Determination of salinity in the river was done to assess if there is any noticeable pattern which can be related to the salinity of the local groundwater. The EC values in the Hout River range from 189µS/cm to 449.6µS/cm with an average of 320µS/cm which is lower than that of groundwater.

Out of all surface water samples, the lowest EC values were observed in areas where there was river flow observed during sampling while the highest values were observed in the standing pools. In a similar study focusing on groundwater-surface water interaction, Moseki (2013) found that higher total dissolved solids values, which tend to give insights regarding electrical conductivity, are likely to occur after prolonged periods of low flows or as a result of displaced pool water partly due to concentrating effects of evaporation. Furthermore, it was also observed in the field that these pools were often used as water points for livestock drinking. This suggests that the elevated EC on these pools could also be due to the anthropogenic activity. One noticeable feature in the study site was that along all these points where sampling was conducted, there was a presence of geological structures either dyke or pegmatite and in areas where these are not exposed, the river was dry. According to hydrogeophysical results in chapter5 groundwater flow is dictated by the local structures and that groundwater occurrence in the Houtriver catchment is structurally controlled.

It is difficult to use EC only as a tool to assess aquifer-river interaction and possible identify groundwater discharge sites along the river. This is due to different possible sources in EC variability along the studied river reach. These sources include groundwater input, evaporation and anthropogenic activities hence, it is vital to use other tools in addition to EC to provide better and improved understanding of the interaction processes.

6.3 Major ions characteristics

6.3.1 General expressions and statistical summary of major ion data

This section discusses major ions analyses during dry period (June). Charge Balance Error (CBE) of ±15% was used as previously discussed in the reliability and validity section of this thesis. Most (99%) of samples were within the adopted range expect one sample from the Hout River dam which had CBE value of 16.94%. The data obtained from this sample can therefore not be validated and not included in the generation of piper diagram. It is though discussed with caution in the description of spatial trend. The possible reason for high CBE can be attributed to either sampling errors or an error during laboratory analysis. Non-inclusion of minor or trace ions in the analysis which could have been present in significant concentrations are assumed be the main cause more especially if there is active discharge of groundwater in this dam. Groundwater in this system was having significant concentrations of nitrate hence suggesting that high CBD from dam samples could be as the results of groundwater discharge to the dam. Table 6.3 presents average results of the analysed parameters.

Table 6.3: June 2019 dry season major ion average ion results. Units are in mg/l

Species	Groundwater	Surface water(average)	Min	Max
Ca^{2+}	38.9	27.81	19.6	47.9
Na^{+}	54.8	42.39	31.1	57.2
K^{+}	7	3.43	1.7	4.7
Mg^{2+}	27.3	9.81	6	18.8
Cl^{-}	60.8	21.06	10	34
SO_4^{2-}	44.2	12.29	10	19

The dominant major cations were in order of Na>Ca>Mg>K for both surface water and groundwater. Meanwhile, major anions data show concentrations range from high to low in the order of HCO_3>Cl>SO_4. The noticeable feature was that sample river (station B) marks the maximum concentration values for all the major ion concentrations except for Mg^{2+} concentrations. Furthermore, sample river in station E and F also have high range while river sample in station A marks the minimum range for all the major ion concentrations. River sample at station B have concentrations which were similar to the groundwater samples (HO4-3126 and HO4-3127) suggesting the presence of connectivity between the two water sources.

6.3.2 Characterisation of water type

Conventional Piper diagram is widely used to classify the water types based on the concentrations of ions in mEq/l. This study adopted this method because of its ability to graphically show large number of analyses in a single plot. The piper diagram (Figure6.1) could not clearly identify the water types as neither anions nor cations are dominant (having no one cation-anion pair exceeding 50%). However, it could be deduced that Na^+ was the dominant cation while HCO_3 was the dominant anion for surface water samples resulting into a Na-HCO_3 water type. The groundwater samples clearly were within the region of mixed water but a cation that almost reached 50% was Na^+ while the anions were HCO_3^- (39.9%) and Cl^- (39.17%). Based on this, a Na-Cl water type was deduced for groundwater. This Na-Cl water type was similar to what was suggested by Witthuser et al. (2011) for the Limpopo plateau region. Witthuser et al. (2011) found dominant water types that range from Na-HCO_3 to a Na-Mg-HCO_3 and Na-Cl and further explains that the Na-Cl water type is a result of prolonged residence and fluid rock interaction times in the subsurface in areas of discharge (i.e. alluvium along rivers). The sampled boreholes for this study are along the Hout River and in support of the above findings by other scholars. The results obtained from the piper diagram (Figure6.1) did not indicate that there is any hydraulic connection between the two water sources in the study area. However, the groundwater type suggested for this study area indicates that there is possibility of groundwater being discharged to the Hout River.

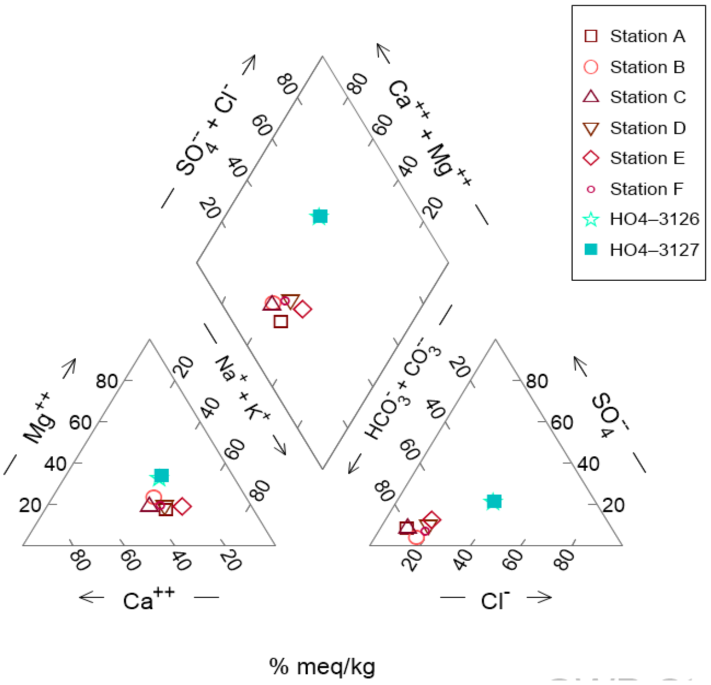

Figure6.1: Piper plot for July 2019 (dry season)

To further confirm whether groundwater quality influences the surface water quality and therefore a hydraulic connection between them, Schoeller diagram was plotted for groundwater samples available and river samples (Figure 6.2). Schoeller diagrams were used to show the relative concentrations of anions and cations typically expressed in mEq/l. Multiple samples from different sources may be plotted on a single diagram to distinguish similar patterns in the ratios of particular anions and cations. These patterns may be used to differentiate samples having similar patterns. Results from the concentrations of major ions during dry (July 2019) season are shown in Figure6.2.

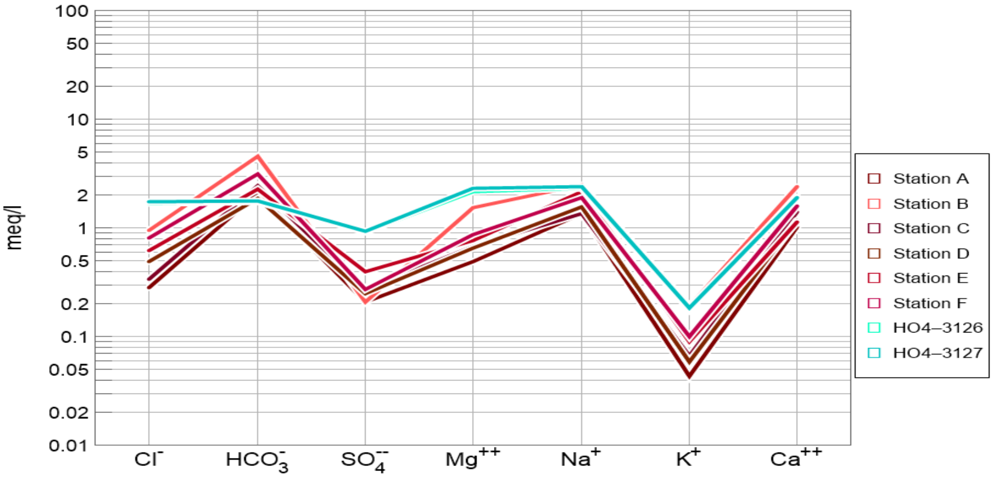

Figure6.2: July 2019 Schoeller diagram showing relationship between groundwater (HO4-3126 and HO43127) and surface water (Station A-F)

Results indicates that groundwater concentrations in major ions are higher except for HCO_3 concentration. However, whenever there was a rise in a particular ion in groundwater there was also such rise of particular ion in surface water. Similar to the fall in the ion concentration between groundwater and surface water. Possible interaction between groundwater and surface water was suggested based on the same type of variation in major ion concentration between two water sources. Banks et al. (2011) used hydrochemical data to study a semi-perennial river (Rocky River dominated by pools) in South Australia. This report indicated a subsurface fresh water source to the Rocky River and based on the salinity of the river and water level data it was confirmed that dominant subsurface water was from the shallow perched aquifer and that there was minimal influence from the deeper saline fractured rock aquifer. Dalasile (2018) also discovered similar chemical signatures of shallow groundwater and surface water and concluded that there was hydraulic connection between the two systems in the Tweefontein farm in the Limpopo Province. Using hydrochemical data, a report by Sentilkumar et al. (2015) from a study in crystalline rocks of Achaean age indicated that the geological structures such as dykes and lineaments play a major role in groundwater flow and quality. In one site Sentilkumar et al. (2015) found that lineament acts as carrier and transmits fresh water directly from the recharge areas. These recharge areas include the Chittar River.

6.4 Environmental stable isotopes

This section reports on findings from the stable isotope of δ^2H and δ^{18}O. These findings were used as confirmatory tool to establish interactions between groundwater and Hout River. In order to identify the relative depletion or enrichment of the sampled water, the local precipitation data is of importance. The results were plotted relative to the Taaibosch local meteoric water line (TLMWL) which was the closest LMWL to the study area, as well as relative to the global meteoric water line (GMWL). The GMWL is defined by the equation $\delta^2H= 8\ \delta^{18}O + 10$ (Craig, 1961). GMWL is a suitable reference for determining the possible rainfall compositions in cases where there is not enough local data to create representative LMWL (Mengistu et al. 2015). However, when conducting local investigations it is important that the groundwater and surface water data are compared to the LMWL. Previous studies within the Limpopo province mainly used Pretoria local meteoric water line (PLMWL) with an equation of $\delta^2H= 6.7\ \delta^{18}O + 7.2$ (Dalasile 2018). Recently Durowoju et al. (2019) suggested Thohoyandou local meteoric water line (TLMWL) within the Soutpansberg group in which northern part of the HRC is mainly composed of. The TLMWL has an equation of $\delta^2H= 7.56\ \delta^{18}O + 10.64$.

During the dry sampling period of this study in July 2019 (Figure 6.3) the δ^2H values of groundwater ranged from -26.4 ‰ to -26.2 ‰ with average of -26.3 ‰; the variation of δ^{18}O ranged from 4.85 ‰ to -4.83 ‰ with average of -4.84 ‰. For surface water, the variation of δ^2H values ranged from 21.0 ‰ and 11.6 ‰ with average of -5.6 ‰; the variation of δ^{18}O values ranged from -4.21 ‰ and 2.93 ‰ with average of -0.87 ‰.

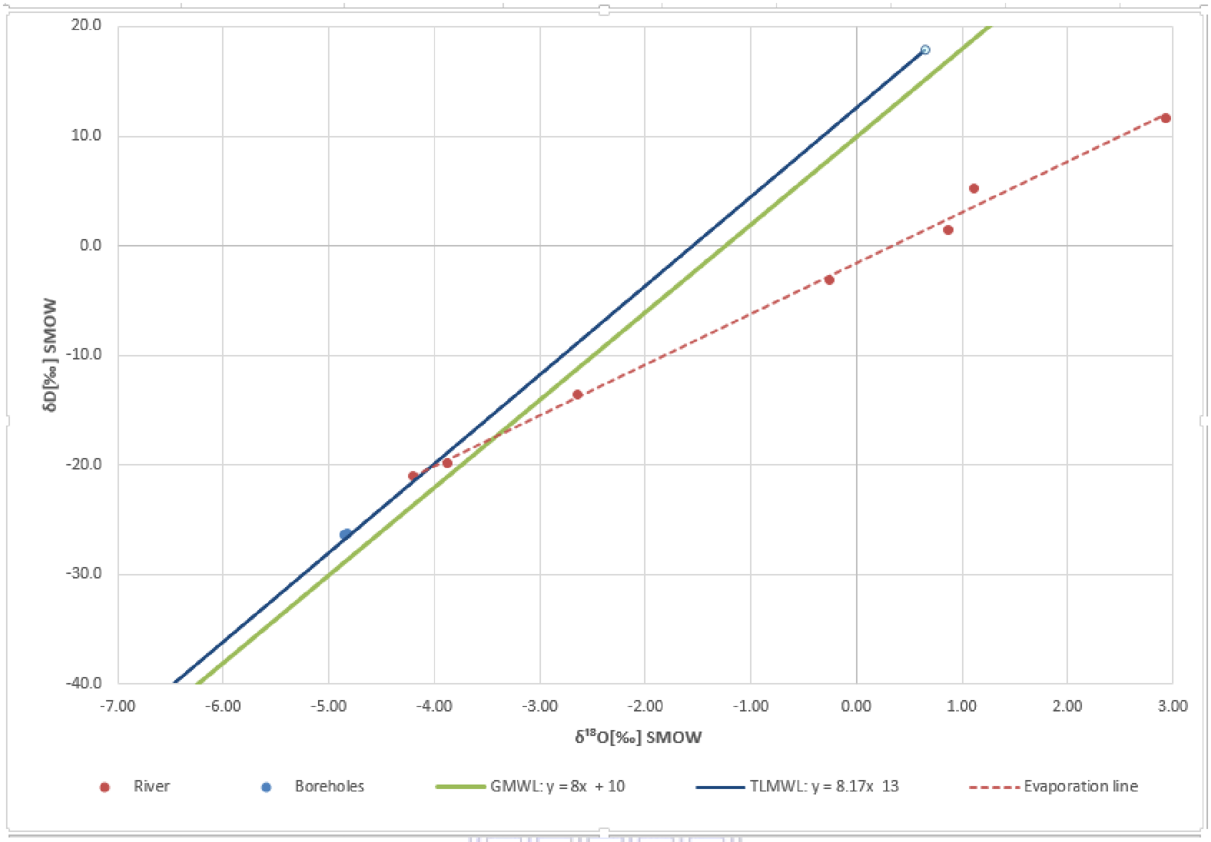

Figure6.3: Stable isotope plot showing groundwater and surface water samples with respect to LMWL and GMWL

The slope and intercept of the LMWLwere 8.17 and 13‰, slope was similar to GMWL of Craig (1961) but high intercept indicating that rainfall within the region is as a result of water vapour evaporation near the land surface i.e., either by re-condensation of evaporated rainfall or evaporation of surface waters (dams and rivers). Furthermore, the high intercept suggest regional moisture circulation. This was observed also for the Thohoyandou area in which the $\delta^{18}O$- $\delta^{2}H$ plot of one hydrological year data gave a regression line that represent local meteoric line with equation $\delta^{2}H= 7.56\ \delta^{18}O + 10.64$ (Durowoju et al. 2019). The groundwater samples plot at the depleted (negative) portion of the LMWL in comparison to surface water samples in which some are enriched. This indicates that groundwater in this study area is as a result of recharge from depleted rainfall after long atmospheric circulation. Rainfall data collected by Abiye et al. (2020) within the HRC had mostly depleted values of $\delta^{18}O$ and $\delta^{2}H$ with very few samples that were enriched. Groundwater samples were highly depleted with average of -4.84 ‰ for $\delta^{18}O$ and -26.3‰ for $\delta^{2}H$. The plot shows that the groundwater samples plot on the LMWL and highly depleted signifying that recharge occurred prior evaporation. This further suggests that rainwater was recharged rapidly along the preferential flow paths. This was because the groundwater samples retained the same isotopic composition as rainwater indicating that rainwater was recharged through geological structures such as fractures, dykes and pegmatite of the study area. Same behaviour was reported by Verhagen et al. (2009) for the Taaibosch area in Limpopo in which borehole samples were plotting between the GMWL and the LMWL suggesting recharge taking place rapidly, possibly via preferred pathways in higher lying areas preventing any significant evaporation. Results also indicated that most of river samples seemed to follow distinct trend along evaporation line. This was expected due to evaporation exposure that leads to enrichment in heavy isotopes. Interestingly, river sample in station A and C plotted close to groundwater samples indicating the contribution of groundwater to the river considering that the samples were taken during the dry period. Furthermore, samples in station D and F were depleted but trending towards the highly enriched river samples. This behaviour suggests mixing of expected enriched river sample with depleted groundwater contribution. Similar behaviour was reported by Leketa et al. (2018) for Upper Crocodile River Basin in Johannesburg where this study provided qualitative information on aquifer-river connectivity at catchment scale and identified river segments where interaction was occurring so that such areas are targeted for more detailed quantitative assessments. Samples from the boreholes were trending towards the highly enriched surface water suggesting possible focused recharge from the Hartbeespoort Dam or possible diffused recharge from irrigation by water from the dam.

Ecological health of rivers is dependent upon exchange fluxes between aquifers and rivers. In semi-arid environments evaporation can be higher than the rainfall input, thus, the influence of groundwater discharge into rivers including ephemeral is significant mostly during the period of no rainfall when there are low flows. In the study area the Hout River is characterised by mainly dry reaches with portions of the river course having pools during the dry period. The river reaches having pools are characterised by the presence of dykes and pegmatite cutting through the river channel. These structures control the groundwater movement within the study sites hence there is hyporheic exchange which is the key for nutrient cycling and contaminant transport (Perrin et al. 2011). Such an environment is important for most biogeochemical and ecological processes as well as for the provision of habitats for various plant and animal species.

6.5 Summary

The above chapter has provided the usefulness of using hydrochemical and environmental tracers in assessing aquifer-river interaction and ultimately identifying discharge zones along the river. Results from the study area indicate that there is a close hydraulic connection between the aquifer and the river. This is observed by major ions trends showing similar characteristics for groundwater and river samples. This is observed on schoeller diagram where an increase and decrease in either ion in groundwater is accompanied by a corresponding increase and decrease in that particular ion suggesting the interaction. The groundwater is mainly characterised by Na-Cl, Na-HCO_3 water type while river samples are characterised by the Na-HCO_3. The Na-Cl water which dominates the groundwater samples are understood to be as a result of low recharge and fluid rock interaction times in the subsurface alluvium along the river.

Groundwater samples plots on the LMWL retaining the same isotopic composition as rainwater indicating that rainwater is recharged through geological structures such as fractures, dykes and pegmatite of the study area. Due to sampling period of this study it was expected that high evaporation in the river will lead to difficulties in ascertaining the groundwater contribution to the rivers using isotopic data as the water ends up being exposed to evaporation leading to change in isotopic signatures. However, isotope data would work in such cases if there is high contribution of groundwater to the river in order to flush the evaporated river water. Station A, C, D and F confirms the contribution of groundwater to the river. It is evident from these results that the groundwater movement within the study area is controlled by geological structures as indicated on chapter 5. Findings from the current chapter fulfil the second objective of the thesis where spatial variation in the interaction between aquifers and river water is characterised. Based on the accumulated understanding in regard to hydrochemistry in the current chapter as well as on groundwater levels, local geology, insights from geophysics and hydraulic characteristics a conceptual model which explains the groundwater processes in relation to geological controls is constructed in the next chapter.

Chapter 7 : Conceptualization of groundwater processes, conclusion and recommendations

7.1 Introduction

Hydrogeological data in this chapter was integrated to create a hydrogeological conceptual model for the study area. To construct the conceptual model, geology, hydrogeology, recharge/discharge, groundwater flow, and hydrology data were used. Chemistry with isotopes were used as confirmatory tools to improve and verify the conceptual understanding of the model. This conceptual model was intended to provide site specific understanding of groundwater processes in relation to surface water (river). Continued river flows are determined by different factors such as evaporation from the river, transpiration from riparian vegetation and human influences such as abstraction. However, this study focussed only on the influence of hydrogeological characteristics in sustaining or reducing flows in a river. Sound conceptual model is important to improve knowledge on recharge, discharge and flow to inform the intervention on abstraction or monitoring practices of groundwater and surface water. The chapter ends with the conclusion and recommendations.

7.2 Conceptual modelling

The main source of recharge water to the Hout River is the depleted rainfall occurring between November and March and groundwater discharge. The shallow groundwater system in the study site appears to flow to the nearest discharge point controlled by complex geological features. Based on the groundwater flow direction it was suggested that mainly groundwater recharge occurs in the southern part of the Hout River catchment. Groundwater with prolonged residence and fluid rock interaction times in the subsurface in areas of discharge (alluvium along the river) is dominant as indicated by the groundwater type. The exchange fluxes do no only influence the quantity of water in the river but also the quality of that water. Thus, there is a need to develop a sound site-specific hydrogeological conceptual model to improve the understanding of groundwater occurrence, recharge, discharge and flow within the Hout River catchment using Mamadila as an experiment site. Line 2 of region 1 in Figure 4.1 was used as the geological cross-section in which the conceptual model in Figure 7.1 was derived from.

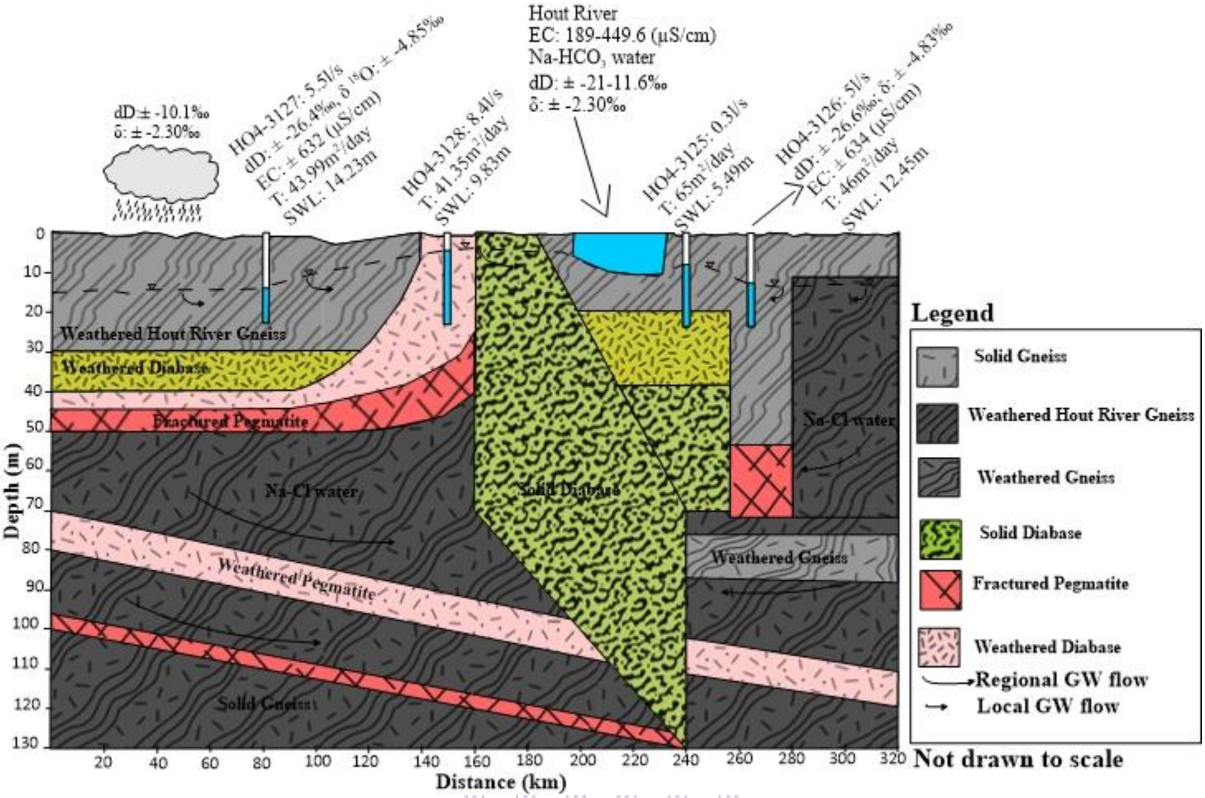

Figure 7.1: Site specific hydrogeological conceptual model of Ga-Mamadila experimental site.

7.3 Conclusion and recommendations

7.3.1 Evaluation of hydrogeological characteristics of the aquifer system.

Objective 1 of the current study focused on the evaluation of hydrogeological characteristics of the aquifer system using geological mapping, geophysics, drilling and aquifer tests. The aim was to identify hydrogeological conditions for groundwater occurrence and its flow dynamics. Based on geophysics, drilling and nature of groundwater levels it was found that groundwater occurrence within Houtriver gneiss aquifer formation was controlled by many structures inclusive of dipping diabase dykes, pegmatite lineaments and varying degrees in weathering and fracturing. Furthermore, diagnostic plots revealed that the study area was characterised by well-connected fracture network as indicated by changing flow regimes. The transmissivity values ranged from 37m^2/day to 65m^2/day while storativity ranged from $2.8\times10^{-06} – 1.4 \times10^{-04}$. Based on these findings it was concluded that groundwater occurrence within Houtriver gneiss aquifer formation was structurally controlled. The results from the study also managed to successfully map out the sections with high weathered zone and fractured regions that were indicative of high groundwater bearing potential. This study therefore recommended the integrated utilization of geological investigations, hydraulic testing and hydrogeophysical methods as a suitable approach for groundwater exploration in the Houtriver gneiss crystalline basement formation. It was further recommended that the network of boreholes be expanded to obtain the full coverage of the aquifer.

7.3.2 Characterising spatial variation in aquifer-river interaction

Objective 2 of the current study focused on characterising the spatial variation in aquifer-river interaction using environmental isotope and hydrochemical analysis. The aim was to identify pools that were sustained by groundwater. Analysis of stable isotope indicated that groundwater was recharged rapidly along preferential flow paths as the groundwater samples collected, retained the same isotopic composition as rain water. River samples at site A and C plotted close to groundwater samples and that indicated the contribution of groundwater to the river base flow. Interestingly, around these sites, there were diabase dykes cutting across the river. Based on these findings it was concluded that diabase dykes were rechannelling groundwater back to the surface. Hydrochemical analysis revealed that piper diagram was not so useful in identifying pools fed by groundwater as there were no dominant anion or cations (having no one cation-anion pair exceeding 50%). Na-Cl water type was suggested for groundwater. Schoeller diagram was further used to confirm interaction between groundwater and surface water. Schoeller diagram suggested possible interaction between groundwater and surface water based on the same type of variation in major ion concentration between two sources. Based on these findings the study concluded that interaction occurred within the identified sites. It was recommended that more data needs to be collected for hydrochemical and environmental isotopic analysis to gain more conclusive evidence on the nature and extent of aquifer-river interaction within the study area.

7.3.3 Conceptual development

Objective 3 of the current study focused on the development of a sound site-specific hydrogeological conceptual model to improve the understanding groundwater occurrence, recharge, discharge and flow. The aim was to integrate insights from the first two objectives and conceptualised the system. The site-specific model developed clearly showed the existence of secondary porosity features resulting into a vertical heterogeneities. Based on these findings, the study concluded that the site-specific investigations yielded sound scientific understanding of the hydrogeological controls of the system than generalisation. It was therefore recommended that more site-specific studies are conducted at catchment scale.

References

Abija, F.A., Essien, N.U., Abam, T. K. S. and. Ifedotun., A.I., 2019 Assessment of Aquifer Hydraulic Properties, Groundwater Potential and Vulnerability Integrating Geoelectric Methods with SRTM-DEM And LANDSAT-7 ETM Lineament Analysis in Parts of Cross River State, Nigeria.

Abiye, T., Mengistu, H. and Demlie, M., 2011. Groundwater Resource in the Crystalline Rocks of the Johannesburg Area, South Africa. Journal of Water Resource and Protection, 03(04), pp.199-212.

Abiye, T., Tshipala, D., Leketa, K., Villholth, K., Ebrahim, G., Magombeyi, M. and Butler, M., 2020. Hydrogeological characterization of crystalline aquifer in the Hout River Catchment, Limpopo province, South Africa. Groundwater for Sustainable Development, 11, p.100406.

Adadzi, P., Coffie, H., Afetorgbor, E. and Takase, M., 2018. Vertical Electrical Sounding Survey for Groundwater Exploration for Rural Water Supply in Parts of Ketu South in the Volta Region of Ghana. Journal of Hydrogeology & Hydrologic Engineering, 07(01).

Aizebeokhai, A. and Oyeyemi, K., 2017. Geoelectrical characterisation of basement aquifers: the case of Iberekodo, southwestern Nigeria. Hydrogeology Journal, 26(2), pp.651-664.

Akinlalu, A.A., Adelusi, A.O., Mamukuyomi E.A., and Akeredolu, B.E., 2016. Ground magnetic and 2-D resistivity mapping of basement structures around Iwaraja area South-western Nigeria,Original Research Article Journal of Basic and Applied Research International. O) International Knowledge Press.

Batte, A., Muwanga, A., Sigrist, P. and Owor, M., 2008. Vertical electrical sounding as an exploration technique to improve on the certainty of groundwater yield in the fractured crystalline basement aquifers of eastern Uganda. Hydrogeology Journal, 16(8), pp.1683-1693.

Banks, E.W., Simmons, C.T., Love, A.J., Cranswick, R., Werner, A.D., Bestland, E.A., Wood, M. and Wilson, T. 2009. Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). Hydrogeology. Journal, 17(8), 1969-1989.

Banks, E. W., C. T. Simmons, A. J. Love, and P. Shand. 2011. Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: Implications for regional scale water quantity and quality. Hydrology. Journal, 404(1–2), 30–49

Barker, J.A. 1988. A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock. Water Resources Res., 24(10): 1796-1804

Batu, V., 1998. Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis, John Wiley & Sons, Inc., New York, 727p.

Brodie, R, Sundaram, B, Tottenham, R, Hostetler, S, and Ransley, T. 2007. An overview of tools for assessing groundwater-surface water connectivity. Bureau of Rural Sciences, Canberra.

Chandra, S., Rao, V., Krishnamurthy, N., Dutta, S. and Ahmed, S., 2006. Integrated studies for characterization of lineaments used to locate groundwater potential zones in a hard rock region of Karnataka, India. Hydrogeology Journal, 14(6), pp.1042-1051.

Chandra, S., Dewandel, B., Dutta, S., Ahmed, S., 2010. Geophysical model of geological discontinuities in a granitic aquifer: analyzing small scale variability of electrical resistivity for groundwater occurrences. Applied. Geophysics Journal. 71, 137–148.

Chilton, P.J. and Foster, S.S.D. 1995. Hydrological characterization and water-supply potential of basement aquifers in tropical Africa. Hydrogeology Journal. 3: 36-49.

Chuma, C., Hlatywayo, D.J., Zuu, J., Muchingami, I., Mashingaidze, R.T., Midzi, V., 2013. Modelling the subsurface geology and groundwater occurrence of the Matsheumhlope low yielding aquifer in Bulawayo urban, Zimbabwe. J. Geography. Geology. 5 (3), 158–175.

Clark, L. 1985. Groundwater abstraction from Basement Complex areas of Africa. Quarterly Journal of Engineering Geology, 18: 25-34.

Clark, I. and Fritz, P. 1997. Environmental isotopes in hydrogeology. Lewis Publishers, New York

Cook, P.G. 2003. A guide to regional groundwater flow in fractured rock aquifers. Seaview Press, Adelaide, Australia.

Cooper, H.H. and Jacob, C.E. 1946. A generalized graphical method for evaluating formation constants and summarizing well field history. American Geophysical Union Transactions, 27: 526-534.

Craig, H. 1961. Isotopic variations in meteoric waters. Science, 133 (3465), 1702–1703

Cuthbert, M.O., Acworth, R.I., Andersen, M.S., Larsen, J.R., McCallum, A.M., Rau, G.C. and Tellam, J. H. 2016. Understanding and quantifying focused, indirect groundwater recharge from ephemeral streams using water table fluctuations, Water Resource. Res., 52, pp 827–840

Datry, T., Larned, S.T. and Tockner, K. 2014. Intermittent rivers: A challenge for freshwater ecology. BioScience Vol. 64 No. 3

Durowoju, O., Butler, M., Ekosse, G. and Odiyo, J., 2019. Hydrochemical Processes and Isotopic Study of Geothermal Springs within Soutpansberg, Limpopo Province, South Africa. Applied Sciences, 9(8), p.1688.

Du Toit, W.H., 2001. An investigation into the occurrence of groundwater in the contact aureole of large granite intrusions (batholiths) located west and northwest of Pietersburg. Dept. of Water Affairs. For., Pretoria, South Afr. 1.

Ebrahim, G., Villholth, K. and Boulos, M., 2019. Integrated hydrogeological modelling of hard-rock semi-arid terrain: supporting sustainable agricultural groundwater use in Hout catchment, Limpopo Province, South Africa. Hydrogeology Journal, 27(3), pp.965-981

Fallon, A., Villholth, K., Conway, D., Lankford, B. and Ebrahim, G., 2018. Agricultural groundwater management strategies and seasonal climate forecasting: perceptions from Mogwadi (Dendron), Limpopo, South Africa. Journal of Water and Climate Change, 10(1), pp.142-157.

Fenicia, F., Kavetski, D. and Savenije, H., 2011. Elements of a flexible approach for conceptual hydrological modeling: 1. Motivation and theoretical development. Water Resources Research, 47(11).

Fleckenstein, J.H., Niswonger, R.G., and Fogg G.E. 2006. River-aquifer interactions, geologic heterogeneity and low-flow management. Groundwater Vol. 44, No. 6—pp 837-852

Freeze, A.R. and Cherry, J.A. 1979. Groundwater. 1st edition Englewood Cliffs, NJ, USA: Prentice Hall

Girmay, E., Ayenew, T., Kebede, S., Alene, M., Wohnlich, S. and Wisotzky, F., 2015. Conceptual groundwater flow model of the Mekelle Paleozoic–Mesozoic sedimentary outlier and surroundings (northern Ethiopia) using environmental isotopes and dissolved ions. Hydrogeology Journal, 23(4), pp.649-672.

Gringarten, A.C. and Ramey, H.R. 1973. The Use of Source and Green’s Functions in Solving Unsteady- Flow Problems in Reservoirs. SPE 3818. SPE Journal, 255:285 – 296

Gringarten, A. C., H.R. Ramey, and Raghavan, R. 1974. Unsteady-state pressure distributions created by a well with a single infinite-conductivity vertical fracture. Society of Petroleum Engrs Journal l, 347-360.

Gringarten, A.C. and Ramey, H.J. 1974. Unsteady-state pressure distribution created by a well with a single horizontal fracture, partially penetrating or restricted entry. Trans. Am. Inst. Min. Eng., 257: 413-426.

Gustafson, G. and Krásný, J. 1994. Crystalline rock aquifers: Their occurrence, use and importance. Applied Hydrogeology, 2: 64-75.

Hiscock, K.M. (2005). Hydrogeology: Principles and Practices. Blackwell Science, UK. 388p.

Hammond, P.A. and Field, M.S. 2014 A Reinterpretation of Historic Aquifer Tests of Two Hydrauli-cally Fractured Wells by Application of Inverse Analysis, Derivative Analysis, and Diagnostic Plots. Journal of Water Resource and Protection, 6, 481-506

Hantush, M.S and Jacob, C.E. 1955. Nonsteady radial flow in an infinite leaky aquifer. Trans Am Geophysics Union, 36: 95-100.

Hantush, M.S. 1961. Drawdown around a partially penetrating well, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Engineering., 87(4): 83-98.

Hiscock, K.M. and Bense, V.F. 2014. Hydrogeology. Principles and practice. Second edition. John Wiley and Sons

Holland, M. 2011. Hydrogeological characterisation of crystalline basement aquifers within the Limpopo Province, South Africa. PhD Thesis, University of Pretoria, Pretoria, South Africa

Holland, M., 2012. Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province. Water SA, 38(3).

Holland, M., Witthüser, K.T., 2011. Evaluation of geologic and geomorphologic influences on borehole productivity in crystalline bedrock aquifers of Limpopo Province, South Africa. Hydrogeology. Journal. 19, 1065–1083.

Holland, M and Witthüser, K.T., 2009. Factors that control sustainable yields in the Achaean basement rock aquifers of the Limpopo province. In: Titus, R.A., Adams S. and Strachan, L. (eds.) The basement aquifers of Southern Africa.WRC Report Nr. TT 428/09. Water Research Commission, Pretoria.

Hughes, D.A. 2005. Hydrological issues associated with the determination of environmental water requirements of ephemeral rivers. River Research Applications 21: 899–908

Jolly, J., 1986. Report No. GH 3495. In: Borehole/Irrigation Survey and Groundwater Evaluation of the Doringlaagte Drainage Basin. DWAF, Pretoria.

Kahn, K.G., Ge, S., Caine, J.S., Manning, A 2007 Characterization of the shallow groundwater system in an alpinewatershed: Handcart Gulch, Colorado, USA, hydrogeology Journal 16: 103–12

Kalbus, E., Reinstorf, F. and Schirmer, M., 2006. Measuring methods for groundwater – surface water interactions: a review. Hydrology and Earth System Sciences, 10(6), pp.873-887.

Londoño, O.M.Q., Martínez, D.E., Dapeña, C. and Massone, H. 2008. Hydrogeochemistry and isotope analyses used to determine groundwater recharge and flow in low-gradient catchments of the province of Buenos Aires, Argentina. Hydrogeology Journal 16: 1113–1127

Olorunfemi, M. and Oni, A., 2019. Integrated geophysical methods and techniques for siting productive boreholes in basement complex terrain of southwestern Nigeria. Ife Journal of Science, 21(1), p.13.

MacDonald, A. M., Davies, J. & Peart, R. J. 2001. Geophysical methods for locating groundwater in low permeability sedimentary rocks: examples from southeast Nigeria. Journal of African Earth Sciences, 32, 115-131.

MacDonald, A., Davies, J., Calow, R., Chilton, J., 2005. Developing Groundwater: a Guide for Rural Water Supply. ITDG Publishing, Rugby, UK.

Maliva, R.G. 2016. Aquifer characterization techniques. Springer Hydrogeology

Martinelli, E., Hubert, G.L., 1985. A report to the ministry of energy and water resources and development. Master plan for rural water supply and sanitation. Norad. Hydrogeology 2, 109–118.

Masiyandima, M., Van der Stoep, I., Mwanasawani, T., Pfupajena, S.C., 2002. Groundwater management strategies and their implications on irrigated agriculture: the case of Dendron aquifer in Northern Province, South Africa. Phys. Chem. Earth, Parts A/B/C 27, 935–940.

Mengistu, H., Tessema, A., Abiye, T., Demlie, M. and Lin, H. 2015. Numerical modeling and environmental isotope methods in integrated mine-water management: a case study from the Witwatersrand basin, South Africa. Hydrogeology Journal 23: 533–550

Metwaly, M., El-Qady, G., Massoud, U., El-Kenawy, A., Matsushima, J., Al-Arifi, N., 2009. Integrated geoelectrical survey for groundwater and shallow subsurface evaluation: case study at Siliyin spring, El-Fayoum, Egypt. Int. J. Earth Sci. 99, 1427–1436.

Moench, A.F. 1985. Transient flow to a large-diameter well in an aquifer with storative semi-confining layers. Water Resource. Res., 21(8): 1121-1131.

Moench, A.F. 1997. Flow to a well of finite diameter in a homogeneous, anisotropic water-table aquifer. Water Resource. Res., 33(6): 1397-1407.

Moench, A.F. 1984. Double-porosity models for a fissured groundwater reservoir with fracture skin. Water Resource. Res., 20(7): 831-846.

Moseki, M.C. 2013. Surface water - Groundwater interactions: Development of methodologies suitable for South African conditions. PhD Thesis. University of the Free State, Bloemfontein, South Africa

Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, Water Resource. Res., 10(2): 303-312.

Owen, R.J., Gwavava, O., Gwaze, P., 2005. Multi- electrode resistivity survey for groundwater exploration in the Harare greenstone belt, Zimbabwe. Hydrogeology. Journal. 14, 244–252.

Papadopulos, I.S. and Cooper, H.H. 1967. Drawdown in a well of large diameter. Water Resource. Res., 3(1): 241-244

Perrin, J., Ahmed, S. and Hunkeler, D., 2011. The effects of geological heterogeneities and piezometric fluctuations on groundwater flow and chemistry in a hard-rock aquifer, southern India. Hydrogeology Journal, 19(6), pp.1189-1201.

Pietersen, K., Beekman, H., Holland, M., 2011. South African Groundwater Governance Case Study. WRC Report No. KV 273/11. Water Research Commission, Pretoria.

Shanafield, M., and Cook P. G. 2014, Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods, Hydrology. Journal, 511, 518–529.

Senthilkumar, M., Arumugam, R., Gnanasundar, D., Thambi, DSC., Sampath Kumar E. 2015. Effects of geological structures on groundwater flow and quality in hardrock regions of northern Tirunelveli district, southern India, Earth System. Sci. Janournal124, No. 2, pp. 405–418

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal, 10(2), pp.348-348.

Sun, X., Xu, Y. and Lin, L., 2015. The diagnostic plot analysis of artesian aquifers with case studies in Table Mountain Group of South Africa. Hydrogeology Journal, 23(3), pp.567-579.

Tanner, J. and Hughes, D., 2015. Surface water–groundwater interactions in catchment scale water resources assessments—understanding and hypothesis testing with a hydrological model. Hydrological Sciences Journal, pp.1-16.

Theis, C.V. 1935. The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a well using Ground-water Storage. American Geophysical Union Transactions, 14, 519-524.

Todd, D. K. and Mays, L. W.: Groundwater Hydrology, Wiley,Hoboken, 2005.

Tóth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. J. Geophysics. Res., 68: 4795-4812.

Van Esse, W. R., Perrin, C., Booij, M. J., Augustijn, D. C. M., Fenicia, F., Kavetski, D., and Lobligeois, F. 2013. The influence of conceptual model structure on model performance: a comparative study for 237 French catchments, Hydrology. Earth Syst. Sci. Journal, 17, 4227–4239

Van Tonder, G. Bardenhagen, I., Riemann, K. Van Bosch, J., Dzanga, P and Xu, Y. 2002. Manual on pumping test analysis in fractured rock aquifers. WRC Report No. 1116/1/02.Water Research Commission. Pretoria.

Varsányi, I., Kovács, L. and Bálint, A., 2015. Hydraulic conclusions from chemical considerations: groundwater in sedimentary environments in the central part of the Pannonian Basin, Hungary. Hydrogeology Journal, 23(3), pp.423-435.

Vegter, J.R. 2003. Hydrogeology of groundwater regions, Region 7, Polokwane/Pietersburg Plateau. WRC Report No. TT 209/03. Water Research Commission, Pretoria.

Vereecken, H., Kemna, A., Munch, H.M., Tillmann, A. and Verweerd, A. 2005. Aquifer characterization by geophysical methods. Encyclopedia of Hydrological Sciences. Edited by M G Anderson. John Wiley & Sons, Ltd

Verhagen, B.T., Butler, M.J., Van Wyk, E and Mutheiwana, S 2009. A multi-tracer study of the orgins, systematic and hydrological linkages of high concentrations in ground water in the Bochum District, Limpopo Province. WRC Report No. 1328/1/09. Water Research commission, Pretoria.

Wenner, F., 1916. A method of measuring earth resistivity. Bull. Bureau of Standards 12, 469–478.

Witthuser, K.T., Holland, M., Rossouw, T.G., Rambau, E., Bumby, A.J., Petzer, K.J., Dennis, I., Beekman, H., Van Rooy, J.L., Dippenaar, M., De Wit, M., 2011. Hydrogeology of Basement Aquifers in the Limpopo Province. WRC Report No. 1693/1/10. Water Research Commission, Pretoria.

Wright, E.P., 1992. The hydrogeology of crystalline basement aquifers in Africa. Geol. Soc. London Special. Publication. 66, 1–27.

Younger, P.L. 2007. Groundwater in the environment. An introduction. Blackwell publishing

Zody, A.A.R., 1969. Application of deep electrical soundings for groundwater exploration in Hawaii. Geophysics 34, 584–600.

Appendix

Sample log image for borehole HO4-3126

Sample log image for borehole HO4-3126

Sample log image for borehole HO4-3127

Sample log image for borehole HO4-3128