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Investigation of factors influencing borehole yields in the Nzhelele – Makhado Area in Limpopo Province, South Africa

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University of Venda

2018

University of Venda

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Dissertation submitted to the Department of Mining and Environmental Geology, School of Environmental Sciences, in fulfilment of the requirements for the degree of

Master of Earth Science in Mining and Environmental Geology

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June 2018

Declaration

I, the undersigned Azwindini Mukheli student number 9711671, hereby declare that this thesis is my own original work with the exception of quotations and references which are attributed on their sources. This thesis has not been previously submitted to any other university and will not be presented at any other university for similar or other degree award.

I, Azwindini Mukheli, hereby declare that I am aware that the copyright is vested in the University of Venda.

Signatureé é é é é é é é é é é é é é é é é é .

Date é

Acknowledgements

Firstly, I would like to express my thankfulness to God the Almighty for providing me strength, health and wisdom throughout my academic endeavour. I earnestly thank God of Mount Zion, through whose providence and blessing I have been able to finally complete this thesis despite all social and emotional challenges I went through during this period.

In May 2015, I contacted Professor Jason Ogola with the intention of completing my postgraduate degree in Earth Sciences, which I started some years back. He showed his faith in me by allowing me another chance to submit my work for review in preparation to get the document ready to complete my Masters. The rest is history!

I wish to thank Professor Jason Ogola, for never losing faith in me and assisting me in many ways to overcome the numerous challenges that I had to face. I am indeed grateful for all the invaluable comments and encouragements that yielded this thesis.

My sincerest gratitude to Dr. Kawawa Banda for proof reading this document and for supplying the much-needed review and guidance.

I wish to express my thanks to my co-supervisor and Dean of School of Environmental Sciences, Prof John Odiyo, for allowing me to register and complete my thesis.

Most importantly, I would like to thank my loving and caring wife, Caroline and children; Rendani, Victor and Tshinaki for their belief in me and sacrifices they made during the time of my studies. The encouragement, assistance, support and faith that they showed through the years kept me going through the difficult times and helped me stay focused on my goal.

My biggest appreciation goes to my brother Alex, who taught me morals of life and through his guidance and deeds; he moulded me into the person I am today.

Finally, I want to express my sincere gratitude to my friends, Freddy, Phumu, Tshepo and Vhalinavho for their continuous support and encouragement. Sometimes I wonder where will I be without you guys!

Abstract

This dissertation focused on the assessment of borehole yields within the Nzhelele-Makhado area, which is located in the northern part of South Africa within the Vhembe District Municipality of Limpopo Province. The aim of the study was to identify factors that influence the yields of water supply boreholes within the study area. This information will be used to improve the groundwater resource knowledge required in assessing the potential of groundwater resources in augmenting the Nzhelele Regional Water Supply Scheme.

The study area is mostly underlain by the óhard rockôformations of the Soutpansberg Group, which practically has no primary porosity. The groundwater is residing mainly within the weathered and fractured or discontinuities, considered being secondary porosities. Due to the complexity of the underlying fractured and hard rock aquifer systems and the fact that most of the boreholes drilled in the area were not scientifically sited, the study area is dominated by very low yielding boreholes.

Majority (48%) of the boreholes were drilled into the Nzhelele formation due to the fact that it occupies the central, relatively flat and low lying sections of the study area. The variations in average yields in boreholes drilled in different formations within the study area is relatively low suggesting that the difference in lithology of different formations do not to have any major influence in the yields of boreholes.

The topographical settings of the area do not have any influence in the borehole drilling depths and yields. The high borehole yields in shallow boreholes located in mountainous areas is due to local groundwater systems, which recharges and discharges locally.

Mapped lineaments are slightly low yielding (average yield of 0.32 l/s) compared to the faults (average yield of 0.43 l/s) within the study area. Boreholes drilled along the NE-SW trending lineaments support double the yields (0.41 l/s) on average of those along the SE-NW (0.28 l/s) and W-E (0.20 l/s) trending lineaments.

The high yields in boreholes closer to non-perennial streams compared to perennial rivers is due to the fact that non-perennial streams are comprised of thick layer of overburden capable of supporting high yielding boreholes, whereas the overburden along the perennial rivers are washed away during rainy season leaving bedrock exposed or covered with thin layer of sediments.

The proximity to the young faults trending SE-NW and dry non-perennial streams has proved to be the most the favourable areas for development of high yielding boreholes in the study area, compared to lithological difference and topographical settings of the area.

However, it should be noted that there are no simple relationship between various factors that control the yield of the boreholes in the area. Despite the similarities in some factors that influence borehole productivity on a regional scale such as faults and drainage systems, the complexity of the weathered-fractured aquifer system suggests an over-riding influence of local features, which results in significant variations in yield and response to abstraction.

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Acronyms and abbreviations

CoC	Chain of Custody
CRDT	Constant Rate Discharge Test
CZ	Central Zone
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
NWA	National Water Act
Ga	Billion years
GIS	Geographical Positioning System
GRIP	Groundwater Resources Information Project
IDP	Integrated Development Plan
LMB	Limpopo Mobile Belt
LMC	Limpopo Metamorphic Complex
Ma	Million years
Mamsl	meters above mean sea level
mbgl	meters below ground level
MDGs	Millennium Development Goals
MLM	Makhado Local Municipality
NGA	National Groundwater Archive
NGDB	National Groundwater Database
NMZ	Northern Marginal Zone
NWRS	National Water Resource Strategy
SMZ	Southern Marginal Zone
SDT	Step Discharge Test
RDP	Reconstruction and Development Programme
TLM	Thulamela Local Municipality
VDM	Vhembe District Municipality

1 Introduction

1.1 Background

Nzhelele-Makhado area is located in the north-eastern part of South Africa within the Vhembe District Municipality (VDM) of Limpopo Province. Nzhelele-Makhado area is located in a predominantly semi-arid area and like most areas in South Africa, experiences low rainfall and high evaporation. Water in the area is provided by the Makhado Local Municipality (MLM) via the Nzhelele Regional Water Supply Scheme (NRWSS). The water is currently sourced from the Mutshedzi Dam, which according to the Department of Water and Forestry (DWAF, 2011), has been over allocated.

According to DWAF (2011) Mutshedzi Dam has an average yield of 3,480 million m^3/yr, however, the current allocation from the dam is 3,67 million m^3/yr. To meet the water demand in the area, a total of 0,43 million m^3/yr of groundwater has been reported to be abstracted from several boreholes in the area (DWAF, 2011). The information regarding the boreholes in which groundwater is being abstracted is not reliable or the confidence level on groundwater data is low (DWAF, 2011).

The DWAF (2011) report shows that there is water deficit in the area and current allocation for the NRWSS of 3,670 million m^3/yr, is in excess of the average firm yield of Mutshedzi Dam of 3,480 million m^3/yr, as a result this increases the risk of supply failure beyond the accepted 98% level of supply assurance. An additional water source is required to meet the current and future water demand in the area.

To secure an additional water source, and to manage water resources to sustainably meet the current and future demands, a comprehensive assessment of the water resources, quality and quantity, will have to be conducted. The need for comprehensive assessments is well recognised in most countries but often-required information is unavailable or unreliable owing to the gaps in hydrological and hydrogeological information and understanding. These gaps are particularly acute with respect to groundwater resources.

Groundwater in most countries has played a major role as a sole source or a supplement to the bulk water system. The groundwater resource is the best and only affordable option to augment the current bulk water supply in Nzhelele-Makhado. DWAF (2011) indicated that, like in most areas, the available data and information regarding the groundwater resource in the area is not reliable and recommended a detailed hydrogeological assessment and borehole hydrocensus for the area. This is aimed at improving the data confidence level and the groundwater resource knowledge base in the area.

The current study is therefore a stepping-stone towards the compilation of the comprehensive water resource assessments in the area and is aimed at assessing the groundwater supply potential of the area as well as factors that influence the yields.

1.2 Study area

1.2.1 Location and study boundary

The study area is located in the north-eastern corner of South Africa. It falls within the boundaries of Makhado Local Municipality (MLM) and Thulamela Local Municipality (TLM) of the Vhembe District in the Limpopo Province. The area lies 30 km northeast of Makhado town (Louis Trichardt) and 20 km west of Sibasa (Figure1-1).

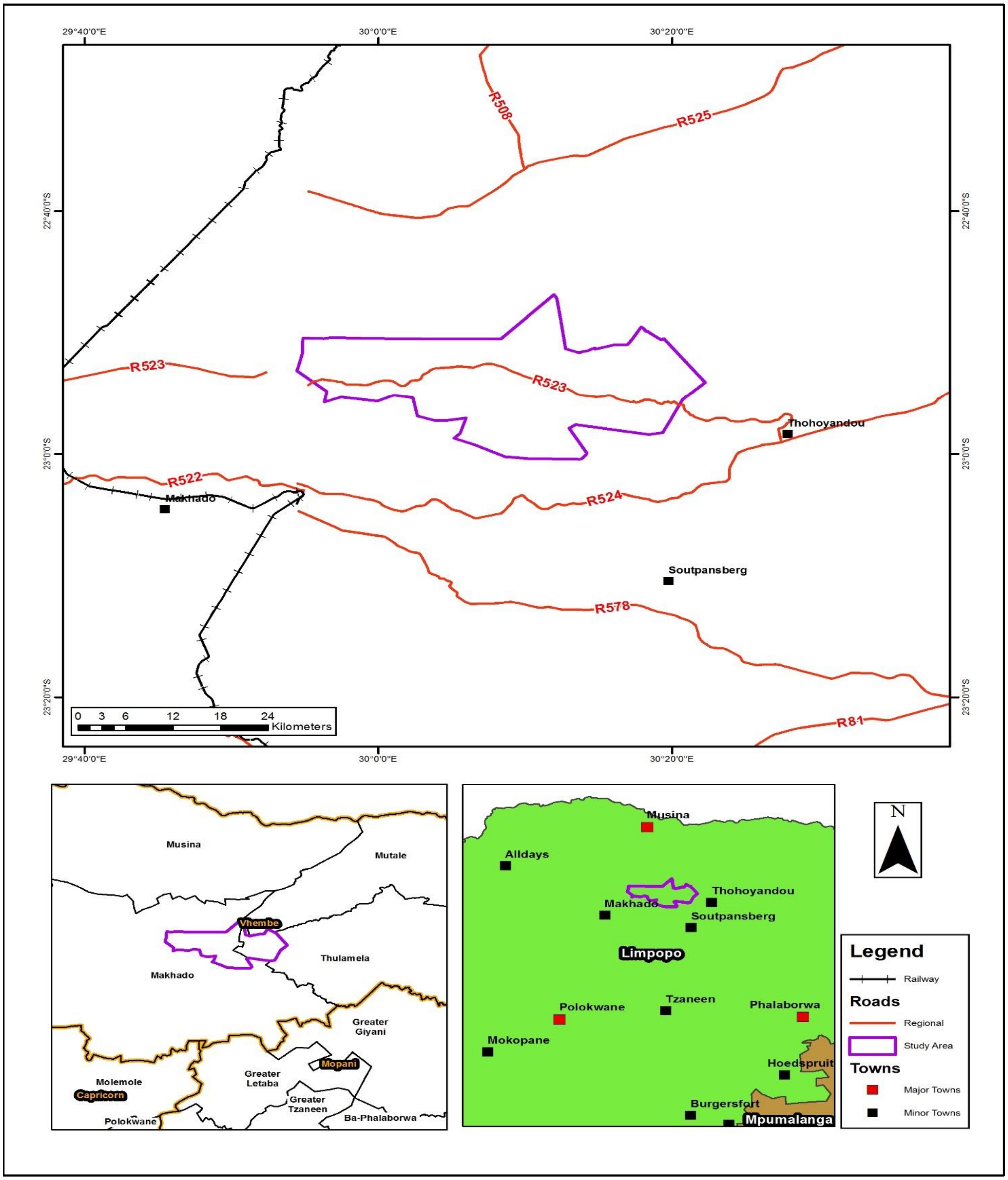


Figure1-1: Location of Nzhelele-Makhado area.

The area is part of the Soutpansberg mountain range and covers a surface area of 444.2 km2. It lies between 22° 50ôand 22° 59ôS (Latitude) and 29°57ôand 30° 19ôE (Longitude). The boundaries of the study area coincide with the boundary of the H27 óquaternaryô catchment boundary.

1.2.2 Climate

The study area is located within a dry tropical climate zone which experiences summer rainfall between October and March. The rainfall information is based on the data obtained from 12 rainfall stations located within and around the study area. The details of the rainfall stations are presented in Table 1-1. Annual rainfall varies from 300 mm in the northern valleys to over 2,000 mm in the south facing ridges of the Nzhelele valley. In the low-lying area in the vicinity of the Nzhelele Dam, rainfall is approximately 500 mm/a (Midgley *et al*, 1994).

Most of the rainfall occurs as afternoon thundershowers between November and December. More than 80% of rainfall occurs during Summer months (Figure1-2).

Table 1-1: Details of rainfall monitoring stations in the study area.

Station No.	**Station name**	**No. of records**	**Mean Annual Precipitation (mm)**
766030	Roodewal	35	905.3
766133	Krantzpoort	22	318.1
766201	Mphefu	23	423.2
766277	Tshipise	25	341.8
766324	Siloam SendingStasie	59	488.1
766276	Tshipise	1	353.7
766462	Gaarside	23	313.1
766480	Entabeni (BOS)	67	1 824
766509	Matiwa (B0S)	58	2 029
766563	Tate (BOS)	27	1 174.1
766568	Mafela Plantation	1	1 041.1
766596	Thathe-Vondo	22	1 140.8

The rainfall is strongly influenced by the Soutpansberg Mountains due to orographic effects. Moist air from the south east drops rain onto the southern and eastern slopes, hence north facing slopes and valleys lie in a rain shadow. As a result, the study area is relatively dry and rainfall is generally below 500 mm/a (DWAF, 2003).

Evaporation increases from south to north. The mean annual Symons Pan evaporation is 1 600 mm/a in the south, increasing to 1 800 mm in the north.

An evaporation station exists at Nzhelele dam. This station records a mean annual S-pan evaporation of 1 835 mm (DWAF, 2003).

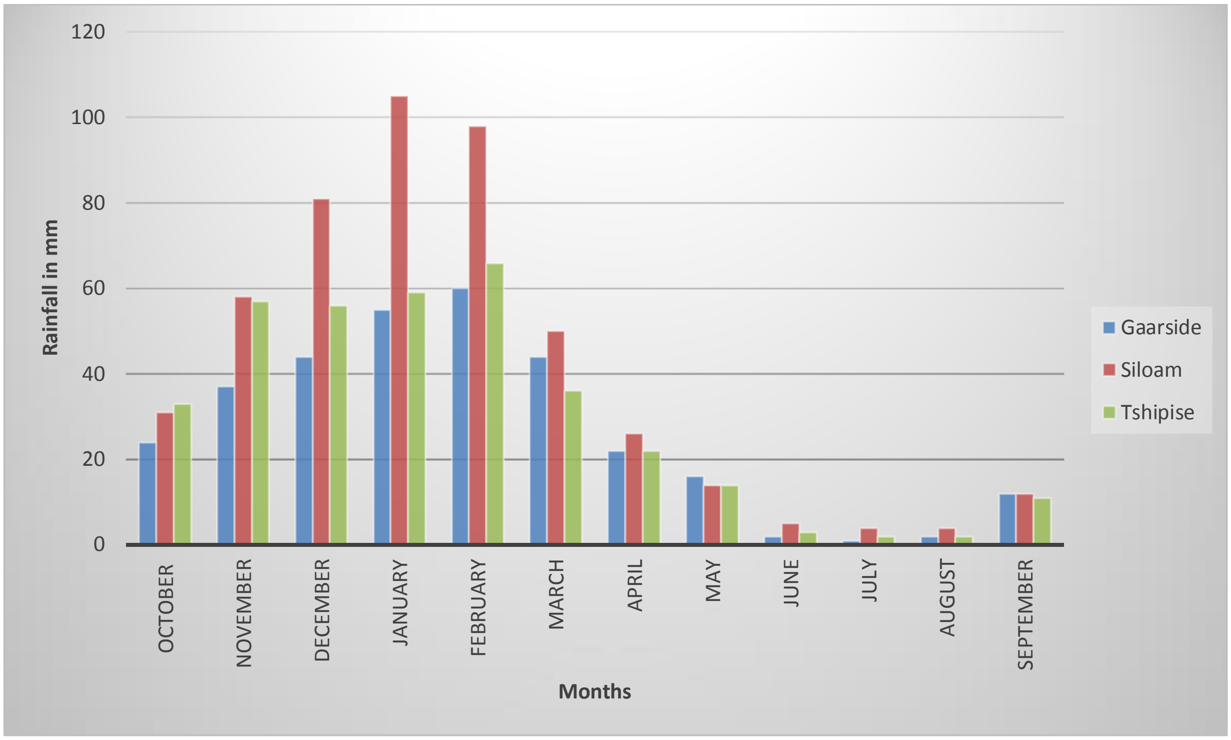


Figure1-2: Average monthly rainfall for Siloam (1931 - 1989), Gaarside (1986 - 1989) and Tshipise (1960 - 2002) (Midgley *et al*, 1994).

1.2.3 Topography and drainage

The topographical setting of the study area is closely related to its geology and structural history. The Soutpansberg forms high mountainous terrain dissected by narrow east-west trending valleys. The topographical maps of the area (2229 DD (Wyllieśs Poort), 2230 CC (Nzhelele) and 2230 CD (Thohoyandou) show that elevation of the hills and valleys within the Nzhelele-Makhado area ranges between 700 to 1400 m above the sea level (National Geo-spatial Information, 1999).

The drainage system of the area is defined by the Nzhelele River Catchment with the main tributaries being the Tshiruru, Mugungudi, Mutshedzi, Wyllie and Mutamba rivers. The study area covers four quaternary catchments (A80A, A80B, A80E and A92A) of the Nzhelele Catchment.

The flows of the tributaries are down the steep mountain slopes from the south and north towards the Nzhelele valley into Nzhelele River. The Nzhelele River flows to the west but in the northern part of the study area, it turns towards the north following a narrow valley before reaching the Nzhelele Dam.

1.3 Problem statement

While several boreholes were drilled in the Nzhelele-Makhado area in the past to provide water during drought in most of the villages, groundwater resources were never considered as an option for augmenting or supplementing the bulk water system in the area. There is very little information available regarding the amount of groundwater that can be abstracted sustainably, from the aquifers underlying the area.

Most of the boreholes drilled in the area were not sited using scientific methods, which include geological and hydrogeological condition assessments as well as geophysical surveys. The regional geological and hydrogeological structures were never investigated and targeted by groundwater development projects completed in the area. This has led to most of the boreholes drilled being low yielding or dry.

The origin, movement and existence of groundwater depends on several factors such as slope, drainage, geology, lineaments and geomorphology. Understanding the regional geological and hydrogeological conditions of the Nzhelele-Makhado area can led to the understanding of the factors that influence the yields of boreholes, leading to the development of high yielding boreholes required in supplementing the bulk water supply in the area. This study is therefore focusing on those factors (slope, drainage, geology, lineaments and geomorphology) that influence the borehole yields within the Nzhelele-Makhado study area.

1.4 Justification of the study

The groundwater resources in the study area are available throughout the area in varying quantities and qualities depending on the characteristics of the underlying aquifer systems. The fragmented nature of the underlying hard rock formations in the Nzhelele-Makhado area has presented considerable difficulties in quantifying groundwater resources and its availability with certainty (Du Toit *et al.*, 2012).

Due to the complexity of the fractured or hard rock aquifer system underlying the study area, development or locating of high yielding successful boreholes in the area requires thorough scientific approaches which include thorough understanding of the geology, hydrogeology and structures which directly or indirectly control the yields of boreholes (Du Toit *et al.*, 2012).

The results of this research will increase the geological and hydrogeological understanding of the area and further identify factors controlling the groundwater yields and productivity leading to identification of potential high yielding aquifer systems capable of supporting high yielding boreholes required to augment the water deficit in the area.

1.5 Hypothesis

The hypotheses under consideration here are that;

- The orientation of the faults and other lineaments has a bearing in the borehole yields.
- The lithological differences within the Nzhelele-Makhado area has influence on the borehole yields.

1.6 Objectives

The main objective of the study was to establish factors that influence the yields of boreholes and groundwater productivity within the hard rock aquifer systems in the Nzhelele ï Makhado area.

Specific objectives were to:

- Investigate the different formations and their potential influence on the borehole yields;
- Investigate the influence of topography, drainage and lineaments (including faults) in the borehole yields;
- Investigate other factors that determines the high yields on boreholes within the Nzhelele-Makhado area.

1.7 Study limitations

The investigation of factors influencing borehole yields in the Nzhelele-Makhado area relied mostly in the existing geological and hydrogeological data gathered in the previous studies. Most the groundwater development programmes, especially those completed during drought periods in the area were led and implemented by individuals with limited geological and hydrogeological knowledge and the developed boreholes were sited closer to targeted settlements without any geological or hydrogeological basis.

Those boreholes which were scientifically sited were for single groundwater scheme targeting a clinic or school and the hydrogeological investigation focused on a specific site without considering the regional geological and hydrogeological settings of the area. Regional geological structures were not explored. Several boreholes data have been captured in the Groundwater Resource Information Project database but the borehole data sets area not fully populated and the positions of some of the boreholes are not accurate.

Very limited number of borehole logs were available for review. The GRIP website only provide the recommended abstraction rate and not pumping test data of the boreholes. The test pumping data, therefore canôt be verified. Not all boreholes were tested, only those boreholes located at a radius of a kilometre from each other were selected. Some high yielding boreholes which are closer to each other might have been left untested.

Most of the boreholes within the study area which were drilled during the drought programmes were reported to have been drilled to a minimum depth of 30 meters below ground level, however, some of the boreholes are now shallower than the drilled depth indicating that some of them might have collapsed or ósilted upô Some of the water strikes might have been covered by collapsed materials, resulting in the reduction of the overall yield of the boreholes.

The extent of the Quaternary sediments is not known because the drilled boreholes where completed within the sediment and some penetrated the top part of the sediments. Therefore, the hydrogeological conditions of the Quaternary sediments within the study area is not known.

2 Literature Review

This chapter sets the scene for this work through examining some important theoretical and empirical issues pertaining to groundwater occurrence, yields of boreholes and factors that control groundwater availability in the Nzhelele-Makhado area. The literature studied therefore ranges from global groundwater assessment studies that have driven the scientific definitions and interpretations of factors that control groundwater occurrence, borehole yields and related concepts. The chapter further describes the regional and local geological settings of the study area as well as the hydrogeological conditions.

2.1 Groundwater occurrence in hard rocks

It is accordingly essential to begin this research by defining the rock formations underlying the study area and how the groundwater occurs and flows within the underlying formations. The study area is underlain by the ôhard rocksôof igneous, metamorphic and sedimentary origin.

In this research, hard rock refers to all rocks without sufficient primary porosity and hydraulic conductivity for feasible groundwater extraction as defined by Gustafsson (1993, 1994). Hard rocks have practically no primary (matrix) porosity as sandstones or other sedimentary rocks do. That is, they are virtually impervious (total porosity 0,0001-0,1); (Carlsson and Olsson 1977a; Carlsson and Olsson, 1977b; Gbürek *et al*., 1999; Lloyd, 1999; Olofsson *et al*., 2001; Healy and Cook, 2002). Groundwater in the hard rocks resides mainly in weathered zones of the bedrock and in fractures and other discontinuities, i.e., what is generally referred to as secondary porosity (Davis and DeWiest, 1966; Larsson, 1977; Freeze and Cherry, 1979; Larsson *et al*., 1984; Greenbaum, 1992; Gustafsson, 1994; Lloyd, 1999; Singhal and Gupta, 1999; Murty and Raghavan, 2002; Tam *et al*., 2004; Henriksen and Braathen, 2006).

2.1.1 Groundwater in hard rock terrains

The development of hard-rock aquifers as a reliable source of rural water supply is notoriously complicated, and transmissivities are spatially highly variable (Wright, 1992; Chilton and Foster, 1995; Banks and Robins, 2002). Due to the low intrinsic primary permeability and porosity of the hard-rock, these aquifers differ in important ways from other aquifer types, and demand specific knowledge and techniques if groundwater is to be extracted and managed efficiently (Holland, 2011).

Understanding the distribution and the dynamics of the groundwater resources within hard-rock aquifers in a given area is necessary and essential for assessment or quantification of the groundwater resources of that area. The understanding of the groundwater occurrence and movement in hard-rock aquifers wherein borehole yields vary considerably from one location to the other, even within the same rock type can be regarded as a first step in determining any form of groundwater availability whether it is on the catchment, basin or borehole scale. Knowledge and good understanding of the relationship between the hard-rock aquifers and factors that determine the borehole yields within these aquifers is required in the development of sustainable water sources in the hard-rock aquifer systems (Mäkelä, 2012).

Several studies and researchers have tried to identify the most important factor or combination of factors that are controlling the borehole yields in the basement or hard rock terrain, in order to identify areas with higher groundwater potential (Mabee, 1999; Henriksen, 2003; Neves and Morales, 2007a). The common goal of all these researchers was to search for the single factor or combination of factors that were most influential in controlling the borehole yield, and then use this information to locate high yielding bedrock boreholes with greater reliability.

Early research focused on the influence of topography, rock type, structure and overburden on borehole yields (Ellis, 1909; Stuckey, 1929; Fucron, 1939; LeGrand, 1949; Cushman *et al.*, 1953) and was soon followed by studies examining the relationship between borehole yields and borehole depth (LeGrand, 1954; Dingman and Meyer, 1954). Du Toit *et al.*, (2012) indicated that independent or interrelated factors such as geomorphology (topography), lithology, brittle (neo-tectonics) and surface water hydrology, all play a significant role in the occurrence of groundwater in crystalline rocks because they control the:

- nature and depth of the regolith;
- development of fracture and fault zones; and
- presence of higher porosity material (or adjacent alluvium).

The studies regarding the optimal location of high yielding boreholes and factors controlling the groundwater occurrence and movement in most areas within Limpopo province are rare and the siting of new boreholes, as indicated by Du Toit *et al*. (2012), is often a wildcard drilling exercise with limited geophysical support. To date, in most areas, drilling in hard rock areas has been associated with a high risk of drilling dry or low yielding boreholes.

Several authors have indicated that evaluating groundwater availability in fractured bedrock poses major problems and that fractured bedrocks have extreme variability in water-bearing properties and highly localized water producing zones, which make geological and geophysical exploration challenging (Larsson *et al*., 1972; Dijon, 1977; Banks, 1992; Sander, 1999; Fernandes and Rudolph, 2001; Moore *et al.*, 2002). It is therefore, difficult to predict consistently whether a borehole at a given location underlain by hard rocks will yield respectable quantities of water. There are no reliable guidelines for the location of high-yield boreholes in crystalline bedrock aquifers and the practice of assuming that topographically and geophysically prominent fracture zones will always give elevated yields has been shown to be, at best, rather unreliable (Carlsson and Olsson, 1977a; 1977b; Filho and Rebouças, 1995).

The hydrogeological characteristics of the crystalline-rock aquifers have been intensively studied worldwide, but relatively few studies (Holland, 2012; Du Toit *et al.*, 2012; Holland and Witthüser, 2011) were undertaken to determine the factors that influence groundwater occurrence and flow in the aquifer systems in Limpopo Province. Therefore, there is need for systematic research on basement aquifers to improve knowledge of the groundwater resource occurrence and factors that determine the borehole yield in a given location.

2.2 Factors controlling groundwater occurrence in hard rocks

Many researchers have tried to explain the variations in borehole yields by examining statistically the specific geologic and other factors that influence the development and distribution of hydraulic properties in the bedrock (LeGrand, 1954; Siddiqui and Parizek, 1971; Daniel, 1987, 1989; Morland, 1997; Moore *et al*., 2002a; Henriksen, 2003, 2006). The goal of these studies has been to search for a factor or a combination of factors that are most influential in controlling yield and to use this information to help locate high yield borehole sites in hard rock terrains with greater reliability. Those hydrogeological factors, which correlate with high yield boreholes and hydraulic properties, may be further used to identify areas of enhanced permeability and potentially good aquifer zones in the similar areas even when there is no existing borehole information (Mabee, 1992, 1999; Kellgren and Sander, 1997, 2000).

According to various studies (Mäkelä, 2012; Holland, 2012; Du Toit *et al*., 2012, Holland and Witthüsser, 2011) factors affecting borehole yield and hydraulic properties in crystalline rock areas include geomorphologic situation, erosion surfaces, topographic setting, size of the drainage area up-gradient of a borehole, rock type, overburden type, overburden thickness, structural setting, joint and fracture characteristics, dip of bedrock strata, proximity to lineaments and lineament intersections, total borehole depth, borehole construction, depth to the groundwater table, saturated aquifer thickness, rock stress, tectonic history, neo-tectonic activity, annual crustal uplift rate in response to the last glaciation, climate (rainfall), the amount of recharge from precipitation, runoff, and the proximity to surface-water bodies.

Some of the factors are important at the local scale, others at the sub-regional scale, and still others at the regional scale (Henriksen, 2003a; Henriksen and Braathen 2006). Despite the coherence of such factors, local conditions may dominate yield and well response at a given site. Reliable predictions of potential well yield cannot be guaranteed even by putting considerable effort into the assessment of existing data and the use of a variety of siting techniques (Chilton and Foster 1995). Moreover, factors affecting well yield in one geologic setting may not be directly transferable to another (Mabee, 1999). The geological settings, topographical settings, lineaments and the distance from the surface water body are considered by most researchers (Tam *et al*., 2004; Mabee, 1999; Rosenberry and Winter, 1993, Johansson, 2005) as the major factors that in influence the groundwater occurrence in the hard rock terrane.

2.2.1 Geological settings

Some of the early researchers recognised that specific rock types, sandstone, quartz vein, carbonates and structures (fold axes, sheet joints) supported boreholes with high yields. Several authors have pointed out the significance of lithology in the borehole yield and hydraulic properties (Larsson 1987; Rohr-Torp 2003; Knopman, 1990; Henriksen, 1995; Morland, 1997; Olofsson *et al*., 2001). However, some authors indicated that the lithology of crystalline igneous and metamorphic rocks are more or less non-significant in the borehole production point of view especially on a regional scale (Havlík and Krásný, 1998; Krásný, 2002).

2.2.2 Topographical settings

The influence of topography on borehole yield has been shown by many (e.g. McFarlane *et al*., 1992; Henriksen, 1995; Mabee, 1999) with the common result that boreholes located in valleys and flat areas show generally higher yields compared to boreholes located on slopes and hilltops. Topography was identified as an important indication of borehole yield, because it may reflect internal structures in the bedrock. Low altitude areas between ridges and hilltops have often been related to bedrock faults or fracture zones, and hence, to higher borehole yields (Mäkelä, 2012). Areas of ridges and hilltops are expected to potentially be less fractured as they have been more resistant to erosion and, therefore, would have the potential of being areas where the water-yielding characteristics of boreholes would be lower.

Many authors have noticed that boreholes on flat uplands or in valleys tend to yield larger amounts of water than boreholes on valley sides or sharp hilltops (Ellis, 1906; LeGrand, 1954, 1967. 1979, 1992, 2004; Davis and Turk, 1964; Davis and DeWiest, 1966; Poth, 1968; Siddiqui and Parizek,1971; Larsson, 1977; Larsson *et al*., 1984; Daniel, 1987; 1989; Knopman, 1990; Lewis, 1990; Huntley *et al*., 1991; Barker *et al*., 1992; Mabee, 1999; Singhal and Gupta, 1999; Krásný, 2000; 2005; Holland and Witthüser, 2011).

Krásný (1975, 1993, 1996c, 1997, 2000) concluded that boreholes in the drainage areas close to valley axis are obviously higher yielding than those located away from the valley. Eftimi (2003) suggested that the topographic and geomorphologic position of drilled borehole is the controlling factor of the transmissivity and yield of the borehole. Daniel (1987, 1989) found that boreholes in draws or valleys have average yields three times those of boreholes on hills and ridges.

In the Limpopo Province basement aquifers, South Africa, Holland and Witthüser (2009) found that, in addition to valley settings, flat surfaces also had higher than average transmissivities suggesting that there are controlling factors other than topography on the productivity of the boreholes.

2.2.3 Lineaments

In the 1960s and 1970s lineament or ófracture traceô analysis emerged as a useful technique for helping to locate high yielding boreholes in the bedrock (Lattman and Parizek, 1964; Siddiqui and Parizek, 1971; Parizek, 1976). In these studies, linear features marked by the alignment of topography, stream channels, or vegetation visible on remotely sensed imagery were interpreted as steeply dipping faults or zones of closely spaced fractures in the bedrock. As such, they represented areas of enhanced permeability and, therefore, were potential target areas for high yielding bedrock boreholes.

Lineament factors, such as fracture densities and distance away from lineaments and lineament intersections, have been applied with variable success to explain the variability of the yield and hydraulic properties of drilled boreholes (Mäkelä, 2012). The basic idea of lineament analysis have been that if boreholes with high yields can be related to the location and properties of lineaments, then the lineament information could be useful in locating zones of high productivity in the aquifer (Larsson *et al.*, 1972; De La Garza and Slade, 1986; Banks *et al*., 1992; Yin and Brook, 1992; Gustafsson,1994; Mabee *et al*., 1994, 2002; Sidle and Lee, 1995; Sami, 1996; Magove and Carr, 1999; Tam *et al*., 2004). Lattman and Parizek (1964) have extensively investigated the relationship between lineaments and groundwater occurrences.

The interpreted lineaments may reflect a number of features such as faults, fracture zones, joints, foliations, dykes, lithological contacts and linear branches of the drainage systems. It is recognised that lineament mapping is often subjective (Wise, 1982; Mabee *et al*., 1994) and that a 2-dimensional lineament of geological origin, mapped on remote-sensing imagery, provides little direct information on the type of feature, its depth, dip or potential infilling (Sander, 2007).

According to Braathen and Gabrielsen (1998) a large lineament can enhance fracturing up to 300 m away, while Clark (1985) suggested that the area of influence might be less than 150 m and Fernandes and Rudolph (2001) reduced it further to 70 m in their studies. For the purpose of this research, all boreholes within 50 m of a lineament were considered to be targeting a lineament and this radius is similar to the one used by Holland (2012).

According to Sami *et al*. (2002), regional-scale lineaments (related to faulting) are the most favourable drilling targets in the Limpopo Mobile Belt whereas small-scale faults have a poorer potential for groundwater. As a result, these (high-resolution) lineaments when mapped may well represent regional scale faulting and lithological or tectonic contacts that may have higher water-bearing potential.

Holland (2012) further concluded that the proximity of lineaments plays a role on borehole productivity and based on the transmissivity results it is assumed that the intensity of fracturing decreases with increasing distance away from the lineament. His analysis on the influence of dykes and lineaments on borehole productivity was based on specific assumptions and limitations. The assumptions include the fact that most of the dykeõs positions are not accurate and so do the zones of influence. Although boreholes that intercepted dykes have higher transmissivities compared to boreholes that did not intercept dykes, there is no relationship between the borehole productivity and proximity to the dyke (Holland, 2012).

These studies found that the specific capabilities of boreholes intentionally located on the or near lineaments in carbonate rocks were higher than for those boreholes in non-linear lineaments areas. Lineaments analysis has gained popularity particularly in the professional consulting industry, because the method is relatively fast and inexpensive compared to field intensive investigations.

2.2.4 Drainage

Holland (2012) concluded that the drainage channels tend to follow zones of structural weaknesses (e.g. lineaments) in the near surface; therefore, rocks in the vicinity of rivers might be more intensely fractured, jointed and/or weathered. In this study, boreholes within the radius distance of 50 m from the drainage channels were assumed to be influenced by the nearby drainage system. Holland (2012) isolated geology and proximity to the surface water drainages as the dominant factors that have obvious influence on groundwater occurrence in the province.

2.3 Geological setting of the Nzhelele-Makhado area

2.3.1 Geology

The study area is underlain by rocks of the Soutpansberg Group which are located within the Southern Marginal Zone (SMZ) of the Limpopo Mobile Belt (LMB). The LMB is composed of highly metamorphosed and intensely deformed rocks situated between the granite-greenstone terrane of the Kaapvaal Craton in the south and the deformed and poly-metamorphosed rocks of the Central Zone (CZ) (Barton *et al.*, 1983). The LMB and its subdivisions as well as shear zones within the belt are shown in Figure 2-1.

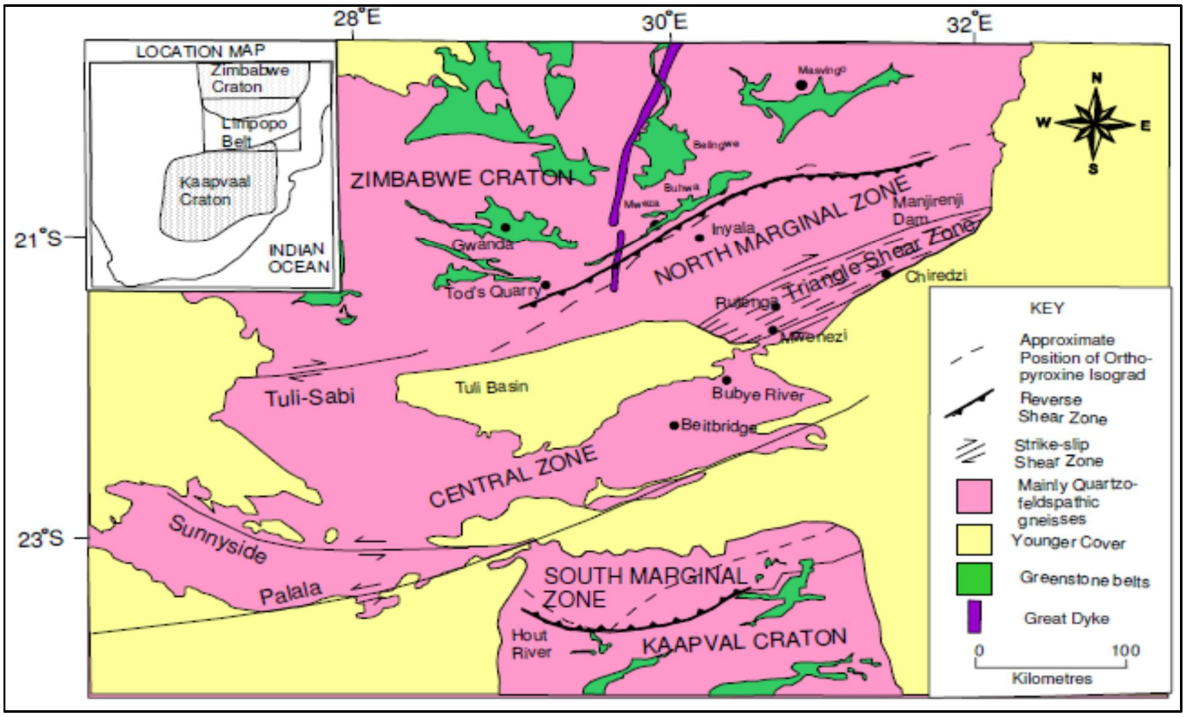


Figure 2-1: Simplified map of the Limpopo Mobile Belt with major subdivisions and shear zones (Waternet, 2009)

The Soutpansberg depositional basin was formed as an east-west trending asymmetrical rift or half-graben along the Palala Shear Belt. It has longitudinal extent of 450 km and a width of 45 km. The total thickness of the Group is about 12 000 m (Barker, 1983).

The deposition within the Soutpansberg basin started with basaltic lavas and was followed by the deposition mainly of arenaceous and argillaceous sediments, which were laid down under fluvitile and shallow water conditions (Jansen, 1975; Brandl, 1981). After an erosional period, pink massive quartzite was deposited (post-rift sequence) and the quartzite covered a much larger area than the original rift (Barker, 1983).

The age of the Soutpansberg Group is uncertain but is not older than 2 000 Ma and not younger than 1 800 Ma (Barker, 1983). The Soutpansberg rocks which developed in a half-graben subsided along a main border fault situated most probably some 10 - 20 km south of the present Soutpansberg mountainous area (Brandl, 2002).

Although featuring so prominently in the landscape of the Limpopo Province, the Soutpansberg Group rocks did not attract much scientific attention in the past, since they are almost devoid of any economic mineralisation. The first published descriptions of the Soutpansberg geology were by Mellor and Trevor (1908) and Rogers (1926) who recognized the physical similarity in colour and composition of sedimentary rocks in the Soutpansberg with those of Waterberg. The authors correlated the Soutpansberg with the Waterberg rocks of the central and western Transvaal.

The actual mapping and fieldwork in the Soutpansberg was carried out between 1949 and 1950 by Van Eeden *et al*. (1955).Some authors published several articles with regard to the subdivision of the Soutpansberg succession and the regional and local structural model. Barker (1977, 1979) showed that the Soutpansberg formations comprised an essentially conformable sequence of volcanic and sedimentary rocks that had been duplicated several times along major east and north-easterly trending strike faults.

The subdivision of the Soutpansberg Group was proposed by Barker (1977) and he further suggested that Soutpansberg Group predates the Upper Waterberg Group. The Soutpansberg Group stratigraphy reclassified by Barker (1979) was subsequently formalised by the South African Geological Survey (SASC) (SASC, 1980). The stratigraphical sequence of the Soutpansberg Group comprises seven Formations. Five of these Formations are present within the study area and their details are presented in Table 2-1. The distribution of different formations within the study area is shown in Figure 2-2. The five Formations are described below from the oldest to the youngest.

Sibasa Formation

This formation occurs in the eastern portion of the study area (Figure 2-2). It constitutes a wide flat lying area of lava in which a few layers of tuff and or agglomerate, sandstone and shale are intercalated. The total thickness of this formation ranges between 2 300 m (Vitry, 1976) and 3 000 m (Brandl, 1999). The formation is at its thickest near Sibasa, thinning out to the east and to the west in the direction of the study area. The lava is deeply weathered throughout and is generally aphanitic to fine-grained, but occasionally may be medium to coarse-grained (Vitry, 1976). It is grey or green in colour and often contains amygdales filled with chalcedony, jasper, agate or calcite.

In the eastern part of the study area, greyish-green and dark red tuff and in places agglomerates are developed as lenticular layers, composed of angular fragments of quartzite and lava with grains of quartz and feldspar scattered in a fine-grained groundmass. The formation also contains minor intercalations of sedimentary rocks that include shale, quartzite, and conglomerate. These rocks occur as thin layers with a maximum thickness of 100 m (Vitry, 1976).

Table 2-1: General stratigraphical sequence of the Soutpansberg Group (adapted and modified from SASC (1980).

Age	Group	Formation	Lithology
Mokolian	**Quaternary deposits**		Sands
	Intrusives		Dolerite dykes and sills
	Soutpansberg	Nzhelele (Mn)	Sandstones, shale, white quartzite, quartzitic sandstones, and pellet conglomerate
		Musekwa (Mm)	Calcareous basaltic, andesitic, trachytic and gabbroid lavas.
		WylliesPoort (Mw)	Siltstones, quartzitic sandstone, sandstone, lava, mudstone, boulder conglomerate, shale and calcareous rocks.
		Fundudzi (Mf)	Quartzitic sandstone, quartzite, gritty or conglomerate, tuff, shale, sandy shale and siltstone.
		Sibasa (Ms)	Andesitic, trachytic and gabbroid lavas, agglomerates, ignimbrite, gritt, shale, mudstone and siltstone.

Fundudzi Formation

Fundudzi Formation overlies the Sibasa Formation and it developed only in the north-eastern corner of the research area (Figure 2-2). It consists mainly of arenaceous and argillaceous sediments with a few thin pyroclastic horizons. The lithology of the formation is dominated by white or pink sandstones and quartzite. These rocks are generally cross-bedded throughout with alternating bands of lava which become less and less abundant towards the top of the formation. Its thickness varies from 2 500 m in the east to 850 m in the west and 2 400 m in the south of the Fundudzi fault (Willoughby, 1976).

From the number of measurements of cross-bedding by Willoughby (1976), it is deduced that the main direction of transport seems to have been from northwest to the southeast. Thin layers of basalt lava (tuff) that occur in this formation bears similar characteristics to the Sibasa basaltic lava but the difference is the wider colour variation, from light green, grey green and dark green (Willoughby, 1976).

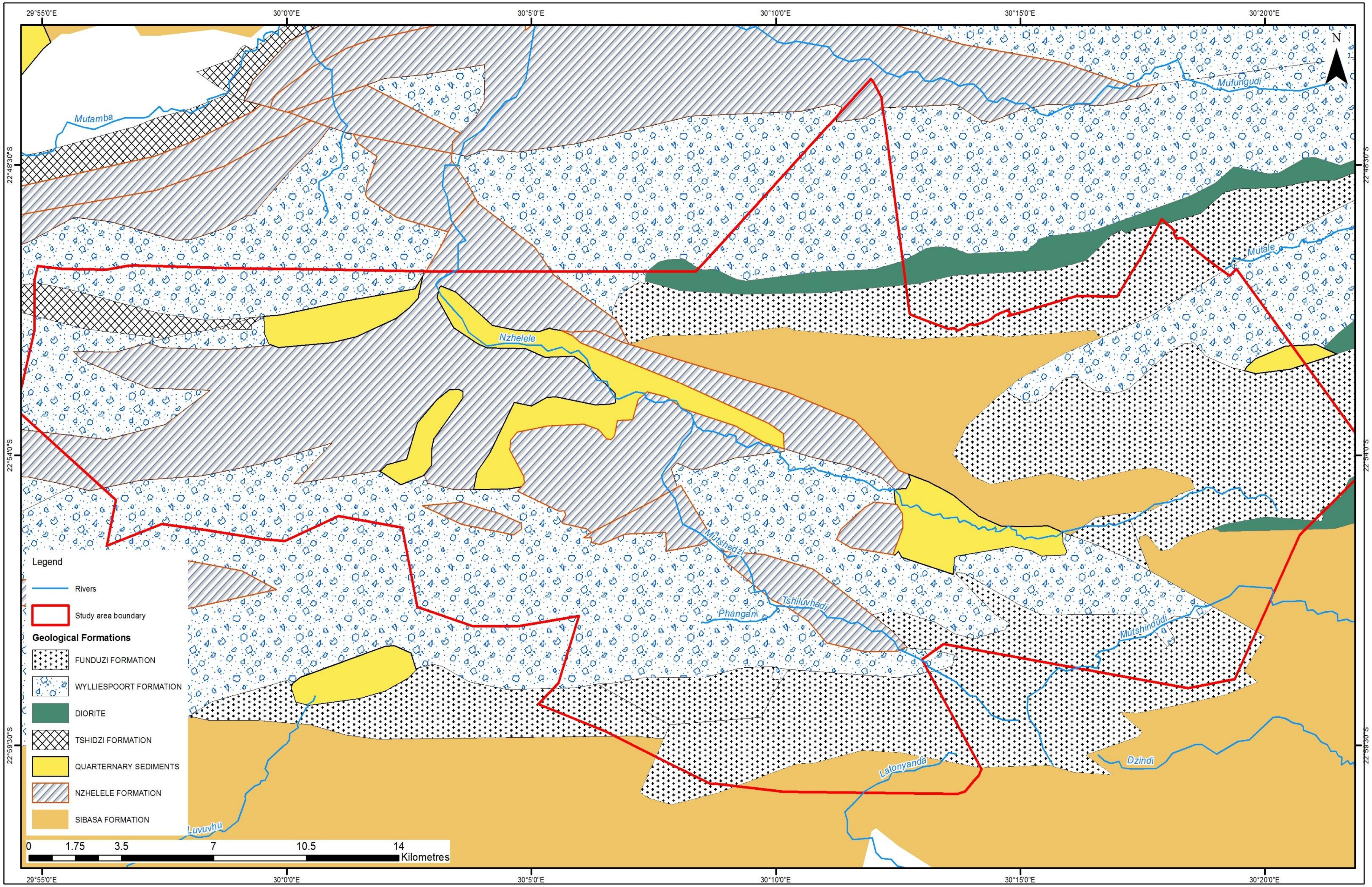


Figure 2-2: Geological map of the study area (adapted and modified from GSSA (1981; 1985 and 2002).

WylliesPoort Formation

This formation occurs as three separate prominent ranges, striking east-west and covering a large portion of the study area (Figure 2-2). It consists of a hard resistant and massive quartzite and somewhat softer quartzitic sandstone. It occupies the highest areas in the mountainous land and forms cliffs of several hundred metres high (Vitry, 1976). About 1 100 m of Nzhelele Formation overlies the WylliesPoort Formation with a fault contact relationship (Figure 2-2). The succession is almost entirely arenaceous, composed largely of two varieties: coarse-grained purple or reddish sandstone; and medium to fine-grained pink or whitish quartzite or quartzitic sandstone. Both types are massive, well sorted and mature. Cross-beddings are present but do not indicate a precise direction of transport.

Though the formation is considered to be entirely arenaceous, Vitry (1976) and Willoughby (1976) reported the presence of 70 m layers of lava or tuff in the south-western portion of Siloam hospital. The rock is a green, epidotised, amygdaloid lava and contains numerous quartz inclusions.

Musekwa Formation

This formation constitutes most of the former Loskop system, and has been preserved from erosion in the central Soutpansberg basin where it occupies down-faulted blocks (Meinster, 1974). It underlies the Nzhelele formation and forms a persistent layer of lava which forms a normal contact with the underlying WylliesPoort formation. This lava is grey-greenish in colour and brown on a weathered surface. It is often strongly epidotised with amygdales present in many places (Vitry, 1976).

Van Eeden (1955) reported the presence of this lava in Mpefuǹs location forming ridges and he identified them as gabbroic lava (Figure 2-2). They form small koppies and ridges in the area and they are coarse-grained with a pitted weathered surface. The thickness of this formation is between 300 and 450 m (Vitry, 1976).

Nzhelele Formation

Nzhelele formation occupies the centre of the study area (Figure 2-2) and is comprised by lower argillaceous and upper arenaceous sediments and they overlie Musekwa Formation. The argillaceous sediments are generally fine-grained, and well-sorted, composed mainly of rounded quartz with a few feldspar grains, mica flakes and shaly interbeds and inclusions.

The arenaceous sediments are commonly cross-bedded and occasionally show ripple marks at the top with shale fragments in sandstones. Sedimentary structures are recognizable, most of them with indication of deposition in shallow water (Vitry, 1976).

Intrusive rocks

In the eastern part of the study area numerous dolerite dykes intruded into the Soutpansberg and Karoo rocks. In contrast there is a distinct absence of dyke of post-Karoo age in the western part of the study area (Figure 2-2). All diabase sills and dykes are younger (post-Soutpansberg) than the Soutpansberg Group (Vitry, 1976). They are expressed in the topography either by positive relief or hollows depending on the relative resistance of the intrusion compared with the host rock. In some cases where these intrusions occur in sandstone or quartzite, they form deep, narrow valleys or gently rising slopes. In this case, their exposure is generally poor and only a few loose boulders can be found in thick red or yellowish soil cover (Vitry, 1976).

Diabase predominates the dykes and occur also as sills trending west-southwest, often cutting slightly diagonally across the bedding (Figure 2-2). Majority of the diabaseôs intruded Soutpansberg Group prior to Soutpansberg faulting as many are displaced and cut-off by faults (Willoughby, 1976). The sills are normally found in the interface between lava and sediments or shale and sandstone and in most cases they attain a maximum thickness of several hundred meters. The general orientation of dykes is east-north-east with a less prominent developed strike direction in west-north-west direction (Willoughby, 1976).

Quaternary deposits

Quaternary gravel and sand deposits build prominent terraces along the Nzhelele and Mutshedzi Rivers (Figure 2-2). These sands together with soils blanket the solid geology in topographical low areas and in valleys. Data on the thickness, lateral extent and nature of the alluvial deposits along Nzhelele River are virtually lacking.

2.3.2 Structural setting

Regional

The research area is located within the SMZ of the Limpopo Metamorphic Complex (LMC), which can be described as poly-metamorphic and highly deformed terrain that is part of the Archaean crust which separates the Kaapvaal craton in the south from the Zimbabwean craton in the north. The detailed study of the LMB recognised the regional east and north-easterly tectonic pattern and the right lateral movement along the major strike-slip faults in the region (Sohnge *et al*. 1948).

The regional tectonic map was compiled by Cox *et al*. (1965) and in recognition of the extensive strike continuity of the major east and north-easterly trending fault; they concluded that the basement structure had a marked influence on the subsequent geological evolution of the area. They further recognised that LMB is composed of CZ which is flanked by two parallel marginal zones to the north (North Marginal Zone) and south (South Marginal Zone). The simplified map of the LMB showing its subdivisions, major shear zones and adjacent cratons is shown in Figure 2-1.

According to Chernicoff (1984) and the Watkeys (1983), the LMB is defined as an approximately linear east-northeast trending zone of Precambrian rocks which have undergone high-grade metamorphism and poly-phase deformation. Large-scale structural features such as the Sand River folds, the Zwartrandjies fold morphology and the Kudus River lineaments are shear evidence of deformation and movement in the LMB (Figure 2-1). Only Zwartrandjies morphology is located in the SMZ. The SMZ had been subjected to four different deformational events and three metamorphic events and any structural crustal development is an integration of these processes (Du Toit *et al.*, 1983). A summary of the major tectonic features of the LMB and the Soutpansberg as well as the Karoo basins are shown in Figure 2-3.

Structural setting of the Soutpansberg Group

Although a considerable amount of information has been published on the tectonic evolution of the LMB, little data are available on the relationship of regional tectonics of the LMB to the Soutpansberg Group.

Faults

The sedimentary and volcanic rocks of the Soutpansberg Group have been faulted by both reverse and normal faults and are oriented longitudinally, diagonally or transversely in relation to the general strike (east-west) of the formations (Van Eeden *et al*., 1955). In almost every case, the fault zones of the strike faults are erratically exposed and commonly covered in variable thicknesses of talus, with dense vegetation along the flanks of the fault scarps. The fault zones are generally wide with the width of the ñdamage zoneò ranging between 200 to 300 m in places and on occasions as much as 500 m where fault-related silicification has penetrated along the secondary faults, away from the centre of the fault zone (Barker, 1979).

The tectonic history of the Soutpansberg fault zones has been mapped from Landsat imagery and aerial photographs by Barker (1979). Four tectonic trends were established of which the east-north-easterly or Limpopo Trend is the most dominant orientation in the Soutpansberg Group (Figure 2-3). The east-north-easterly trending has been remobilised repeatedly through time and the Soutpansberg stratigraphy has been duplicated several times along these faults (Barker, 1979). Major faults striking east-northeast are the Fundudzi, WylliesPoort, Afton, Vondo, Perseus and a fault displacing the Soutpansberg Group against the Karoo rocks (Figure 2-3).

All major strike faults identified along the northern edge of the Soutpansberg fault zone and within the Soutpansberg Group are normal faults and dip steeply to the south, except for the Afton, Tshamavhudzi, Zoutpans and Kranspoort faults which dip to the north (Barker, 1979).

The Siloam fault is one of the major faults, which strikes northwest and has an estimated displacement of 1.5 km. The Siloam fault, though oriented obliquely to all the other strike faults (Figure 2-3), nevertheless, dips in a southerly direction towards its down-throw side (Willoughby, 1976). It is the only major post-Soutpansberg fault trending in the west-north-westerly direction and along which duplications of the stratigraphy occurred.

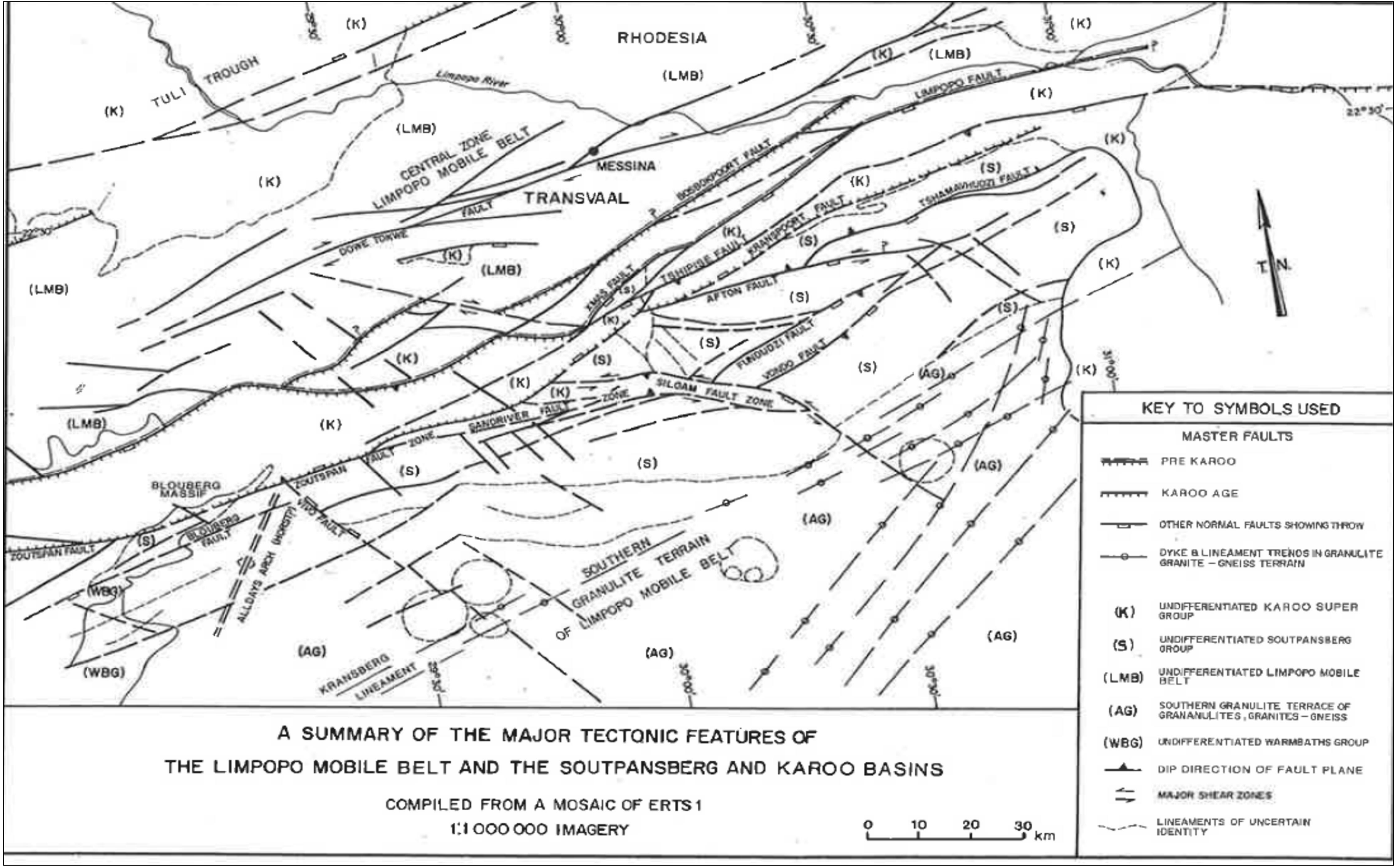


Figure 2-3: Major tectonic features of Limpopo Mobile Belt, Soutpansberg and Karoo basins (Barker, 1979).

The Siloam fault is sufficiently prominent in the Landsat image to constitute a subdivision of the Soutpansberg region.

Except for Siloam, the north-westerly tectonic trend has not produced major faults in the Soutpansberg of comparable size or lateral continuity to east and east-north-easterly trend. The north-westerly trending lineaments appear to be much more dominant in the western region than in the eastern region (Figure 2-3).The age of the Siloam fault is difficult to assess. This fault is younger than most of the post-Soutpansberg faults such as Fundudzi and Mandale faults (Barker, 1979). There is no evidence that the Soutpansberg or Limpopo Fault zones took part in post-Jurassic trans-current fault movement (Barker, 1983).

Most of the faults are sealed with silica and iron oxide cement as well as anastomosis of the Karoo sediments along the contact (Barker, 1979). The hydrothermal activity in some of the faults has continued through to the present time as witnessed by the numerous hot-water mineralised springs present in the region (Van Eeden *et al.*, 1956).

Folds

The Archaean rocks have been intensely folded and underwent denudation during a long period before they became covered by the Soutpansberg Group. Fold-axes in the Archaean complex mostly trend east-northeast and the rocks are isoclinically over-folded to the north or northwest. Those above-mentioned folds have themselves again been cross-folded. (Van Eeden *et al.*, 1955).

Joints and minor structures

Jointing is ubiquitously closely spaced both in the lavas and sediments of the Soutpansberg Group. The rocks are not only jointed vertically, but also have a strongly developed joint system sub-parallel with the bedding plane and regional dip of rocks. Besides in-situ brecciation near major faults, no movement was seen in the vertical joints. Mylonisation has occurred in some places along bedding plane joints where these coincide with clay-partings in the quartzite. Minor structures such as slicken-sides are seldom seen due to poor exposure and infrequent preservation in the brecciated and/or cemented fault zones (Van Eeden et al., 1955).

2.4 Hydrogeology

Several hydrogeological studies aimed at developing the groundwater resources for domestic water supply purposes within the study area and the surroundings were completed in the past. Other studies focused on identifying and characterising the existing underlying aquifer systems as well as establishing the groundwater movement and quality. The existing reports compiled and data were reviewed to understand the hydrogeological conditions of the project area.

Groundwater development in the Nzhelele ï Makhado area dates back when the area was still under the jurisdiction of the Venda homeland. During drought of 1985, 1986 and 1992, several boreholes were drilled in the area but most of these boreholes were not sited. Since that time hundreds of boreholes had been drilled in the area.

Hydrogeological and Engineering Consulting firms, mostly within the Limpopo Province, completed several groundwater development projects within the area. Most of these studies and projects focused on small-scale groundwater development aimed at supplying water to either a school or health facility.

The Department of Water and Sanitation (DWS) had commissioned several feasibility studies in the study area and in the surrounding areas. The feasibility studies mostly focused on the assessment of the available and potential groundwater resources.

DWS together with several hydrogeological consulting firms as well as data management companies started Groundwater Resources Information Project (GRIP) in Limpopo which was aimed at identifying and recording all existing groundwater sources within the Limpopo province. The project (GRIP) was established as an on-going programme to gather existing and additional groundwater resource information as they are being developed. GRIP further included the testing of identified boreholes within the province.

The hydrogeological map, 1:500 000 Hydrogeological Map series 2127 Messina (first edition), which covers the study area, was developed in 2002 by Mr. Du Toit of the Department of Water Affairs and Forestry (DWAF). A detailed explanation report for the 2002 published map, 1:500 000 Hydrogeological map series 2127 Messina, was later compiled by Du Toit and Sonnekus in October 2014. Du Toit and Sonnekus document was aimed at displaying, in an easy to understand format, the known basic properties of the area under investigation. The document represents the synthesis of the most up-to-date data and Hydrogeologists knowledge and understanding of the area during the time. The summary of the hydrogeological conditions of the study area based on the reviewed existing information is presented in the sections below.

2.4.1 Aquifer systems

The distribution of water strikes in a borehole is evidence of the presence or absence of groundwater and can thus be used as a semi-quantitative assessment of whether the geological units are potential aquifers or aquitards. Geological interpretation, results from drilling (water strikes) and pumping tests were used by Du Toit and Sonnekus (2014) to determine the occurrence of groundwater and to assess the types of aquifer systems that occur in the area. This analysis revealed that there are three dominant aquifer types or categories that occur in the area (Table 2-2); intergranular (Category A), fractured (Category B) and fractured and intergranular (Category D) aquifer systems (Du Toit and Sonnekus, 2014). The distributions of the identified aquifer systems within the study area is shown in Figure 2-4.

The classification of the aquifer system by Du Toit and Sonnekus (2014) was adopted from UNESCO classification for hydrogeological maps (UNESCO, 1983) and adapted to suit South African hydrogeological conditions and groundwater occurrences. UNESCO classification distinguishes the occurrence of groundwater only according to the primary or secondary nature of interstices. The borehole production or yields were classified into five ranges as follows (Orpen, 1994):

- High yielding: greater 5 L/s;
- Moderate yielding: 2 ï 5 L/s;
- Low yielding: 0.5 ï 2 L/s;
- Very low yielding: 0.1 ï 0.5 L/s;
- Un-economic yielding: 0.0 ï 0.1 L/s.

Table 2-2: Aquifer systems within the Nzhelele-Makhado area (Du Toit and Sonnekus, 2014).

Aquifer categories (UNESCO)	**Aquifer systems in Nzhelele – Makhado area**		
Characteristics	**Category A**	**Category B**	**Category D**
Formations (hydrogeological unit)	Quaternary sediments	Nzhelele Formation; WylliesPoort Formation; Fundudzi Formation	Sibasa Formation, Dolerite and Diabase
Aquifer type	Intergranular	Fractured	Intergranular and fractured
Occurrences	Alluvial deposits of limited extent along river terraces such as sand and gravel.	Sedimentary rocks of arenaceous origin. Acid volcanic rocks and other igneous rocks with very limited overlying residual weathered products.	Sedimentary and Igneous rocks with significant thicknesses of overlying saturated residual weathering.
Groundwater occurrences	A water saturated zone, generally unconsolidated but occasionally semi-consolidated. Groundwater storage and flow through intergranular interstices in porous	Where the principal water strike is in a fracture or in the contact between two different rock types, inter-porosity groundwater flow can occur within the rock matrix (double-porosity matrix).	Fractured zone overlain by varying thicknesses of weathered saturated material. Storage and flow in both. Fractures act as conduits during abstraction, vertical

Aquifer categories (UNESCO)	**Aquifer systems in Nzhelele – Makhado area**		
Characteristics	**Category A**	**Category B**	**Category D**
	and permeable medium.		recharge from intergranular zone.
Groundwater potential	A3	B3	D3 and D2

Category A - Intergranular aquifer system

These are primary aquifers or unconfined aquifers which are formed by quaternary deposits and located mainly along the low lying drainage system, basically along the river channels The deposited material relates to the upstream regional geology and the sorting, grain size distribution as well as the deposition is a function of the river flow. The thickness of these aquifer systems vary considerably, and is controlled to some degree by paleo-topography. The details regarding the extent and thicknesses of these aquifer systems are virtually lacking due to the fact that most of the previous groundwater investigations focused on geological structures such as dykes, faults and lithological contacts (Du Toit and Sonnekus, 2014).

The aquifers comprise gravel and sandy clays and they are high yielding in some places. The major aquifer systems within the study area are reported to be found along the Nzhelele and Mutshedzi Rivers (Figure 2-4).

Category B – Fractured aquifer system

These aquifer systems are formed by the development of secondary porosity in the rock formations. This can be due to micro cooling fractures, interconnecting vesicles in volcanic rocks, fractures formed by tectonic deformation (folding, faulting), re-crystallising and cooling in the contact area with intrusive rocks, or unloading through erosion, enhanced by weathering, dissolution and solution cavities in the hard rocks. The distributions of the secondary aquifer systems within the study area are shown in Figure 2-4. The secondary aquifers cover almost the whole study area and are significant throughout the area (Du Toit and Sonnekus, 2014).

Structural features such as fault zones, lithological contacts, weathered zones and bedding surfaces largely control the groundwater occurrences and flow in these aquifers. Because the factors that affected the rock formation which results in the formation of the secondary porosity seemed to have impacted different lithologies, differently, different hydraulic parameters were formed in different lithologies. This has resulted in different secondary aquifer systems based on the different lithological formations in the area (Du Toit and Sonnekus, 2014). The formed secondary aquifers systems include:

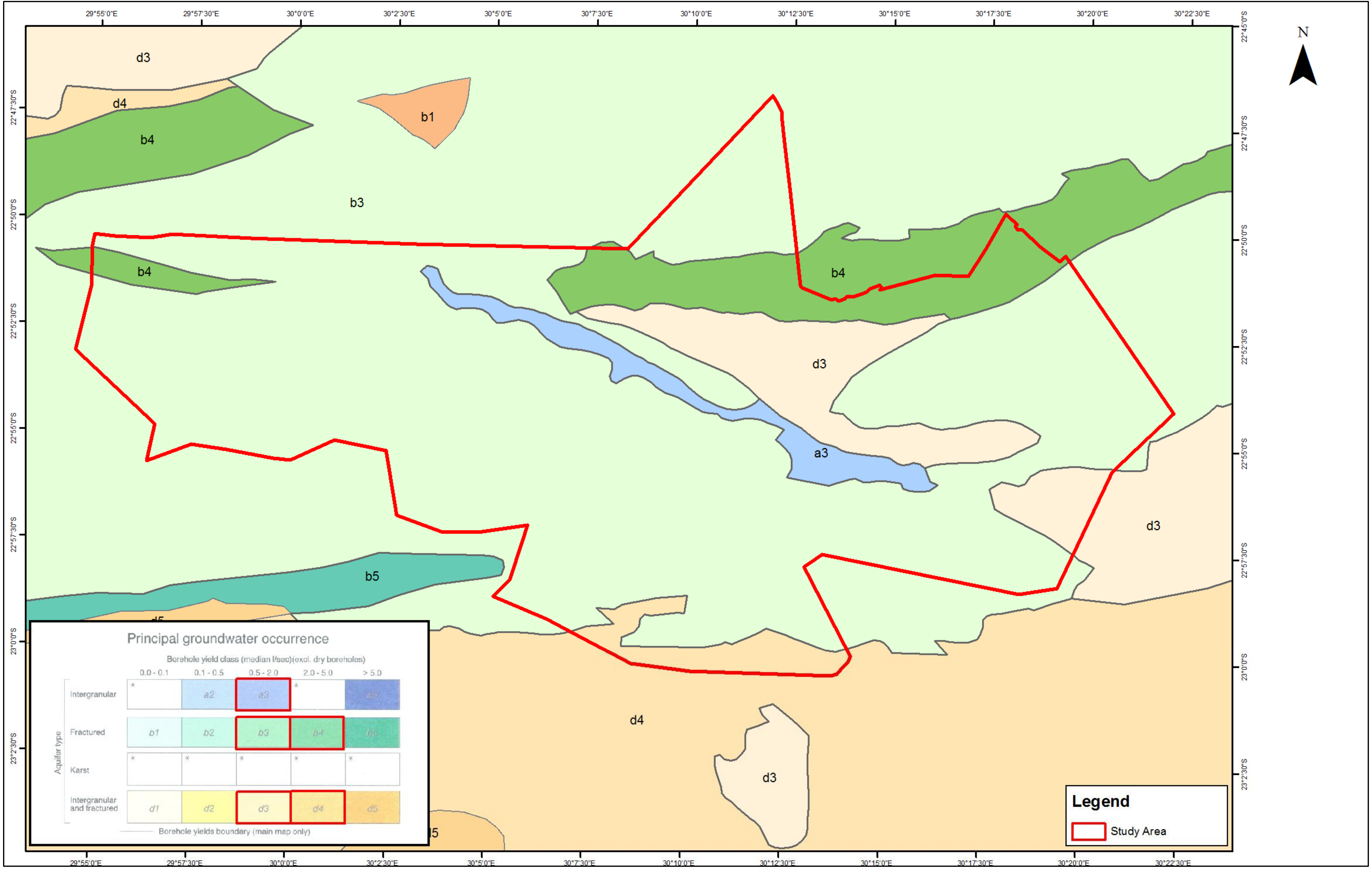


Figure 2-4: Hydrogeological map of the study area (Du Toit, 2002).

- **Nzhelele aquifer systems**

The extent and the distribution of the Nzhelele aquifer systems is shown in Figure 2-4. The borehole yield potential of the Nzhelele aquifer system is classified as b3 (Figure 2-4), indicating that the aquifer system is capable of supporting an average borehole yield between 0.5 and 2.0 l/s (DWAF, 2002).

Du Toit and Sonnekus (2014) reported that the aquifer system has a good groundwater potential with 36% of the drilled boreholes yielding between 0.5 and 2 l/s and 44% more than 2 l/s.

The high number of high yielding boreholes can be attributed to secondary fracturing associated with the numerous faults that border or cut through the unit, diabase dykes and joints. Water strikes associated with bedding planes, contact zones between sediments, and the contact with the lava are reported to be low in yields (Du Toit and Sonnekus, 2014). Some of the high yielding boreholes are reported to be located in the contact between the unit and the quaternary sediments along Nzhelele River (Du Toit and Sonnekus, 2014).

- **WylliesPoort aquifer system**

Primary porosity in the fresh rocks of the WylliesPoort Formation is almost zero, making the occurrence of secondary fractures and fissures the determining factor in finding water. Water bearing zone within the formation is limited to a depth of 100 m (Du Toit, 1998). The overall groundwater potential in the WylliesPoort aquifer systems is low and this is evident in the high number of boreholes, which were drilled dry.

The borehole yield potential of the WylliesPoort aquifer system is classified as b3, indicating that the aquifer system is capable of supporting average borehole yields between 0.5 and 2.0 l/s (DWAF, 2002). The drilling results show that the groundwater potential is low with 18% of the drilled boreholes reported to be dry (Du Toit and Sonnekus, 2014). Statistics indicate that 65% of the successful boreholes yield less than 2 l/s and 18% of the successful boreholes yield more than 5 l/s (Du Toit and Sonnekus, 2014).

Secondary fractures relate to the numerous faults transecting and bordering the formation, diabase sills and dykes and jointing are responsible for the improved groundwater potential of the aquifer system.

- **Fundudzi aquifer system**

The depth of the weathered and fractured zones within the Fundudzi Formations were reported to be limited up to 60 m. The groundwater occurrence within Fundudzi aquifer system is limited to secondary openings associated with geological structures such as faults, shear zones, dykes and sills. The aquifer system is considered to be a double porous medium with water being stored in the fractured zones and matrix. Due to the low transmissivity of the unit the groundwater potential is very low unless secondary fractures and fissures are present (Du Toit, 1998). The groundwater yield potential of the Fundudzi aquifer system is classified as b3, indicating that is capable of supporting an average borehole yields between 0.5 and 2.0 l/s (DWAF, 2002).

The drilling results from the previous studies show that 40% of the drilled successful boreholes yield more than 2 l/s, 42% yield between 0.5 - 2 l/s and 18% is less than 0.5 l/s. The 11% of the drilled boreholes were dry (Du Toit and Sonnekus, 2014).

Even though it is reported that the groundwater potential in this unit is low, several high yielding boreholes were drilled. The high number of high yielding boreholes drilled in this unit can be attributed to the successful use of scientifically approved methods and methodologies in the identification of geological lineaments that has potential to support high yielding boreholes (Du Toit and Sonnekus, 2014).

Category D – Intergranular and fractured aquifer system

This type of aquifer system comprised fractured zone overlain by varying thicknesses of weathered saturated material. The groundwater is stored and moves in both fractures and weathered saturated zones. Fractures act as conduits during abstraction and during vertical recharge from intergranular zone (Du Toit and Sonnekus, 2014).

- **Sibasa hydrostratigraphic unit**

Numerous faults are reported to have cut through the Sibasa hydrographic unit and the unit occurs in a high rainfall area with chemical weathering being the dominating process. The intense weathering has produced thick layer of clay which reduces the permeability of the underlying fractures subsequently affecting the borehole yielding potential. The occurrence of groundwater is now restricted mostly on the contact between the basalt and the overlaying sandstone (Du Toit and Sonnekus, 2014).

The borehole yield potential of the Sibasa hydrostratigraphic unit is classified as d3, indicating that an average borehole yield in the group ranges between 0.5 and 2.0 l/s. However, the borehole yields decrease towards the east to d2 and d1 (DWAF, 2002).

- **Dolerite dykes**

Dolerite dykes are good targets for groundwater development, however, the direction and the dipping of the dyke is crucial in siting the potential high yielding borehole. Statistics indicate that 41% of the successful boreholes drilled into the dolerite dykes yield more than 5 l/s with 45% yielding between 0.5 and 5 l/s (Du Toit and Sonnekus, 2014). A total of 29% of the boreholes drilled targeting dolerite dykes were reported to be dry in some places. High percentage of dry boreholes indicate lack of hydrogeological understanding or poor methods and methodologies applied in siting of the boreholes (Du Toit and Sonnekus, 2014).

- **Diabase**

Very few boreholes were drilled targeting the Diabase within the study area. The existing data indicate that 61% of boreholes targeting the diabase were dry. The remaining percentage of the boreholes drilled into diabase yield less than 2 l/s (Du Toit and Sonnekus, 2014). Secondary fractures associated with diabase dykes might be good groundwater targets but there is no enough information to confirm that (Du Toit and Sonnekus, 2014).

3 Materials and Methods

The methods and materials, which were used in the study, are presented below.

3.1 Desktop study

The desktop study started by literature search to establish and gather existing information related to geology and hydrogeology of the study area. This was followed by searching of existing borehole data in several databases mostly developed and managed by DWS.

3.1.1 Existing geological and geohydrological information

Maps and satellite images were used to develop a visual understanding and representation of the study area as a means to understand its physical attributes. This include the following:

- The 1:250 000 geological map sheets (which were used to determine the regional and local geology of the area, viz):
    - 1:250 000, 2230 Messina geological map compiled and partly revised by Brandl (1981);
    - 1:250 000, 2228 Alldays geological map compiled by Brandl *et al.* (2002);
    - 1:250 000, 2330 Tzaneen geological map compiled by Coetzee and Coetsee (1985);
- The published 1:50 000 topographic map sheets 2229 DD (Wyllie's Poort), 2230 CC (Nzhelele) and 2230 CD (Thohoyandou) from National Geo-spatial Information (NGI) (1999) were used as base maps for the study area.
- The 1:500 000 Map, 2127 Messina (first edition) hydrogeological map, developed in 2002 by Du Toit (W.H) of the Department of Water Affairs and Forestry, was used to establish the hydrogeological conditions of the area.
- The satellite imagery (obtained from the Department of Water and Sanitation, Limpopo Regional Office) were used for lineaments mapping and analysis. The satellite imagery used for the capturing of lineaments was from the medium resolution Advanced Space Borne Thermal Emission and Reflectance (ASTER) missions. The mapping of lineaments in the Limpopo Province took place in a digital environment using GIS and was mapped at a scale of 1:50 000 (Anke, 2008).

Several reports compiled as part of previous groundwater resource development in the study area and the surrounding areas have detailed the geological and hydrogeological settings of the area. Some of the borehole logs and test pumping were included in the compiled reports.

3.1.2 Existing borehole data in the database

Limpopo Province, like any other province in South Africa has a form of borehole records archived in the different DWS databases. The borehole data in the existing databases were supplied, in most cases, by DWS, hydrogeological consulting companies, consulting engineering firms, drillers and owners.

Existing DWS databases were queried for records of existing borehole data within the study area. The queried databases included both national (National Groundwater Database (NGDB) and National Groundwater Archive (NGA)) and provincial (Provincial groundwater H-regions, Provincial Aquabase, Groundwater Resource Information Project (GRIP)) databases. While there are several databases in which borehole records of the province (Limpopo) is stored, the groundwater information and data for this study was only queried from the NGDB and GRIP databases.

National Groundwater Database (NGDB)

The National Groundwater Database (NGDB) data set was most comprehensive borehole data set in South Africa with an estimated records of 225 000 boreholes (http://www.dwaf.gov.za/geohydrology/database). The borehole data in the NGDB is stored with an assigned site identification number known as a site ID and linked to a geographical position. The NGDB is not an internet-based and it was later replaced by National Groundwater Archive (NGA) and started operation after 2004. More than 300borehole records were found to exist in this database.

GRIP Database

GRIP database was developed in the Limpopo province to capture data (borehole point data) and to use the data for management of groundwater with emphasis on water availability and aquifer characteristics. GRIP has over the time enhanced and promoted the importance of groundwater resource in most of the municipalities within Limpopo province. GRIP database was queried and shows that there is only 214 boreholes and 19 springs within the study area. Some of these boreholes were tested and sampled. The data obtained GRIP Limpopo was used as a base for establishing the borehole positions in the area during the site visit.

3.1.3 Data consolidation and review

Borehole data gathered from the databases were consolidated by linking the records using borehole number, coordinates and or equipment, where possible. The data were compared and linked to data obtained from geohydrological reports that were reviewed as part of the study. The consolidated information from reports and databases were then used to develop base maps for each village, to be used during the site visit.

3.2 Hydrocensus and data verification

A good borehole database is naturally, a prerequisite for any statistical analysis of borehole characteristics. It is also important to understand the possible sources of error connected to any large data set collected over a period. Quite commonly, the borehole data will exhibit poor spatial completeness and difficult control of uncertainty and incompatible coordinates system. The essential requirement of this type of study is to be able to record the correct locations of the boreholes. In cases wherein there is uncertainty regarding the location of the borehole, the position of the borehole should be verified by a site visit.

After reviewing the existing data from the queried databases, it was clear that available data sets were not fully populated and most of them had not been verified in the field for position accuracy and other related information, therefore, a comprehensive hydrocensus was required to record the positions of the boreholes within the study area.

A hydrocensus (groundwater reconnaissance) at the Nzhelele-Makhado study area was undertaken to verify positions of the recorded existing groundwater sources and record any additional groundwater sources that were not found in the database (GRIP). The hydrocensus was also used to inspect the topographical and geological settings of the area in which the borehole is located.

After the hydrocensus, a comprehensive data-quality filtering was done in the initial borehole dataset to remove doubtful and inaccurate data before the data can be considered as final and plotted in a map. It was important that the borehole data represent the correct information regarding the position, geology and the topographical settings. Private boreholes within the study were not included in the study. The springs were also included as groundwater sources in the area. The springs were interpreted to represent groundwater discharge in the surface.

3.2.1 Groundwater sources within the study area

The summary of the visited groundwater sources in the area is presented in Appendix A. The positions of the existing boreholes within the study area are shown in Figure 3-1. The positions of the identified springs within the study area are shown in Figure 3-2.

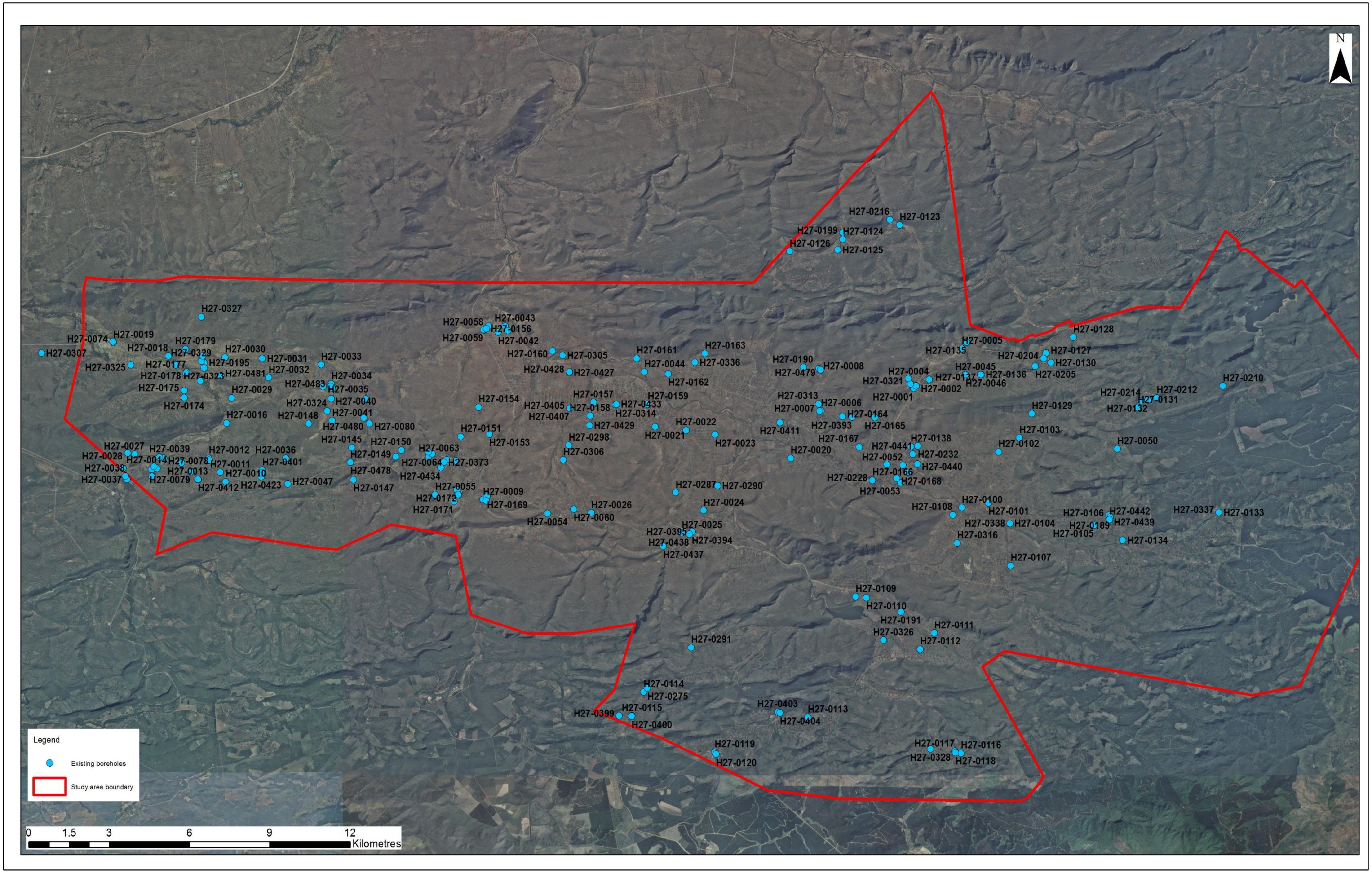


Figure 3-1: Positions of the existing boreholes within the study area shown in a Google-map.

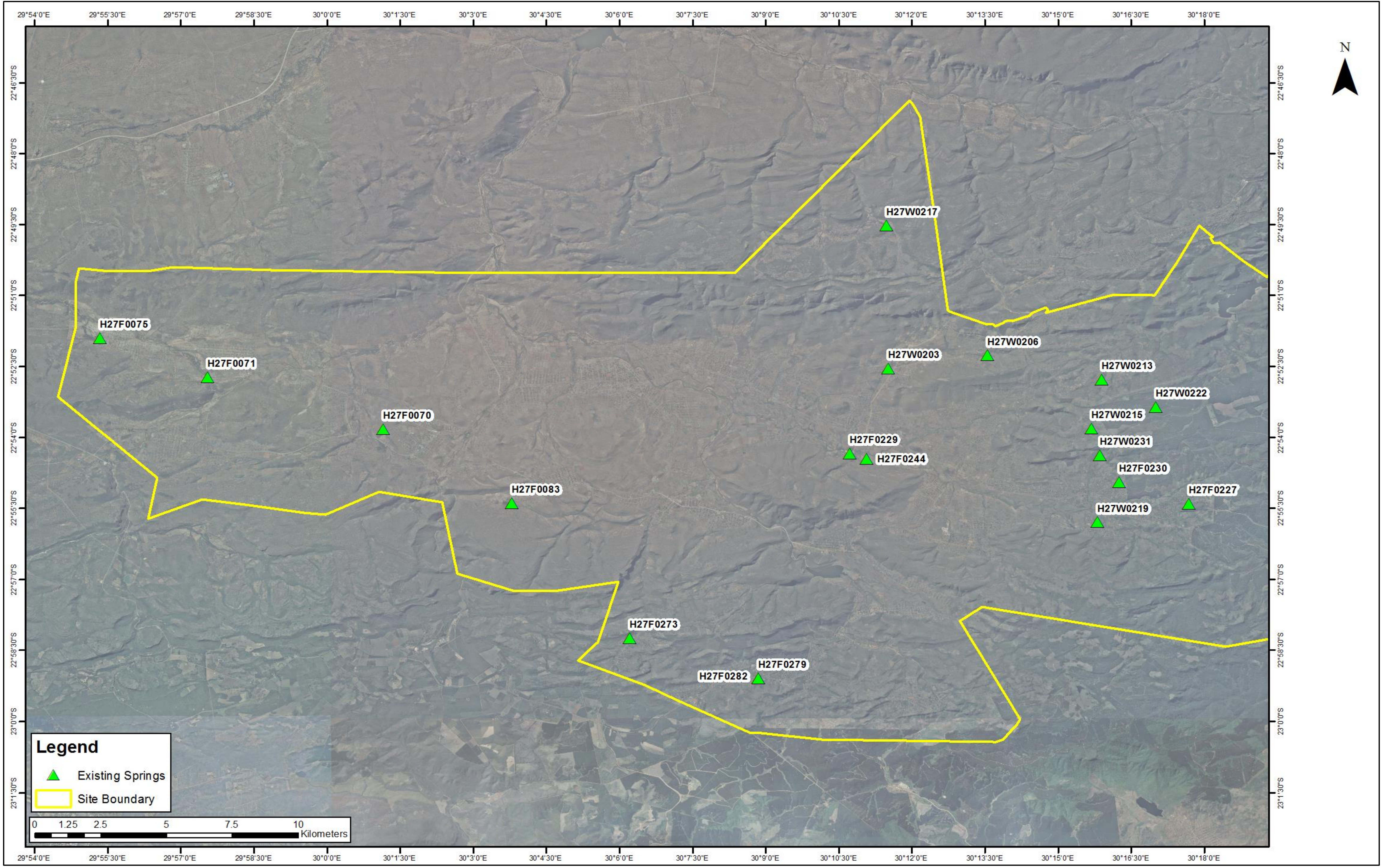


Figure 3-2: Positions of the springs within the study area shown in Google map.

3.3 Determination of borehole yields

3.3.1 Pumping test

The principle of a pumping test is that if we pump water from a borehole and measure the distance of the borehole and the drawdown in the borehole and in piezometers at a known distances from the pumping borehole, we can substitute these measurements into an appropriate well-flow equation and can calculate hydraulic characteristics of the aquifer (Kruseman and de Ridder, 1994). Pumping tests can give information about how much groundwater can be extracted from a borehole, ósustainablyô For the purpose of this study, the sustainable pumping yield is the amount of water that can be withdrawn from the aquifer or aquifer system based on the hydraulic characteristics of the aquifer or aquifer system, subject to specified conditions (Devlin and Sophocleous, 2005). It gives an initial indication about the success of a borehole and whether the borehole should be abandoned due to low yielding or poor aquifer performance (Tessema *et al.*, 2014).

Aquifer test helps to characterise the efficiency of the borehole and determine the properties, i.e. how the aquifer responds during recharge and discharge. Tessema *et al.* (2014) recommended that the pumping test should be routinely done in order to prove the sustainable yield of a borehole before commissioning for water supply. Aquifer test is one of the classical approach and perhaps the only way to provide important information about bulk in-situ aquifer hydraulic properties such as hydraulic conductivity, transmissivity and storativity.

in most cases, especially in rural areas, if a borehole supplies any quantity of water it is generally assumed to be productive and pumping test is usually not done. However, the high failure rates and poor sustainability of rural water supply such as in the study area, Makhado-Nzhelele, makes the results of the aquifer tests increasingly important. Knowing the borehole performance and its sustainability after it was drilled makes it easy to work out reasons for failure should it occur at a later stage.

The duration of the tests is usually determined by the level of data reliability required, which is a function of the water userôs dependence on the borehole(s) and of the consequences (usually financially) of borehole failure.

In the present study, the pumping tests were conducted to provide information on the hydraulic behaviour of the boreholes, aquifer yields and aquifer boundaries, which were essential for characterising the hydrogeological groundwater zones, assessing the borehole efficiency and optimising the pumping cycles.

All existing boreholes located in a 1 km radius from each other and feasible for pumping test were subjected to a full pumping test programme. The pumping test programme was carried out in accordance with the DWS test pumping guidelines:

- Minimum Standards and Guidelines for Groundwater Resource Development for the Community Water Supply Programme and Sanitation Programme (April 1997), and

- A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa (March 2008).

The pumping test programme comprised the following tests:

- **Step Drawdown Test (SDT):** During the SDT the boreholes were pumped at a constant yield for a 60-minute interval, thereafter at a higher discharge rate. A minimum and maximum of one and five 60-minute test intervals, respectively, were carried out per borehole. The drawdowns over time were recorded in pumping and observation boreholes. Once the pump was stopped, residual drawdown was measured until 95% recovery of the water level had been reached before the Constant Rate Discharge Test (CRDT) could start. The discharge rate for a longer duration constant rate discharge test (see below) was estimated from the interpretation of the time drawdown data generated during the SDT;
- **Constant Rate Discharge Test (CRDT)** followed after the SDT. During the CRDT, boreholes were pumped for a predetermined time (between 8 and 72 hrs) at a constant rate. The drawdowns over time were recorded in the pumping and observation boreholes. Discharge measurements were taken at predetermined intervals to ensure that the constant discharge rate is maintained throughout the test period. Any changes in discharge rate were accurately recorded and reported. During CRDT the aquifer systems were sufficiently stressed to identify boundary effects that may impact on long-term aquifer utilization; and
- **Recovery Test (RT)** followed directly after pump shut-off at the end of the SDT and CRDT. The residual drawdowns over time (water level recovery) were measured in the pumped and observation boreholes until 95% recovery was reached or for a length of time at least equal to the pumping time.

Boreholes within 250 m radius of the tested borehole were used as observation boreholes as this information provides a greater confidence in determining sustainable and reliable aquifer yield, indication of possible borehole interference and the identification of possible hydraulic barriers to flow.

A total of 41 boreholes were subjected to a full pumping test programme comprising of SDT and CRDT followed by recovery monitoring. The positions of the tested boreholes are shown in Figure 3-3.

The majority of the pumping tests were single-borehole tests, primarily to determine sustainable abstraction rates for rural water-supply schemes.

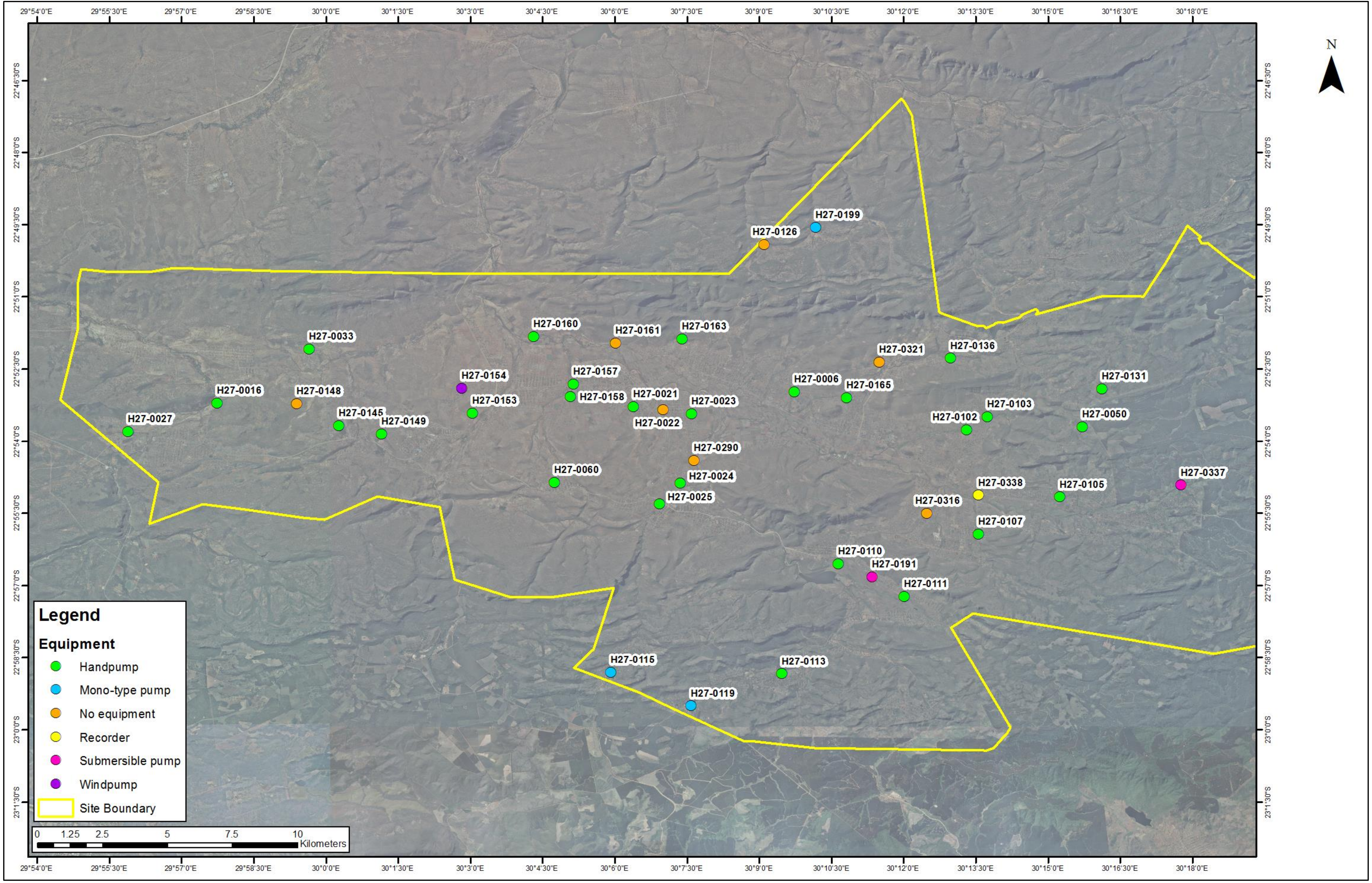


Figure 3-3: Positions of the pump tested boreholes within the study area.

3.3.2 Pumping test data analysis

Method

The pumping test data were interpreted using Flow Characteristics (FC)-Method. FC-Method is an excel based pumping test interpretation software developed by the Institute of Groundwater Studies (IGS) of the University of Free State on behalf of the Water Research Commission (WRC) to analyse the pumping tests in fractured rocks (Van Tonder *et al.*, 2001).

The FC-method interpretation is based on mathematical models that relate drawdown response to discharge in the abstraction borehole. The results obtained in these short tests can then be used to project the borehole's performance over a longer period of time.

It should be noted that in fractured rock aquifer, the geometry and permeability of the rock system have a large influence on the drawdown. The scale of heterogeneity in a fractured rock system may be large in relation to the scale of the test; therefore, the conventional models developed for homogenous porous aquifers might not be viable in fractured rock systems. The FC-Method software was developed specifically to analyse the pumping tests conducted in fractured rock (Van Tonder *et al.*, 2001).

The FC-Method estimates the sustainable yield of the borehole which is considered as the discharge rate that will not cause the water level in the borehole to drop below prescribed limit (critical level), usually the position of a major water strike.

Recommended abstraction rates

The details of the recommended installation and pumping cycle as well as pumping yields are presented in Appendix B. The recommended sustainable abstraction rates have been calculated on a 24-hrs duty cycle. The surrounding groundwater use in the area were not considered in recommending the pumping yields, because the abstractions in most of the private boreholes in the area were not known.

Existing pumping test data collected, interpreted and captured in the GRIP database (website) was also included in the assessment of the factors that influence the yields of boreholes within the study area. The existing data (recommended abstraction rates) from GRIP database were also incorporated in the current study to improve the data coverage within the study area as well as the confidence level.

3.4 Factors influencing borehole yields

For the purpose of the study, factors affecting the borehole yields were divided into four groups as follows:

- geological factor;
- topographical factor;
- lineaments factor; and
- drainage factor.

It is known that the borehole construction related aspects such as diameter, casing depth and length and borehole depth, have been considered to be important when accounting for the differences in boreholes yield before attempting to assess yield to natural factors. Very limited number of borehole logs were available for review in the current study. The reviewed logs were used to confirm the intercepted lithologies and borehole constructions.

For the purpose of the study, the recommended ósustainableô pumping yield of each borehole was considered to represent the borehole productivity. The borehole productivity was assumed to represent the groundwater yielding potential of the underlying aquifer system in which the borehole has penetrated.

The approach used in the study was to assess the influence of the topography, geology, drainage and lineaments on the yields of drilled boreholes. To assess the influence of these factors, the yield of each borehole was assumed to be a product of the influence of a factor given its location within the study area.

The approach used in this study was based on a multivariate approaches used to assess the relation between the borehole yield (sustainable yield) to the geology, topographical setting, proximity to the drainage system and proximity to lineaments. The assessment relied mostly on the application of the geographical information systems (GIS) programme to provide the visual representation of the associated geographical phenomena together with their spatial dimensions and their associated attributes which provide a rapid, integrated and cost effective tool in any groundwater investigations.

The thematic maps were created in ArcGIS using the 1:250 000 geological and 1:50 000 topographical vector files as well as google map background. The distribution of these boreholes were later plotted against the thematic maps of geology, topography, lineaments and drainage system; and then GIS was used for analysis. With this approach, it was possible to extract spatial information based on the location of the borehole such as geology, topographical setting, proximity to drainage and lineaments.

However, it should be noted that limited number of borehole logs were reviewed to confirm the lithologies intercepted in the drilled boreholes. Boreholes were grouped according to their locations or lithological settings based on the created map. The study assumed that the yields of boreholes were associated with the closest major structures in the area and the identified structures controlled the occurrence and movement of groundwater.

3.4.1 Geologic factors

The bedrock geology determines the regional hydrogeological settings upon which water table configuration and groundwater flow systems (local, intermediate or regional) are manifested (Pascal *et al*., 2013). These authors (Pascal *et al.*, 2013), further indicated that the bedrock geology provides the conduit system for water movement, which controls the amount, rates, patterns and distribution of groundwater.

The formation lithology and rock type do affect the rate of weathering and fracturing which, in most cases, control the yields of the drilled boreholes in an area. The infiltration of water into the sedimentary rock or sediments is primarily a function of primary hydraulic properties of the rock structures, whereas, in the igneous and metamorphic rocks the rate of infiltration is determined by the secondary structures and the degree at which the rock has been affected by the secondary processes. Therefore, the difference in lithology has direct impact on the rate at which the rock will be able to transmit the water in an area.

As described in Section 2.3.1, the study area is underlain by hard rocks (metamorphic, sedimentary and lavas) and sediments of different formations. The metamorphic, sedimentary and lavas are generally described as having low porosity and permeability. However, over the course of the geological time, various tectonic forces and release of confining pressure caused the rocks to break along horizontal and vertical sets of fractures, which can then serve as water bearing openings.

The Quaternary sediments consist of poorly sorted materials and sands and are located along the rivers and dry channels. The yields of boreholes within these sediments depend on the proximity to the river channel, low cementing material (siliceous or clay) and rainfall intensity. The geological setting of the study area is classified into five different formations based on the geological map (Section 2.3.1).

To assess the distribution of boreholes in different formations mapped within the study area, the borehole data set was plotted against the digital 1: 250 000 geological surface GIS map (Figure 3-4). The surface geological GIS layers were created from 1:250 000 geological map sheet 2230 (Messina), 2228 (Alldays) and 2330 (Tzaneen). The created maps made it possible to determine the geological unit in which each borehole was drilled. Where possible, the intercepted lithologies were also confirmed by geological logs, which were reviewed. For the purpose of this study, Musekwa and Nzhelele formation were grouped together, as one formation, Nzhelele formation.

Borehole located within 50 m radius of the major faults, formations lithological contacts and rivers (perennial and non-perennials) were excluded. For the purpose of this study, it was assumed that these factors (fault, contacts and rivers) will have major influence in the borehole yields.

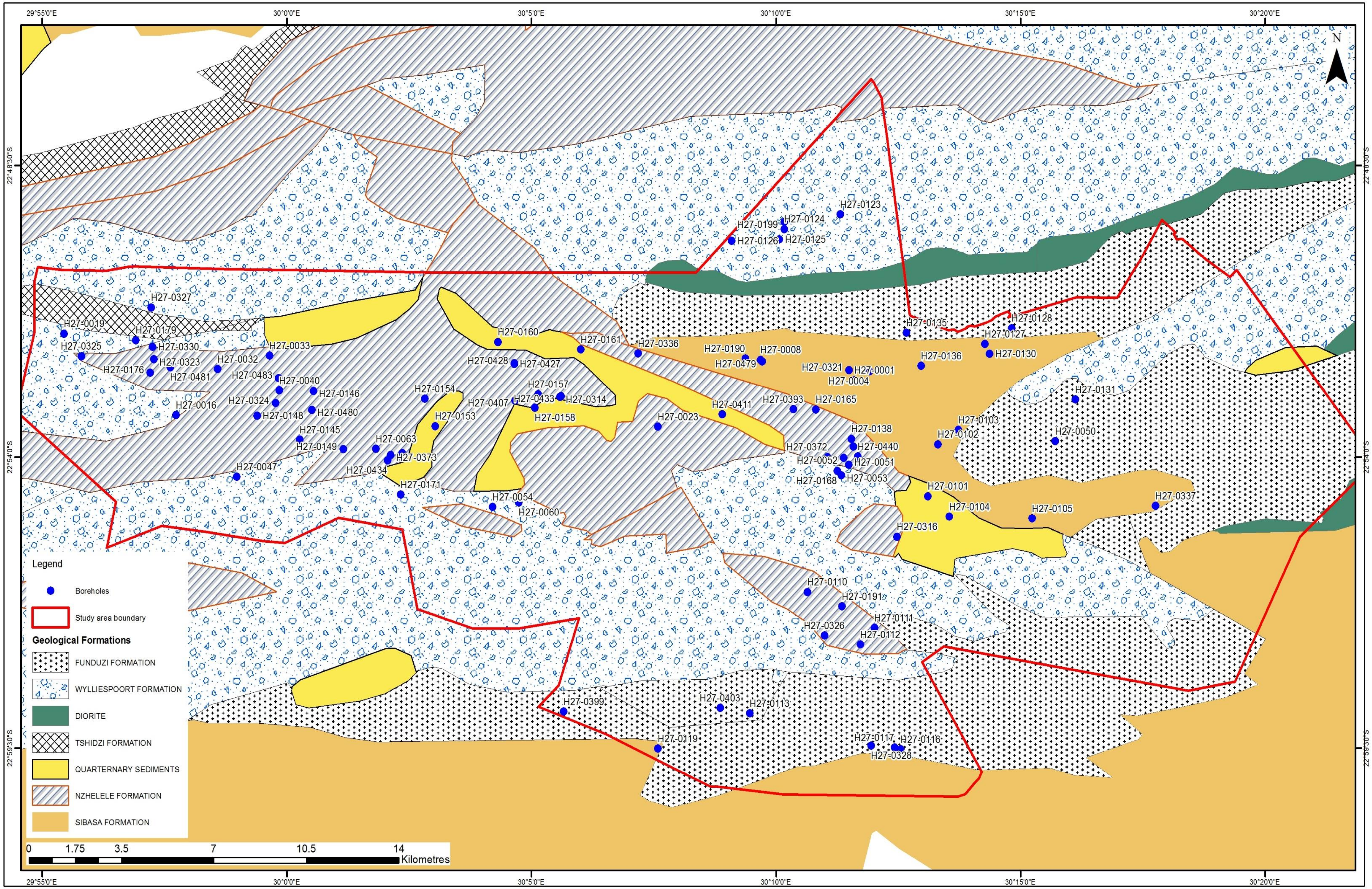


Figure 3-4: Borehole distribution of in different geological Formations within the study area.

3.4.2 Topographic factors

Previous studies have concluded that boreholes that were drilled in flat areas or valleys tend to yield larger volumes compared to those located at the slopes or hilltops. It has been assumed that steep slopes result in higher runoff rates, lower groundwater recharge rates, and hence lower borehole yields than in gentle slopes and flatlands (Clarke and Mcfadden, 1991). Topography of the land surface also determines the general direction of groundwater flow, and it influences groundwater recharge and discharge.

While it is understood that the boreholes for water supply are mostly located closer to the targeted settlement, borehole location in each area will therefore be influenced by the settlement pattern of the area. The settlement pattern in the study area was largely influenced by the topography of the area, which was highly influenced by the historical geological and structural settings of the area. Most of the settlements are within the Nzhelele valley with few settlements occupying the mountainous and slope areas. Nzhelele valley is relatively flat compared to the surrounding areas.

It is important to consider that even though topographical high (hilltops or mountainous) areas are considered to be groundwater recharge zones, in some of these topographical high areas there are local groundwater systems that recharges and discharges locally. The recharge area is still a topographical high spot but the discharge is at a nearby topographical low spot, which is relatively located in a higher elevated area compared to the regional topography. The borehole yields in topographical high and low areas are also affected by different topographical settings. For the purpose of this study, the influence of topography in the yields of drilled boreholes was divided into topographical elevation and topographical settings as follows.

Surface elevation

For the purpose of this study, three topographical elevate areas; mountainous, slopes and flatlands were identified based on the elevation at which each borehole is located. The distribution of boreholes in different elevations within the study area is shown in Figure 3-5. The mountainous areas were those with elevation ranging between 1 000 and 1 400 mamsl, whereas the slope areas were those located between 800 and 1 000 mamsl. The flatland areas are located in elevation below 800 mamsl.

Topographical maps sheets, 2229DD, 22030CC and 2330AD, were used to determine the elevation of each borehole. To determine the elevation of the each borehole, the borehole positions were plotted against the digital topographical map and the elevation of each borehole was interpolated from the 1:50 000 topographical map.

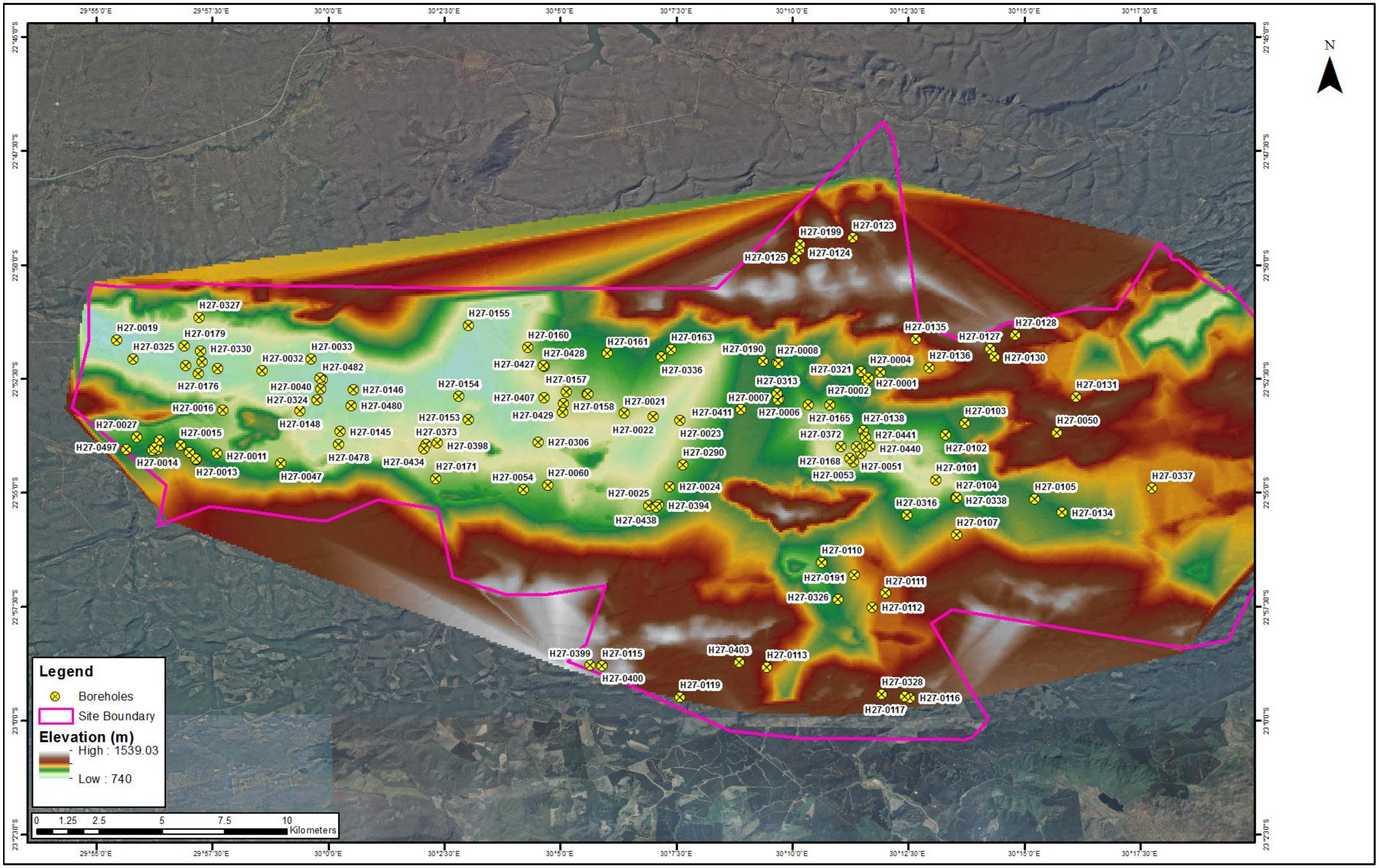


Figure 3-5: Borehole distribution in different elevations (digital elevation model) within the study area.

Topographical settings

To assess the influence of the topographical settings in the yields of the drilled boreholes within the study area, three topographical settings (slope, flatland and valley) were identified based on the location of each borehole in 1:50 000 topographical map (2229DD, 22030CC and 2330AD). The distribution of boreholes in different topographical settings is shown in Figure 3-6. The topographical settings of each borehole was recorded during the site visit and verified on Google earth map.

3.4.3 Lineament factors

The difference in borehole yields intercepting different lithologies is usually enhanced or influenced by presence of secondary features such as faults, fractured zones and joints. Despite the unresolved relationship between lineaments and subsurface permeability, the use of lineament identification in groundwater exploration will continue to be an important initial guide to borehole drilling target selection at the regional level. The use of lineament mapping especially in crystalline lithologies with poor porosity is of major importance for groundwater exploration (Holland, 2012).

For the purpose of this study, the mapping and interpretation of lineaments, which were conducted by Anke (2008), a geological remote sensing consultant, on behalf of then DWA Limpopo Regional office, was used.

The satellite imagery used, by Anke (2008), for the capturing of lineaments was from the medium resolutions Advanced Spaceborne Thermal Emission and Reflectance (ASTER) missions. The ASTER data was considered, by Sander (2007) to be a good choice for groundwater development projects, due to their large spectra resolution, reasonable high spatial resolution, ability to derive DEMÕs and low cost of acquiring the imagery.

Lineaments mapping were done (by Anke, 2008) digitally making use of geographical information technology and was done at a scale of 1:50 000. The mapped structures were not described in details but these structures may reflect a number of features such as faults, fracture zones, joints, foliations, dykes, lithological contacts and linear branches of the drainage systems. The digital 1:250 000 geological maps (sheet 2230 (Messina), 2228 (Alldays) and 2330 (Tzaneen)) were used to improve the identification and classification of the mapped lineaments.

For the purpose of the study, the mapped lineament were interpreted as faults and lineaments. The extent at which a lineament can enhance the permeability of the different lithologies varies with the size of the lineament and may reach up to 300 m. For the purpose of this study, all boreholes within 100 m of a lineament were considered to be targeting a lineament of fault zones. To assess the distribution of boreholes with respect to mapped lineaments and faults within the study area, the boreholes data sets were plotted against the digital geological map and mapped lineaments (faults and lineaments). The created map made it possible to determine which boreholes have been drilled closer to the faults or lineaments (Figure 3-7).

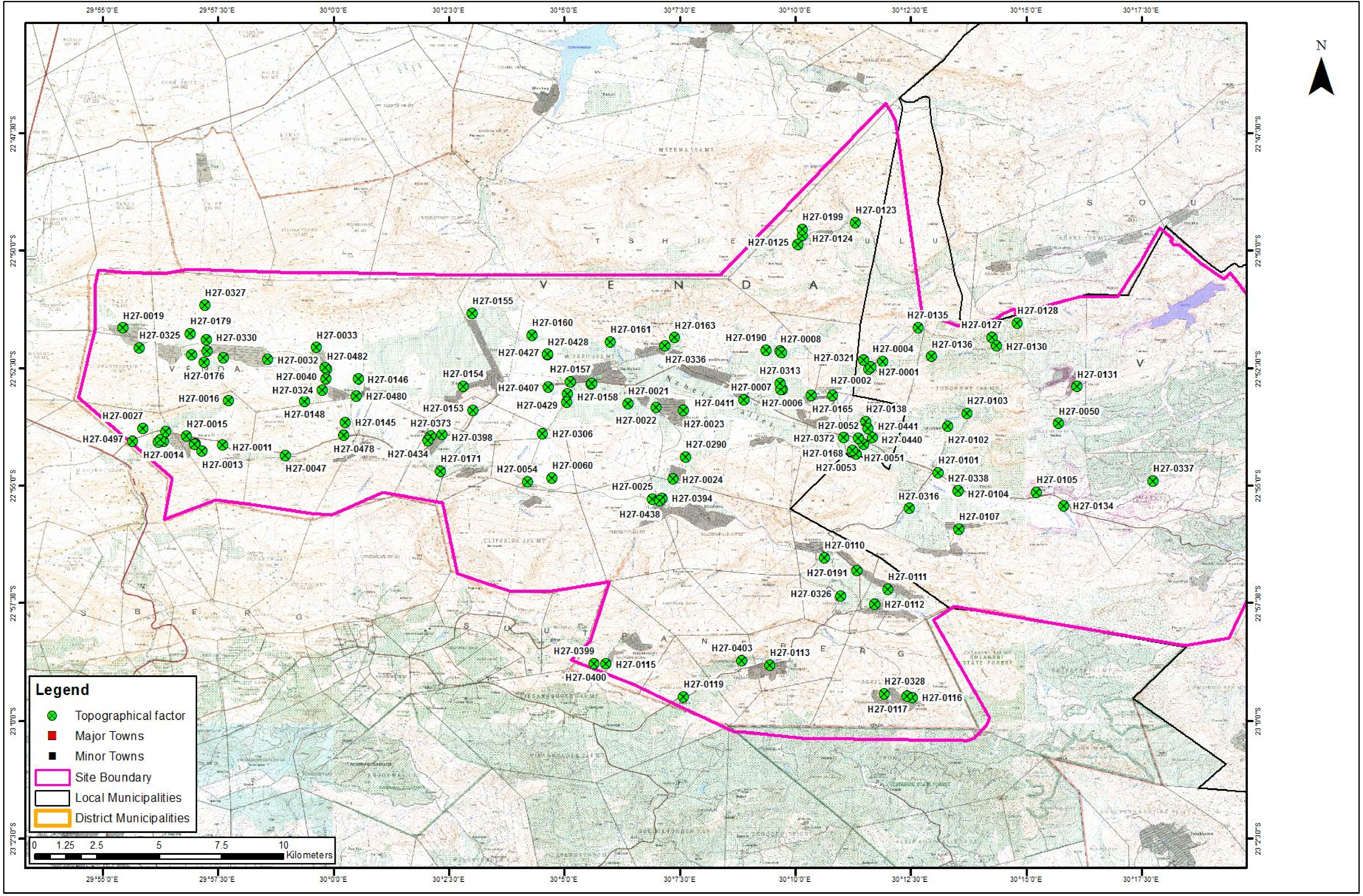


Figure 3-6: Borehole distribution in different topographical settings within the study area.

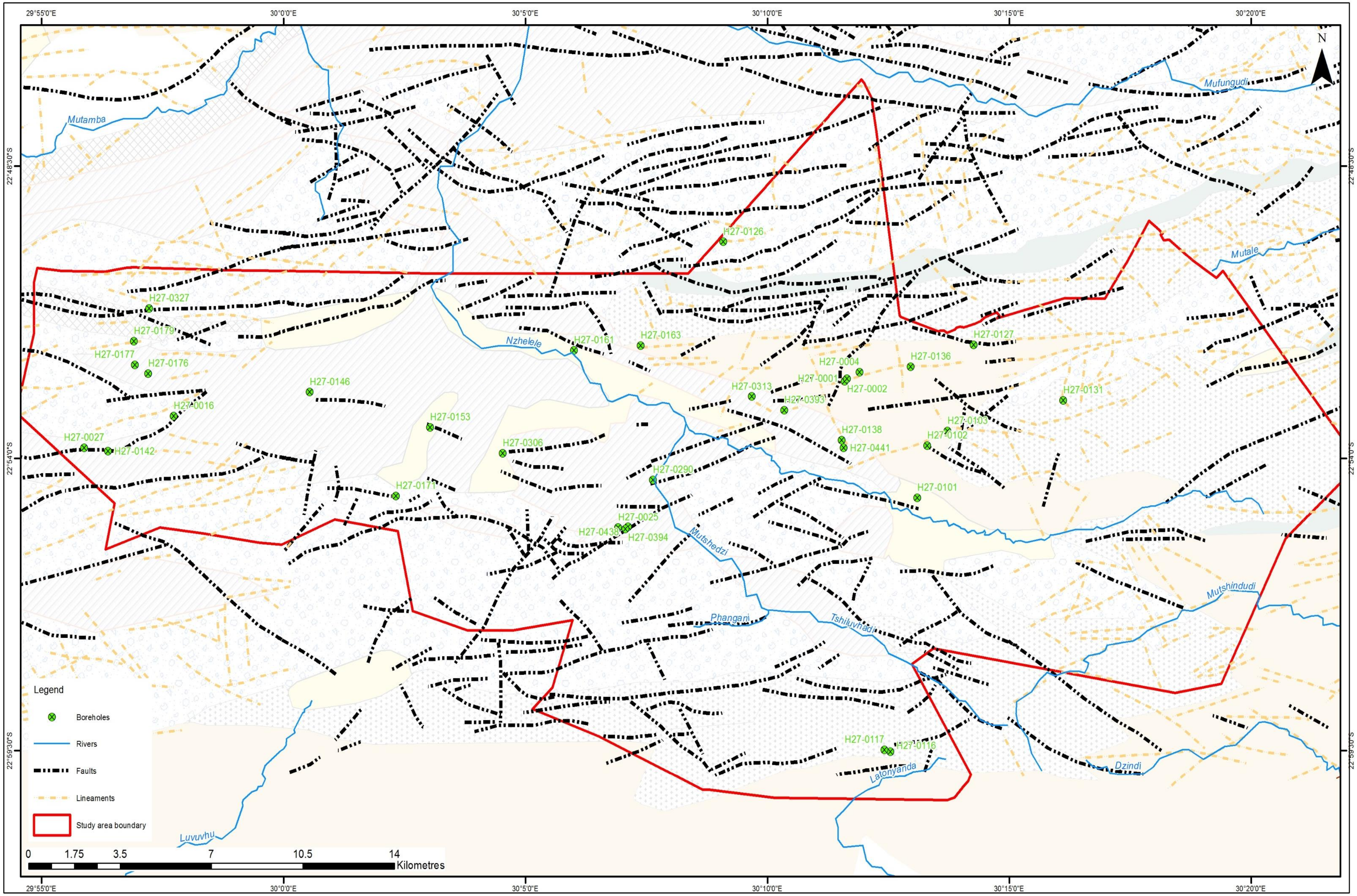


Figure 3-7: Borehole distribution along faults and lineaments within the study area.

The orientation of the lineaments in most cases is identical to the orientation of the preferential flow path. The lineament orientation can also be used as a tool that may reveal points of the groundwater recharge and discharge as well as flow direction. On this basis, the current study also assessed the influence of faults and lineaments orientation on the yields of boreholes. The orientation of the lineaments and faults were obtained from the lineaments map developed by Anke (2008).

3.4.4 Drainage factors

In hard rock area, drainage channels tend to follow zones of structural weakness (faults or other lineaments) located in the near surface; therefore, rocks in the vicinity of the rivers might be more intensely fractured, jointed and /or weathered.

The drainage systems in the area were divided into perennial and non-perennial and their influence on the borehole yield were assessed based on the distance from the nearest drainage system. For the purpose of this study, three drainage zones were identified as follows:

- **away from the drainage system** - representing all boreholes located away, > 100 m from any perennial or non-perennial streams or rivers.
- **Intermediate** ï representing boreholes located between 50 and 100 m from perennial or non-perennial streams or rivers;
- **Within the drainage** ï boreholes located closer, < 50 m, or within the perennial or non-perennial streams.

To assess the influence of drainage in the borehole yields, the borehole data sets were plotted against digital drainage maps and on Google earth map. The borehole positions in different drainage zones are shown in Figure 3-8. The created maps made it possible to measure the horizontal distance from each borehole to the nearest drainage system.

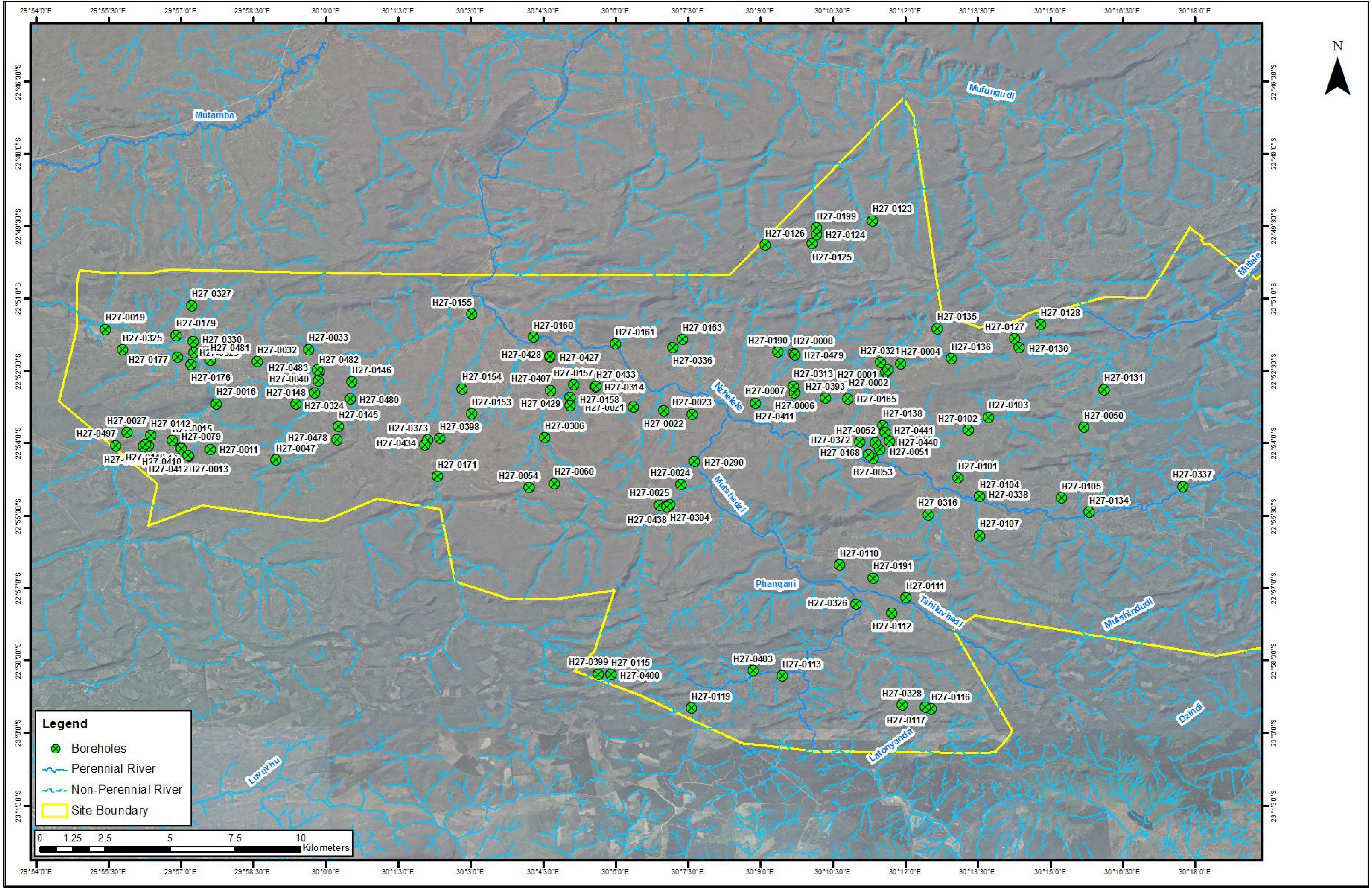


Figure 3-8: Borehole positions against drainage system

4 Data analysis and interpretation

4.1 Existing boreholes

The hydrocensus revealed that there is a good borehole distribution throughout the study area, with boreholes covering most parts of the study area. Most of the boreholes in the area were drilled closer to settlements indicating that they were targeting the nearby settlements rather than any geological structure. The spatial pattern of the drilled boreholes within the study area follows the settlements distribution and most of the boreholes were drilled in slope areas where most people have settled.

Most of the boreholes in the area were equipped with hand pumps (69 %). About 17% of the boreholes were equipped with a Mono-type pumps, whereas 11% of the boreholes were equipped with submersible pumps. Only two boreholes were reported to be equipped with groundwater monitoring devices and 1% of the boreholes were equipped with windmills (Figure 4-1).

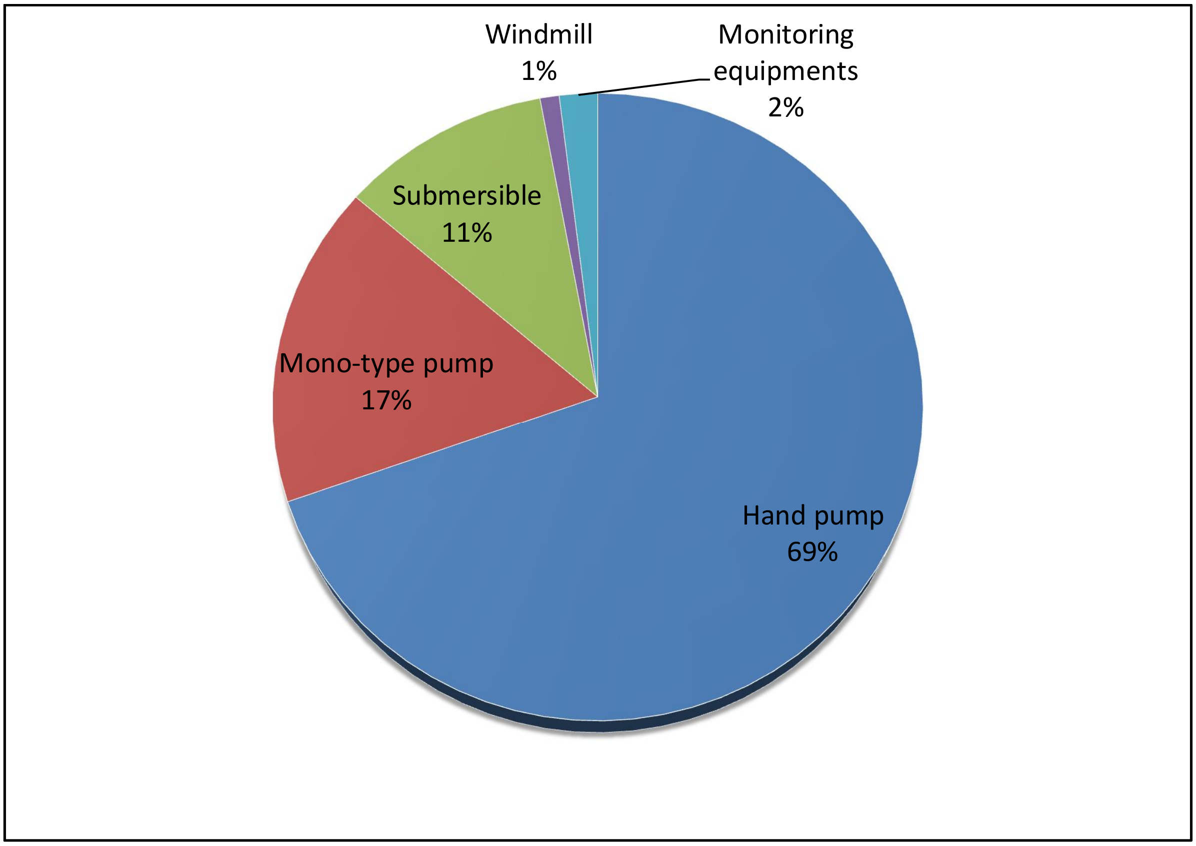


Figure 4-1: Types of equipment installed at the boreholes within the study area.

Most of the visited springs in the area are located at the foot of the mountains or on the hilltops. Most of these springs are non-perennial and are associated with shallow perched aquifer systems. Only one spring, located at the foot of the Tswime Mountain, was high yielding (> 20 L/s) and is fed by water from a fault.

4.2 Borehole yield assessment

4.2.1 Pumping test

A summary of the pumping test activities completed is presented in Table 4-1. The majority of the pumping tests were single-borehole tests, primarily to determine sustainable abstraction rates of each borehole. The CRDT drawdown and recovery data for the tested boreholes are presented in Appendix B.

The depth of the tested boreholes ranged between 6 and 105 mbgl and the depths of most of the boreholes averages around 45 m. The static water level ranged between 1.2 and 24.37 mbgl. The available drawdown in the tested boreholes ranged between 4 and 91 m.

Most (60%) of the tested boreholes attained a minimum of 80% of the available drawdown during the Constant Rate Discharge Test. The CRDT durations ranged between 120 and 4 320 minutes. The CRDT pumping yields varied between 0.3 and 14 l/s. The percentages of the average yields pumped during the CRDT in the tested boreholes are graphically presented in Figure 4-2. Most (68%) of the boreholes were pumped (CRDT) at a yield of less than 2 l/s and only 5% of the boreholes had CRDT yields of above 10 l/s.

The variations in CRDT yields within the study area are large and heavily skewed towards the low yields. The mean value of the CRDT yield (1.1 L/s) is slightly lower than the average yield of 2.0 L/s. This is expected given the fact that most the borehole were not scientifically sited and this is (low yielding boreholes) also common in hard rock terrains.

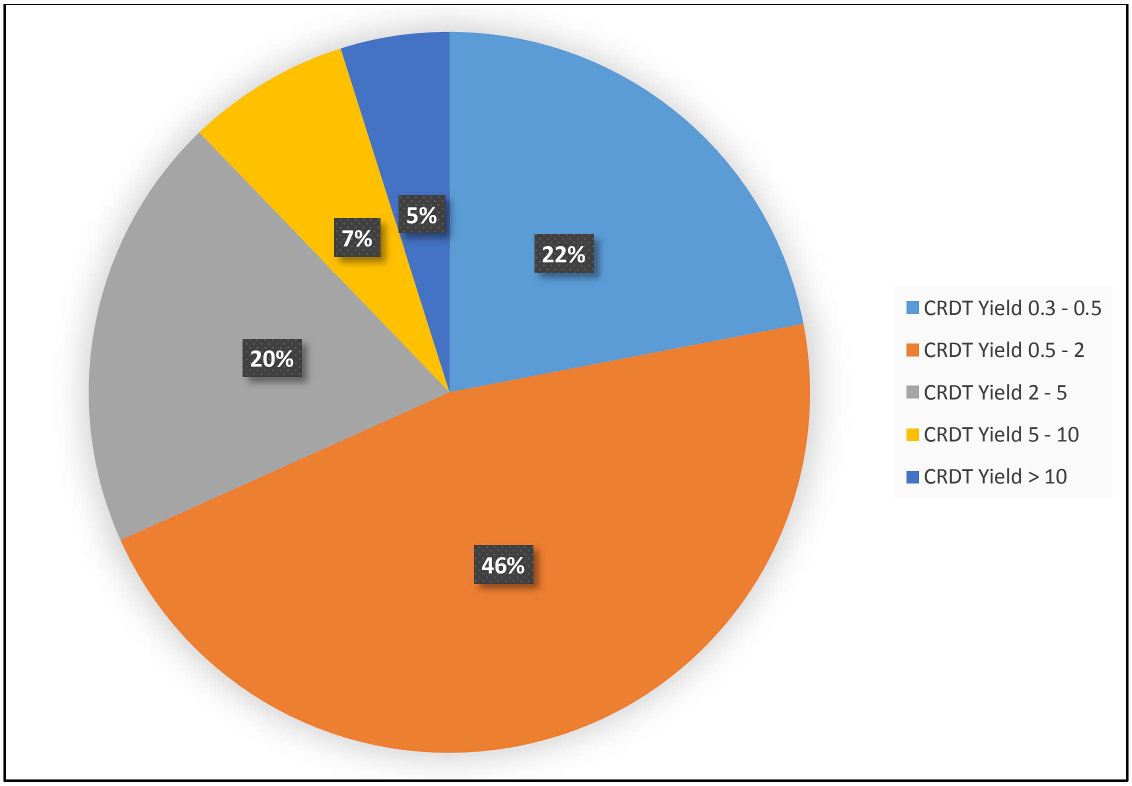


Figure 4-2: Graphical presentation of CRDT yields of the tested boreholes.

Table 4-1: Summary of the pumping test programme

Borehole No.	Depth (mbgl)	Static Water Level (mbgl)	Pump setting (mbgl)	Estimated available drawdown (m)	Testing programme	*Constant Rate Discharge Test (CRDT)			Recovery
						Yield (L/s)	Duration (minutes)	Maximum drawdown (m)	
H27-0016	37.0	6.65	35.0	28.35	*SDT and *CRDT	1.33	300	27.3	81% recovery after 300 minutes. Outstanding drawdown of 5.17 m
H27-0006	36.0	5.06	32.0	26.94	SDT and CRDT	0.54	720	1.94	80% recovery after 1 440 minutes. Outstanding drawdown of 0.37 m
H27-0021	36.4	12.23	32.7	20.7	SDT and CRDT	0.84	720	15.79	100% recovery after 420 minutes.
H27-0022	28.8	3.40	26.8	23.4	SDT and CRDT	14.0	4 320	19.63	96% recovery after 4 320 minutes. Outstanding drawdown of 0.82 m
H27-0023	73.2	19.30	68.1	48.8	SDT and CRDT	1.50	540	47.88	98% recovery after 540 minutes. Outstanding drawdown of 0.79 m
H27-0024	16.4	6.72	14.7	7.98	SDT and CRDT	0.90	720	5.79	99% recovery after 720 minutes. Outstanding drawdown of 0.02 m
H27-0025	43.5	11.00	41.7	30.7	SDT and CRDT	0.33	480	27.65	97% recovery after 480 minutes. Outstanding drawdown of 0.79 m
H27-0027	48.43	18.87	45.4	26.53	SDT and CRDT	0.55	720	26.49	98% recovery after 720 minutes. Outstanding drawdown of 0.44 m
H27-0033	62.23	13.03	68.7	55.7	SDT and CRDT	1.50	720	55.0	97% recovery after 720 minutes. Outstanding drawdown of 1.27 m
H27-0050	16.86	6.00	14.7	8.7	SDT	0.3	150	7.26	96% recovery after 30 minutes. Outstanding drawdown of 0.26 m
H27-0060	35.68	1.20	32.0	30.8	SDT and CRDT	2.50	1 440	26.45	100% recovery after 1 440 minutes.
H27-0107	48.37	15.50	45.4	29.6	SDT and CRDT	0.33	240	27.76	91% recovery after 240 minutes. Outstanding drawdown of 2.30 m
H27-0110	30.50	13.30	26.7	13.4	SDT and CRDT	0.31	480	10.57	98% recovery after 480 minutes. Outstanding drawdown of 0.12 m

Borehole No.	Depth (mbgl)	Static Water Level (mbgl)	Pump setting (mbgl)	Estimated available drawdown (m)	Testing programme	*Constant Rate Discharge Test (CRDT)			Recovery
						Yield (L/s)	Duration (minutes)	Maximum drawdown (m)	
H27-0111	31.80	12.74	29.1	16.4	SDT and CRDT	1.01	840	15.22	99% recovery after 480 minutes. Outstanding drawdown of 0.05 m
H27-0113	18.42	8.36	17.7	9.34	SDT and CRDT	0.62	120	8.05	85% recovery after 120 minutes. Outstanding drawdown of 1.15 m
H27-0115	39.50	8.42	38.7	30.3	SDT and CRDT	5.03	2 880	24.06	99% recovery after 2 880 minutes. Outstanding drawdown of 0.15 m
H27-0119	23.65	3.25	20.7	17.5	SDT and CRDT	0.91	720	16.65	100% recovery after 120 minutes.
H27-0126	39.62	6.58	38.7	32.1	SDT and CRDT	0.92	720	24.17	99% recovery after 720 minutes. Outstanding drawdown of 0.12 m
H27-0131	6.10	1.62	5.7	4.1	SDT and CRDT	0.33	360	3.10	97% recovery after 360 minutes. Outstanding drawdown of 0.08 m
H27-0136	13.03	5.40	11.0	5.6	SDT and CRDT	0.31	480	5.23	100% recovery after 360 minutes.
H27-0145	26.60	7.16	23.0	15.8	SDT and CRDT	1.40	720	12.27	99% recovery after 720 minutes. Outstanding drawdown of 0.04 m
H27-0148	52.46	17.61	50.5	32.9	SDT and CRDT	1.21	540	32.45	98% recovery after 540 minutes. Outstanding drawdown of 0.38 m
H27-0149	28.00	8.40	23.0	14.6	SDT and CRDT	0.80	720	13.40	98% recovery after 720 minutes. Outstanding drawdown of 0.17 m
H27-0153	45.58	9.41	41.7	32.3	SDT and CRDT	1.0	480	31.02	90% recovery after 480 minutes. Outstanding drawdown of 3.06 m
H27-0154	51.70	21.62	44.0	22.4	SDT and CRDT	6.1	1 440	22.38	100% recovery after 720 minutes.
H27-0157	26.14	3.00	20.7	17.7	SDT and CRDT	2.82	1 440	17.25	100% recovery after 540 minutes.
H27-0158	82.28	2.73	75.0	72.3	SDT and CRDT	2.1	1 440	32.49	100% recovery after 720 minutes.
H27-0160	42.53	2.83	38.7	38.70	SDT and CRDT	1.1	1 200	35.10	100% recovery after 540 minutes.

Borehole No.	Depth (mbgl)	Static Water Level (mbgl)	Pump setting (mbgl)	Estimated available drawdown (m)	Testing programme	*Constant Rate Discharge Test (CRDT)			Recovery
						Yield (L/s)	Duration (minutes)	Maximum drawdown (m)	
H27-0161	36.68	10.96	35.8	24.8	SDT and CRDT	10.02	840	24.45	100% recovery after 840 minutes.
H27-0163	44.51	8.59	41.7	33.1	SDT and CRDT	3.40	540	30.1	94% recovery after 540 minutes. Outstanding drawdown of 1.92 m
H27-0165	51.17	15.70	50.7	35.0	SDT and CRDT	5.07	2 880	30.39	100% recovery after 720 minutes.
H27-0191	69.79	24.37	68.7	44.3	SDT and CRDT	0.35	480	43.53	98% recovery after 480 minutes. Outstanding drawdown of 0.84 m
H27-0199	76.90	5.15	74.7	69.6	SDT and CRDT	0.40	480	51.75	98% recovery after 480 minutes. Outstanding drawdown of 1.15 m
H27-0102	66.70	11.33	62.7	51.4	SDT and CRDT	1.71	960	51.40	100% recovery after 960 minutes.
H27-0103	75.61	2.89	68.7	65.81	SDT and CRDT	0.90	480	65.45	98% recovery after 480 minutes. Outstanding drawdown of 0.99 m
H27-0105	23.57	2.25	20.7	18.5	SDT and CRDT	0.36	480	14.12	100% recovery after 480 minutes.
H27-0290	53.22	6.97	50.7	43.7	SDT and CRDT	2.50	1 440	41.02	100% recovery after 720 minutes.
H27-0316	76.30	14.00	72.8	58.8	SDT and CRDT	1.50	720	5.12	100% recovery after 720 minutes.
H27-0321	55.35	5.86	53.0	47.1	SDT and CRDT	2.51	720	1.76	99% recovery after 720 minutes. Outstanding drawdown of 0.02 m
H27-0337	69.39	17.29	68.70	51.4	SDT and CRDT	1.7	960	50.98	95% recovery after 960 minutes. Outstanding drawdown of 2.31 m
H27-0338	104.70	3.76	95.2	91.4	SDT and CRDT	3.24	480	90.05	60% recovery after 480 minutes. Outstanding drawdown of 36.35 m

*CRDT ï pumping of a borehole for a predetermined time (between 8 and 72 hrs) at a constant rate.

*SDT ï pumping of a borehole at a constant yield for a 60-minute interval, thereafter at a higher discharge rate.

4.2.2 Pumping test data analysis and recommending sustainable abstraction rates

The pumping test data was interpreted to determine the sustainable abstraction rate that will not cause the water level in the borehole to drop below a prescribed limit, usually the position of the major water strike. The CRDT tests were short (between 4 and 72 hrs) and adequate to predict the sustainability of an abstraction (Figure 4-3).

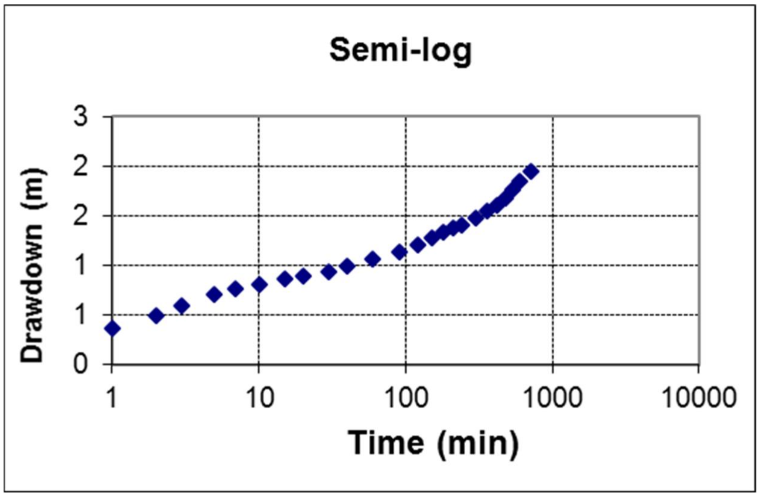


Figure 4-3: Test graph for borehole H27-0006 showing CRDT of 24hrs.

The CRDT data was used to identify the characteristics of the flow regime which is very important in sustainable yield estimation. The flow regime identification in all the tested boreholes was accomplished by plotting the observed drawdown from the dataset simultaneously with the log derivative (Figure 4-4). The diagnostic plots of the tested boreholes check to assess the drawdown behaviour which will be required in estimating the sustainable yield.

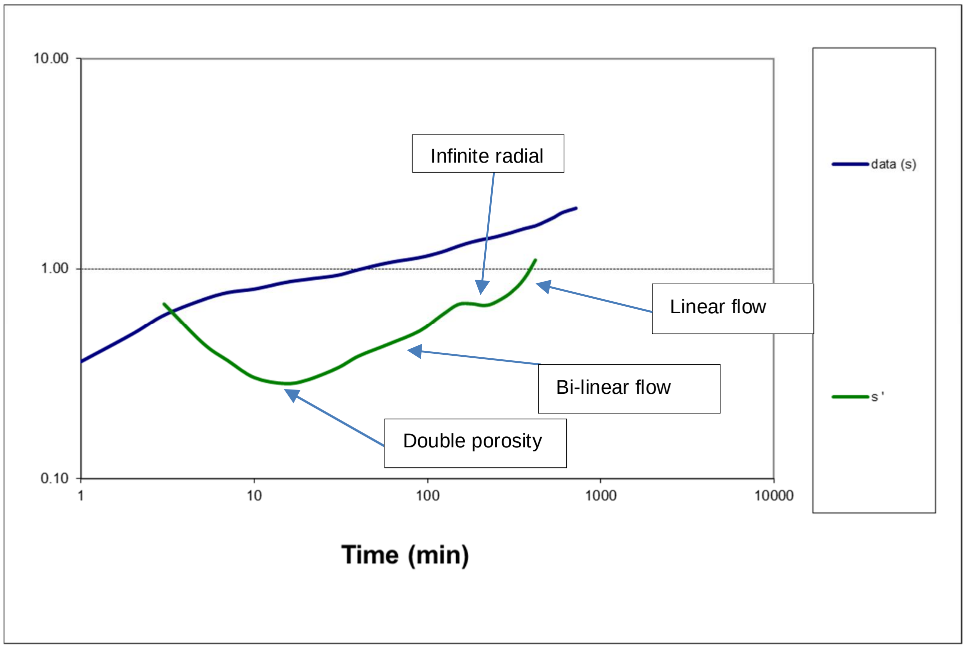
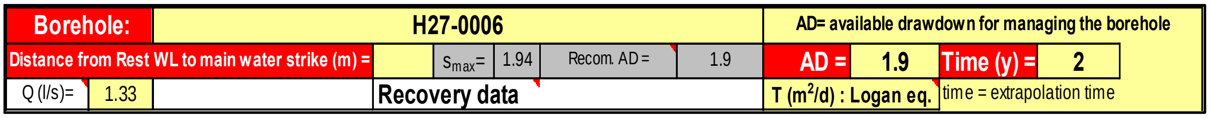


Figure 4-4: Flow diagnostics from the derivative plot of borehole H27-0006.

Due to lack of borehole drilling information for most of the boreholes that were tested, the available drawdown used in the estimation of the sustainable yield was the maximum drawdown achieved during the pumping of the CRDT (Figure 4-5).



Borehole: H27-0006

AD= available drawdown for managing the borehole

Distance from Rest WL to main water strike (m) =

S_{max}= 1.94

Recom. AD = 1.9

AD = 1.9

Time (y) = 2

Q (l/s)= 1.33

Recovery data

T (m^2/d) : Logan eq.

time = extrapolation time

Figure 4-5: Estimating the available drawdown.

The sustainable abstraction rate of each borehole was estimated using Cooper-Jacob Method, Basic FC and FC Inflection point method. The abstraction yield in Cooper-Jacob Method was done by fitting the curves and graphs in the Cooper-Jacob Method spreadsheet (Figure 4-6).

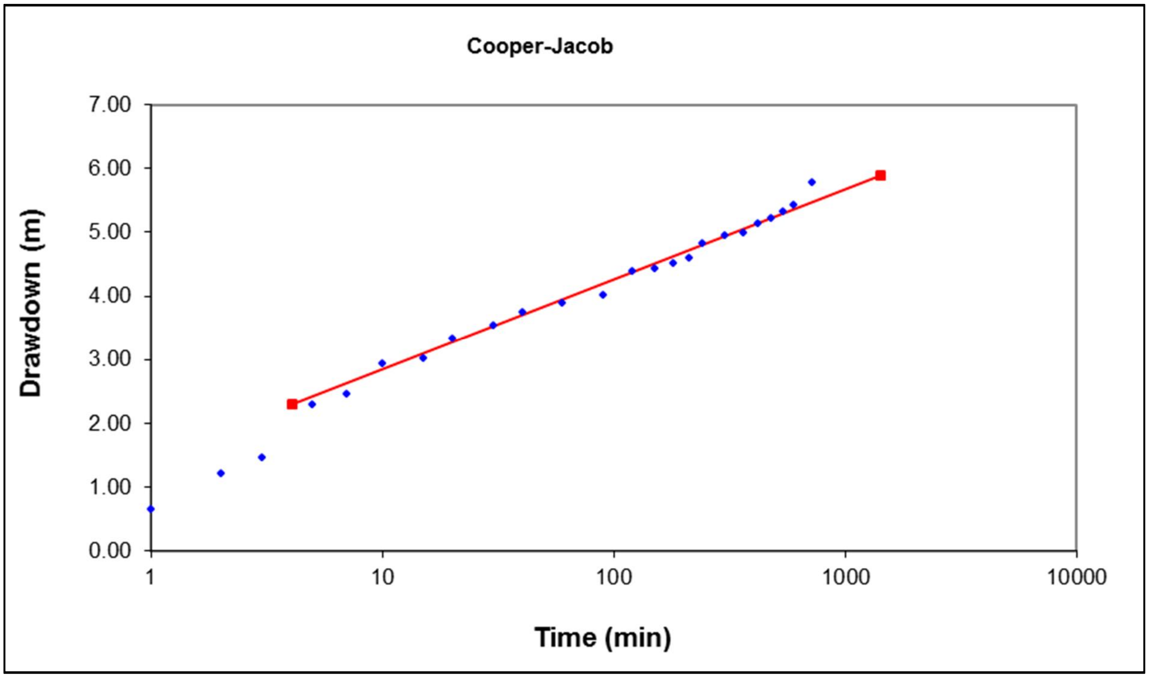
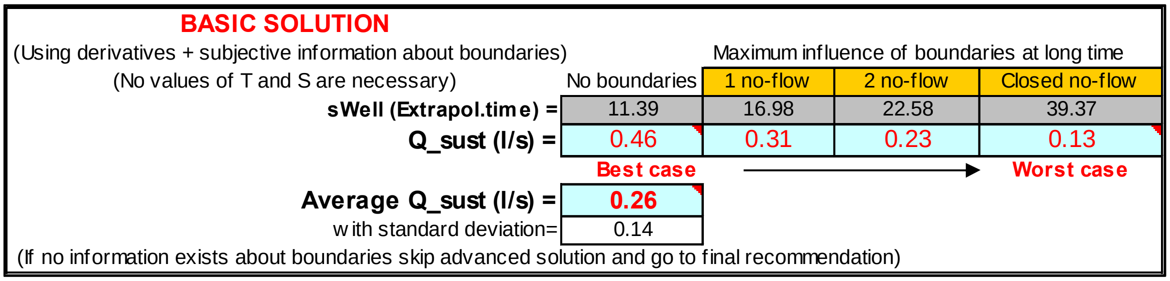


Figure 4-6: Cooper-Jacob Method fitted curve of Borehole H27-0024.

The sustainable yield in Basic FC was estimated considering different boundary conditions and rating the boundary conditions from best to worst conditions. The geometric mean of the estimated yields in different boundary conditions was considered to be the average sustainable yield (Q) of the borehole (Figure 4-7).



BASIC SOLUTION

(Using derivatives + subjective information about boundaries)

(No values of T and S are necessary)

Maximum influence of boundaries at long time

	No boundaries	1 no-flow	2 no-flow	Closed no-flow
sWell (Extrapol.time) =	11.39	16.98	22.58	39.37
Q_sust (l/s) =	0.46	0.31	0.23	0.13
	Best case	→		Worst case

Average Q_sust (l/s) = 0.26

with standard deviation= 0.14

(If no information exists about boundaries skip advanced solution and go to final recommendation)

Figure 4-7: Sustainable yield estimations using Basic FC for borehole H27-0024.

Where inflection point exist in the test pumping data, FC inflection method was also used in the estimation of the sustainable abstraction rate. The inflection point marks the drawdown level in which if reached, this might lead to over abstraction or dewatering of the aquifer system. Inflection level marks the depth at which the main water strike was dewatered (Figure 4-8).

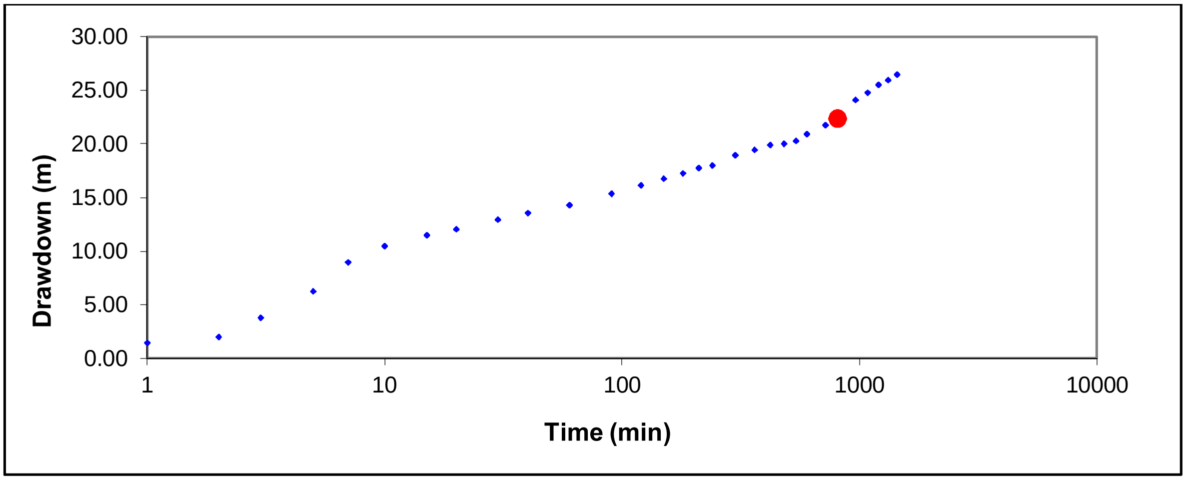
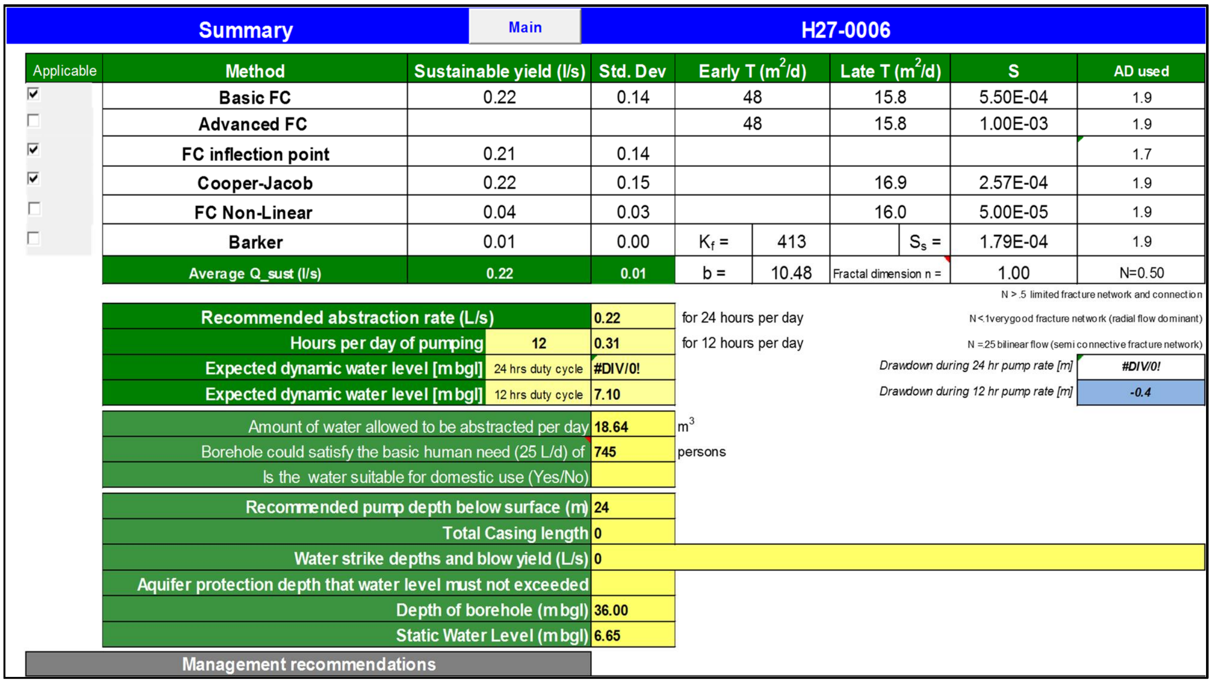


Figure 4-8: Inflection point of borehole H27-0060.

The overall estimated sustainable abstraction rates of each borehole was estimated as an average of the methods (Cooper-Jacob, Basic FC and FC Inflection point) used in data analysis of each borehole (Figure 4-9). The estimated sustainable abstraction rates, methods used, transmissivity as well as theoretical inflow in each tested borehole are presented in Table 4-2. The details of the recommended installation and pumping cycle as well as pumping yields are presented in Appendix C.



Summary | Main | **H27-0006**

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	0.22	0.14	48	15.8	5.50E-04	1.9
☐	Advanced FC			48	15.8	1.00E-03	1.9
☑	FC inflection point	0.21	0.14				1.7
☑	Cooper-Jacob	0.22	0.15		16.9	2.57E-04	1.9
☐	FC Non-Linear	0.04	0.03		16.0	5.00E-05	1.9
☐	Barker	0.01	0.00	K_f = 413	S_s =	1.79E-04	1.9
	Average Q_sust (l/s)	0.22	0.01	b = 10.48	Fractal dimension n =	1.00	N=0.50

N > .5 limited fracture network and connection
N < 1 very good fracture network (radial flow dominant)
N = .25 bilinear flow (semi connective fracture network)

Recommended abstraction rate (L/s)		0.22	for 24 hours per day
Hours per day of pumping	12	0.31	for 12 hours per day
Expected dynamic water level [m bgl]	24 hrs duty cycle	#DIV/0!	
Expected dynamic water level [m bgl]	12 hrs duty cycle	7.10	
Amount of water allowed to be abstracted per day		18.64	m^3
Borehole could satisfy the basic human need (25 L/d) of		745	persons
Is the water suitable for domestic use (Yes/No)			
Recommended pump depth below surface (m)		24	
Total Casing length		0	
Water strike depths and blow yield (L/s)		0	
Aquifer protection depth that water level must not exceeded			
Depth of borehole (m bgl)		36.00	
Static Water Level (m bgl)		6.65	

Drawdown during 24 hr pump rate [m]	*#DIV/0!*
Drawdown during 12 hr pump rate [m]	*-0.4*

Management recommendations

Figure 4-9: Summary of the recommended sustainable abstraction of borehole H27-0006.

Table 4-2: Estimated sustainable abstraction rates

Borehole No.	Theoretical inflows	Methods used in the estimation of abstraction rate			Final Average abstraction rate (l/s). For 24 hrs per day	Transmissivity
	l/s	Basic FC (l/s)	FC Inflection point (l/s)	Cooper Jacob (l/s)		M^2/day
H27-0016	1.10	0.21	-	0.25	**0.23**	1.33
H27-0006	0.28	-	-	0.18	**0.20**	19.87
H27-0021	0.67	-	-	0.33	**0.33**	5.33
H27-0022	7.0	-	6.74	5.61	**6.18**	73.90
H27-0023	1.09	0.22	0.24	0.25	**0.23**	0.78
H27-0024	0.6	0.26	0.25	0.27	**0.26**	10.05
H27-0025	0.25	-	0.04	-	**0.04**	0.30
H27-0027	0.37	0.22	0.24	0.18	**0.21**	1.73
H27-0033	1.0	0.22	0.22	0.39	**0.28**	1.23
H27-0060	1.25	0.43	0.59	0.84	**0.62**	6.26
H27-0107	0.28	0.04	0.03	-	**0.03**	0.40
H27-0110	0.23	006	0.04	0.07	**0.06**	1.33
H27-0111	0.76	0.16	0.11	0.17	**0.15**	1.56
H27-0113	0.54	-	-	0.08	**0.08**	3.58
H27-0115	2.51	0.40	0.42	2.26	**1.03**	19.16
H27-0119	0.88	0.38	0.35	0.32	**0.35**	5.80
H27-0126	0.74	0.19	0.20	0.19	**0.19**	1.26
H27-0131	0.29	0.03	-	0.05	**0.04**	2.07
H27-0136	0.28	0.09	0.09	0.08	**0.09**	2.89
H27-0145	1.13	0.26	0.23	0.68	**0.39**	17.92
H27-0148	1.02	0.10	0.25	0.10	**0.15**	1.35
H27-0149	0.64	0.18	0.15	0.19	**0.17**	2.68

Borehole No.	Theoretical inflows	Methods used in the estimation of abstraction rate			Final Average abstraction rate (l/s). For 24 hrs per day	Transmissivity
	l/s	Basic FC (l/s)	FC Inflection point (l/s)	Cooper Jacob (l/s)		M^2/day
H27-0153	0.86	0.29	0.22	0.23	**0.25**	1.34
H27-0154	4.88	1.88	1.14	2.87	**1.96**	20.55
H27-0157	2.37	1.44	0.75	1.38	**1.19**	8.18
H27-0158	1.48	0.25	0.22	0.61	**0.36**	2.92
H27-0160	0.65	0.08	0.07	0.67	**0.27**	3.68
H27-0161	5.01	2.05	2.11	2.17	**2.11**	14.69
H27-0163	1.45	0.32	0.26	0.56	**0.38**	2.55
H27-0165	4.06	0.82	0.60	1.05	**0.82**	2.60
H27-0191	0.18	0.05	0.04	0.06	**0.05**	0.18
H27-0199	0.20	0.05	0.04	0.1	**0.06**	0.32
H27-0102	0.85	0.16	0.22	1.28	**0.55**	8.13
H27-0103	0.45	-	-	0.08	**0.08**	0.96
H27-0105	0.18	0.10	0.09	0.10	**0.10**	1.40
H27-0290	1.67	0.68	0.83	-	**0.75**	3.48
H27-0316	0.75	0.35	0.41	0.45	**0.40**	18.18
H27-0321	1.26	0.87	0.82	1.17	**0.95**	351.64
H27-0337	0.85	0.28	0.19	0.75	**0.41**	1.14
H27-0338	1.50	0.61	0.74	0.83	**0.73**	1.74

The percentage distribution of the recommended sustainable abstraction yields of the tested boreholes in the study area are presented in Figure 4-10 and ranges between 0.01 and 6.0 L/s. These yields are lower compared to the CRDT yields.

The recommended yields represent the average rate of pumping that can be maintained without endangering either the quantity or quality of pumped water. The estimate assumed that recommended yield is a suitable percentage of annual recharge, the percentage varying with local hydrogeologic conditions.

The results show that the area is dominated (69%) by very low yielding (0 - 0.5 l/s) boreholes, not suitable for motorised abstractions. Only 5% of the tested boreholes can be pumped at a yield more than 2 L/s. This is expected given the fact that most of the boreholes in the area were not scientifically sited.

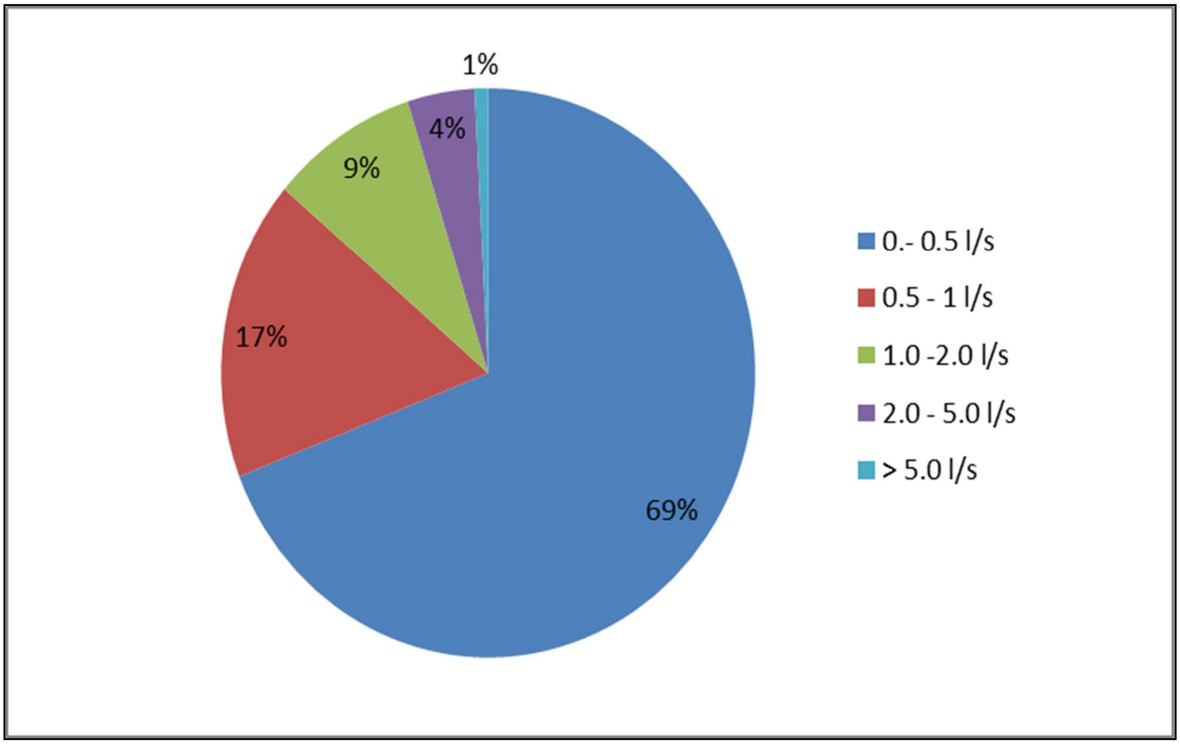


Figure 4-10: Graphical presentation of the recommended abstraction rates in L/s.

4.3 Geological influence

The formations which were intercepted by the drilled boreholes as well as the number of boreholes that were drilled in each formation are presented in Table 4-3. For the purpose of this study, Musekwa and Nzhelele formation were grouped together, as Nzhelele formation.

A total of 88 boreholes with pumping test data were considered in assessing the influence of geology on the borehole yields within the study area.

Table 4-3: Borehole distribution in different formations

Formations	**Number of boreholes tested**	**Borehole depths in mbgl**			**Borehole Yield in L/s**			**Water level mbgl**		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Sibasa	14	13.3	81.84	47.0	0.02	0.9	0.31	1.9	21.5	10.7
Fundudzi	10	14.7	100.3	53.5	0.05	4.4	0.83	1.5	25.5	8.9
WylliesPoort	13	31.9	108.4	67.3	0.05	0.7	0.20	1.2	57.9	9.12
Nzhelele and Musekwa	42	26.1	141.0	63.8	0.05	6.0	0.51	0.0	24.1	9.6
Quaternary	9	35.1	115	67.0	0.15	2.0	0.52	1.68	10.9	5.4

The percentage distribution of the tested boreholes in different formation within the study area are shown in Figure 4-11. Almost half (48%) of the boreholes tested within the study area were drilled in the Nzhelele Formation.

A total of 31% of the drilled boreholes were shared almost equally between WylliesPoort (15%) and Sibasa Formation (16%). The remaining 21% of the boreholes are shared between Fundudzi and the quaternary sediments (Figure 4-11).

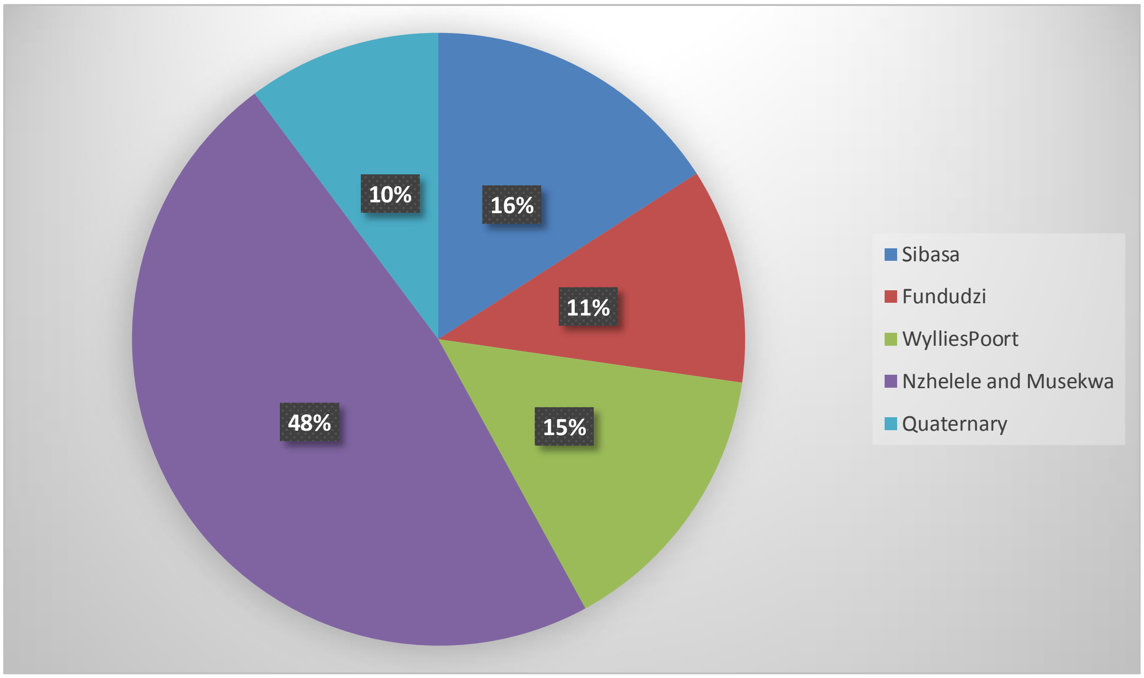


Figure 4-11: Percentage of borehole distributions in different geological formations.

The high percentage of boreholes in the Nzhelele Formation is expected because most of the study area is underlain by the Nzhelele Formation. Nzhelele Formation underlies the gentle slopes and low lying areas which are the most targeted areas for settlements within the study area. Wylliespoort, Sibasa and Fundudzi occupy the mountainous areas of the study area and few settlements were found.

The borehole depths in the study area ranged between 13 and 141 metres below the ground level (mbgl). The thickness of the sediments within the area is not know because all the drilled boreholes were completed within the sediments, with no borehole reaching the end of these sediments.

The borehole statistical depths in different geological formations within the study area are shown in Figure 4-12. The average deepest (67 mbgl) boreholes were drilled within Wylliespoort Formation and in Quaternary sediments. The average depths of boreholes in Sibasa Formation is 47 mbgl, indicating shallower borehole depths compared to average depths in the Fundudzi, Nzhelele and Sibasa Formations. Even though Fundudzi and Sibasa Formations are located in high elevation, mountainous areas, compared to Nzhelele Formation and Quaternary sediments, shallow boreholes were drilled in these formations compared to Nzhelele (63.8 mbgl) and Quaternary sediments (67 mbgl).

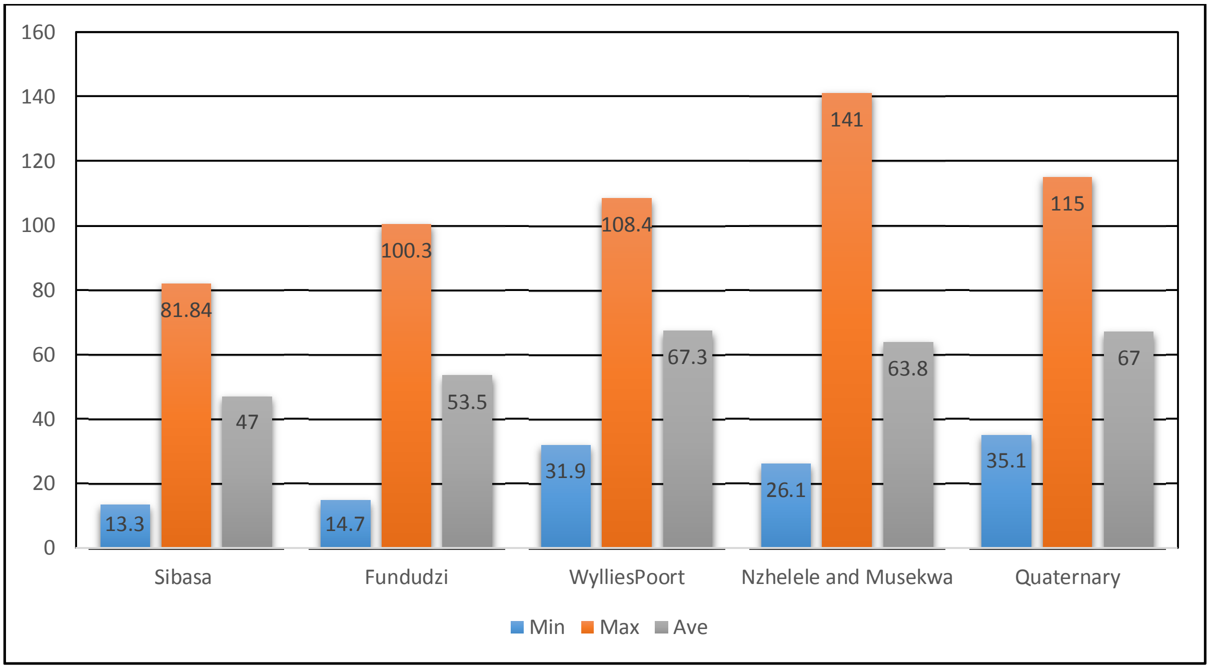


Figure 4-12: Statistical depths of the boreholes in different formations within the study area.

The maximum and average recommended abstraction rates in each geological formation within the study area are shown in Figure 4-13. The figure shows that Nzhelele, Fundudzi and the Quaternary sediments are the most yielding formations within the study area. Fundudzi Formation has high average borehole abstraction yield compared to other formations except Nzhelele Formation that has the highest recommended abstraction rates. Sibasa and Wylliespoort formations are the least in terms of supporting high yielding boreholes in the area, with average yields of 0.3 l/s and 0.2 l/s, respectively.

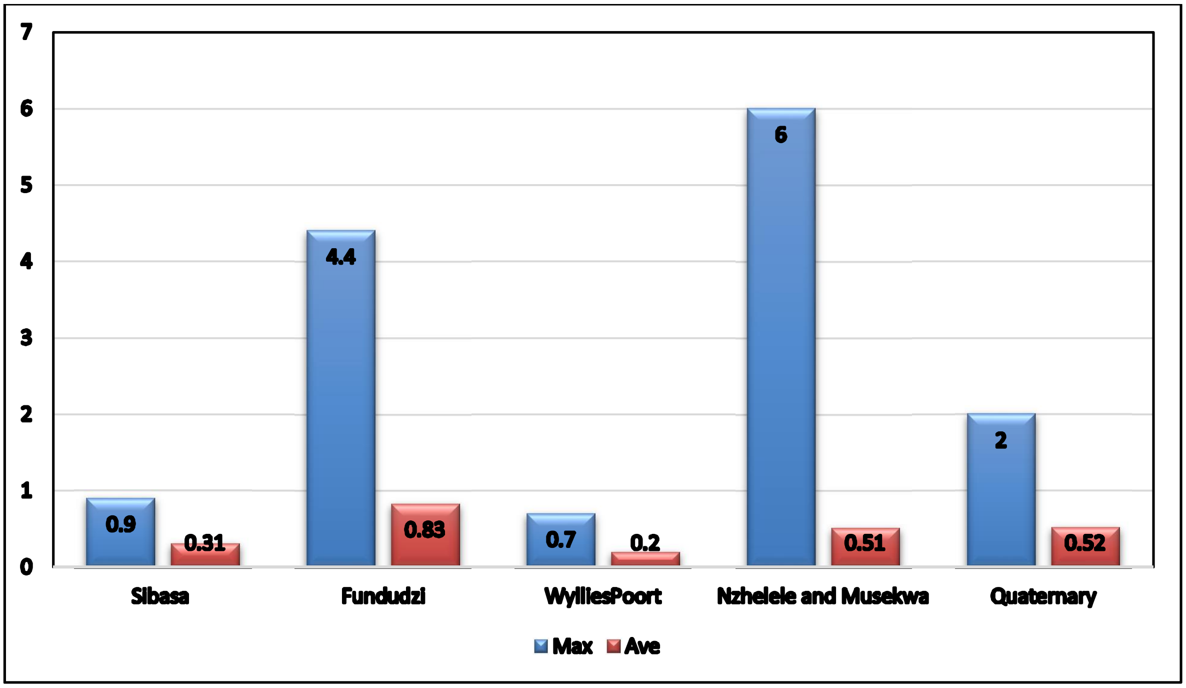


Figure 4-13: Max and Average recommended abstraction rates (L/s) in different formations.

4.4 Topography influence

4.4.1 Elevation influence

The elevation ranges of the boreholes within the study area as well as statistical analysis of yields, water levels and borehole depths are presented in Table 4-4.

A total of 118 boreholes with pumping test data were considered in assessing the influence of topographical elevation in the borehole yields within the study area.

Table 4-4: Borehole distribution in different elevations within the study area

Surface Elevation ranges	Number of boreholes tested	Borehole depths in mbgl			Borehole Yield in L/s			Water level mbgl		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Flatland (<800 mamsl)	33	10.6	141	65.3	0.1	4.0	0.7	1.5	21.4	8.0
Slope	62	16.4	181	60.7	0.1	6.0	0.6	0.0	58.0	11

Surface Elevation ranges	**Number of boreholes tested**	**Borehole depths in mbgl**			**Borehole Yield in L/s**			**Water level mbgl**		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
(800 - 1 000 mamsl)										
Mountainous (> 1 000 mamsl)	23	6.1	108	53.7	0.0	4.4	0.6	1.5	25.5	9.4

Most of the boreholes drilled (53%) within the study area are situated in areas classified in this study as slope, with elevation between 800 and 1 000 mamsl, while only 19% of the boreholes are located on mountainous areas (> 1 000 mamsl). A total of 28% of boreholes drilled in the area are located in the flatland, elevation below 800 mamsl (Figure 4-14). Topographic setting of the area and the elevation has been reported to have important influence on the depth of the borehole. The statistical (maximum, minimum and average) borehole depths in different elevations within the study area are shown in Figure 4-15. The deepest boreholes were drilled in the slope and flatland areas compared to the mountainous areas.

Most of the boreholes within the study area were reported to have been drilled to a minimum depth of 30 mbgl during the drought relief programmes. The shallow boreholes (< 30 mbgl) within the study area were assumed to have collapsed. Therefore the measured borehole depths is considered not the ŕealôborehole drilling depths.

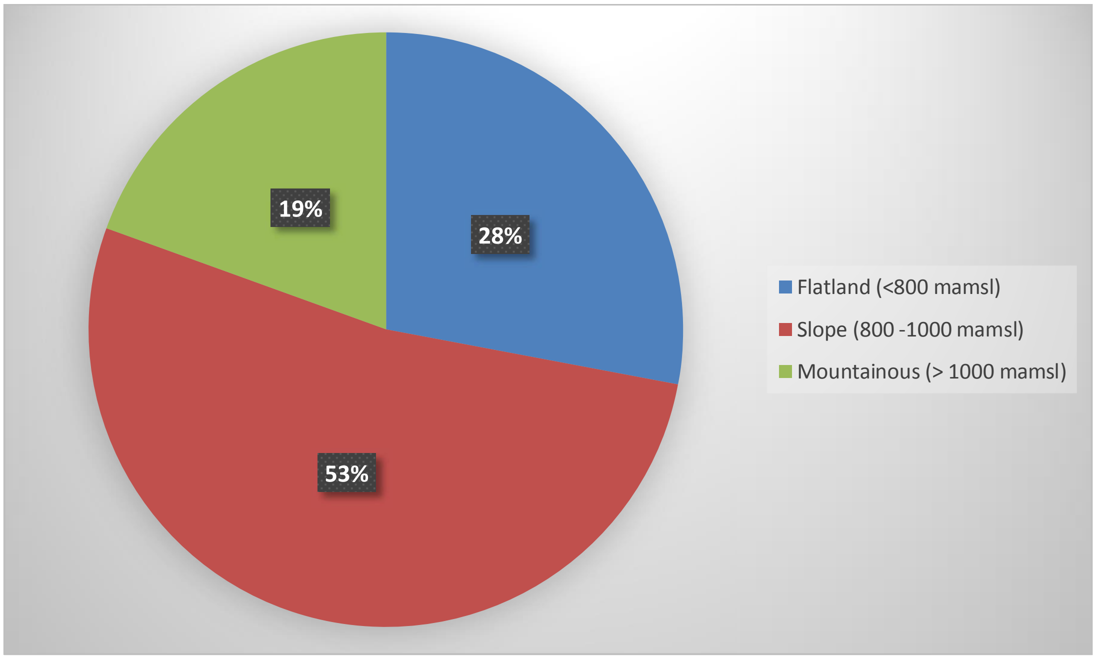


Figure 4-14: Borehole distribution in different elevations within the study area.

The average borehole depths in slope and flatland (60.7 and 65.3 mbgl) areas are deeper than the average borehole depth (53.7 mbgl) in the mountainous areas. The average borehole depths within the study area (Figure 4-15) show a decrease from flatland towards the mountainous areas. The shallowest borehole, 6.1 mbgl, within the study area was reported in the mountainous area.

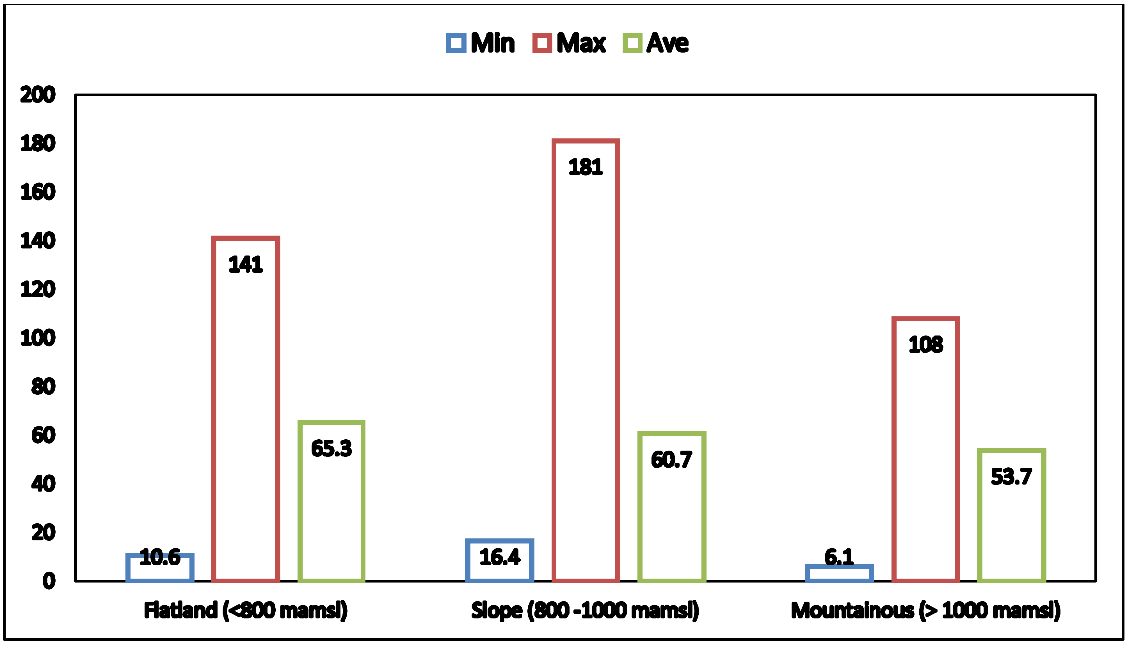


Figure 4-15: Statistical borehole depths (mbgl) in different elevations within the study area.

The statistical borehole yields in different elevations within the study area are shown in Figure 4-16.

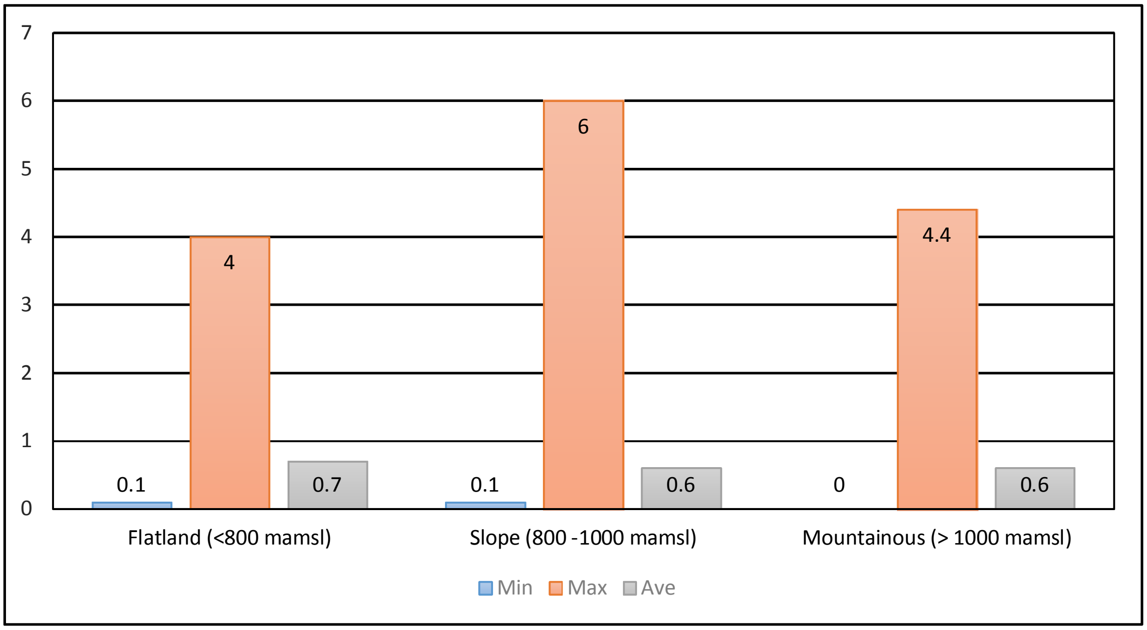


Figure 4-16: Statistical borehole yields (L/s) in different elevations within the study area.

The borehole yields data show that the slope areas supported the most higher yielding (6 l/s) borehole in the area compared to the maximum yields in boreholes located on flatlands and mountainous areas with maximum abstraction yields of 4 and 4.4 l/s, respectively.

The average borehole yields are almost similar, between 0.6 and 0.7 l/s, irrespective of the topographical elevation in which the boreholes are located. The elevation of the borehole seem not to have any serious effects with regard to borehole depth within the study area.

4.4.2 Topographical setting influence

The topographical setting of the boreholes within the study area as well as statistical analysis of yields, water levels and borehole depths are presented in Table 4-5. A total of 120 boreholes with pumping test data were considered in assessing the influence of topographical elevation in the borehole yields within the study area.

Table 4-5: Borehole distribution in different topographical settings within the study area

Topographical settings	**Number of boreholes tested**	**Borehole depths in mbgl**			**Borehole Yield in L/s**			**Water level mbgl**		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Flatland	62	23.7	181	68.5	0.02	3.0	0.5	0.0	58.0	11.8
Valley	36	6.1	115	51.7	0.05	4.0	0.5	1.4	17.7	7.1
Slope	22	10.6	118	54.4	0.05	6.0	0.9	2.5	24.8	9.0

The percentage distribution of boreholes in different topographical settings are shown in Figure 4-17.

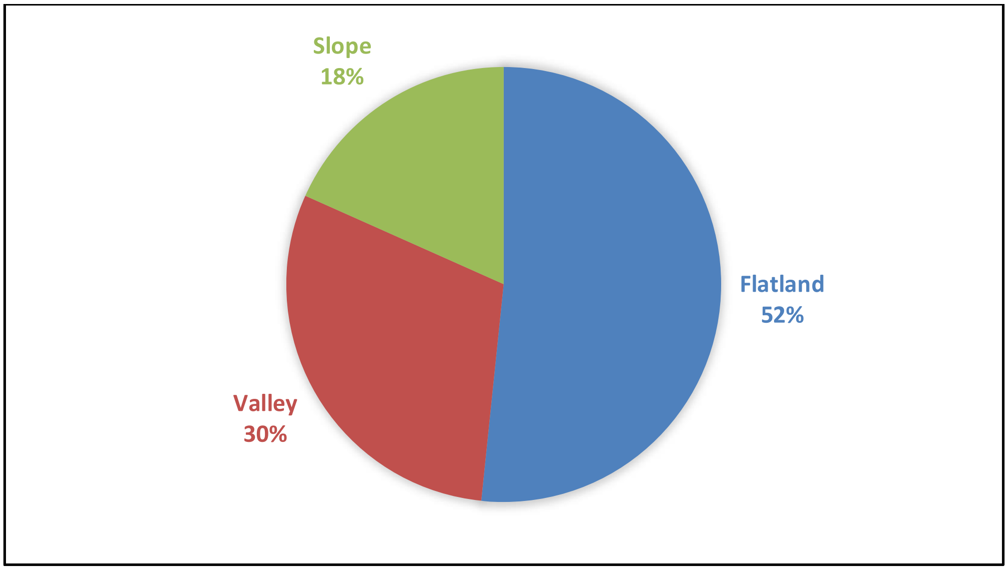


Figure 4-17: Borehole distribution in different topographical settings.

Majority (52%) of boreholes in the study area were drilled in flatland, whereas 18% of the boreholes were drilled in gentle slopes. A total of 30% of the boreholes were drilled within the valleys.

The deepest borehole (181 mbgl) was drilled in the flatland compared to the depth 118 and 115 mbgl in slope and valley areas, respectively. The average borehole depths in these topographical settings show that the shallow boreholes are in valleys (51.7 mbgl) followed by slopes (54.4 mbgl) and then flatland (68 mbgl).

The most high yielding (l/s) borehole was drilled in the slope area with a maximum recommended abstraction rate of 6 l/s, compared to 3 and 4 l/s in flatland and valley areas, respectively (Figure 4-18). The average borehole yields in the valley and flatland is 0.5 l/s, whereas in the slope the average is 0.9 l/s (Figure 4-18).

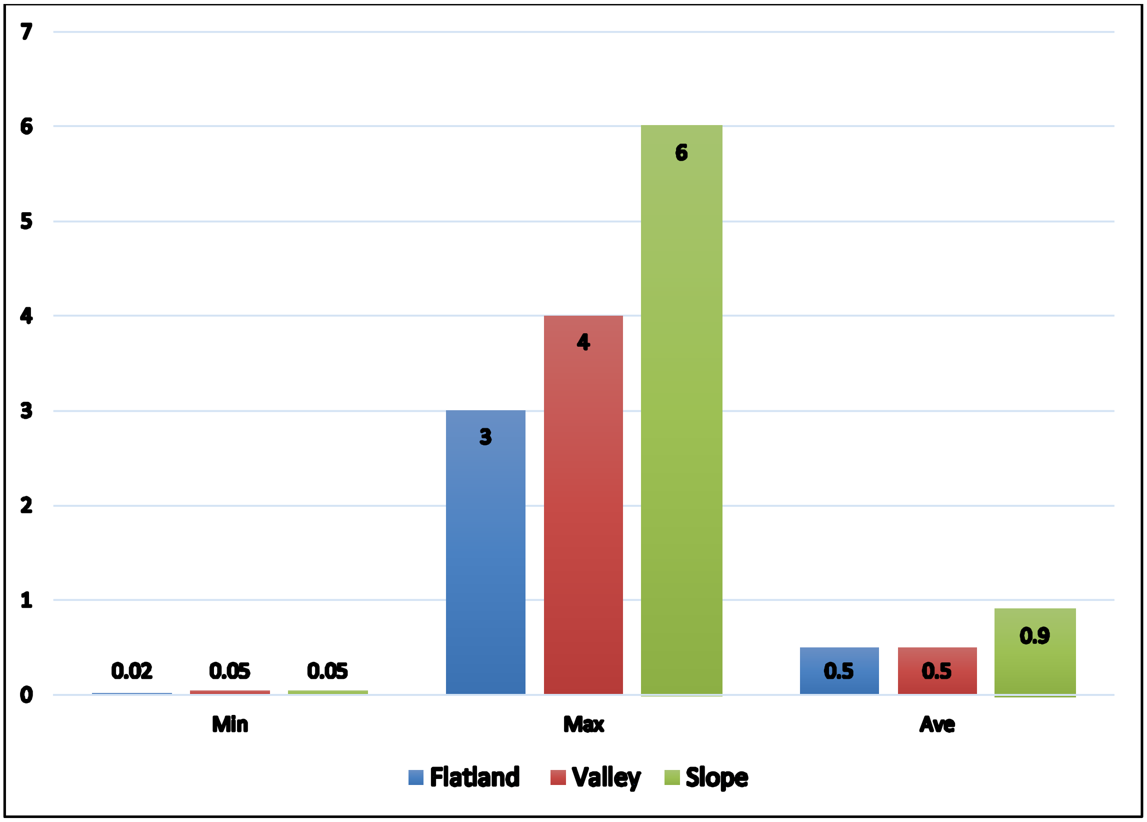


Figure 4-18: Statistical borehole yields in different topographical settings within the area.

4.5 Lineaments influence

4.5.1 Faults and lineaments influence

The statistical analysis of the borehole depth, water level and yields of boreholes drilled closer to faults and lineaments are presented in Table 4-6. A total of 35 boreholes with pumping test data were considered in assessing the influence of faults and lineaments in the boreholes yields within the study area.

Table 4-6: Borehole distribution in different lineaments within the study area

Mapped lineaments	Number of boreholes tested	Borehole depths in mbgl			Borehole Yield in L/s			Water level mbgl		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Fault zone	25	10.5	118	48.7	0.05	2.0	0.43	0.03	18.7	7.44
Lineament	10	6.1	101	50.9	0.05	0.7	0.32	0.25	8.59	4.12

Of these boreholes, 71% were drilled closer to faults compared to 29% of boreholes drilled closer to other lineaments. This is expected given the fact that most of the faults are mapped in geological maps and making them the most targets for siting boreholes. Lineament identification and mapping usually requires remote sensing, scarce skills to most drilling and groundwater developers, therefore they are least targeted in drilling programmes.

The yields (l/s) comparison of boreholes closer to faults and lineaments is shown in Figure 4-19. Boreholes located closer to the faults show a maximum yield which of 2 l/s, which is higher than those located closer to the lineaments (0.7 l/s). While low yielding (0.05 l/s) boreholes were drilled in both faults and lineaments, the average borehole yields in faults (0.43 l/s) is slightly higher than the average yield (0.32 l/s) in lineaments boreholes.

The influence of the real distance (in meters) closer to fault or lineament on boreholes within the mapped area ranged was considered to be insignificant and was not assessed; only the distance range was assessed. The proximity to the faults has proven to be of great importance with regard to borehole yield compared to proximity to other lineaments.

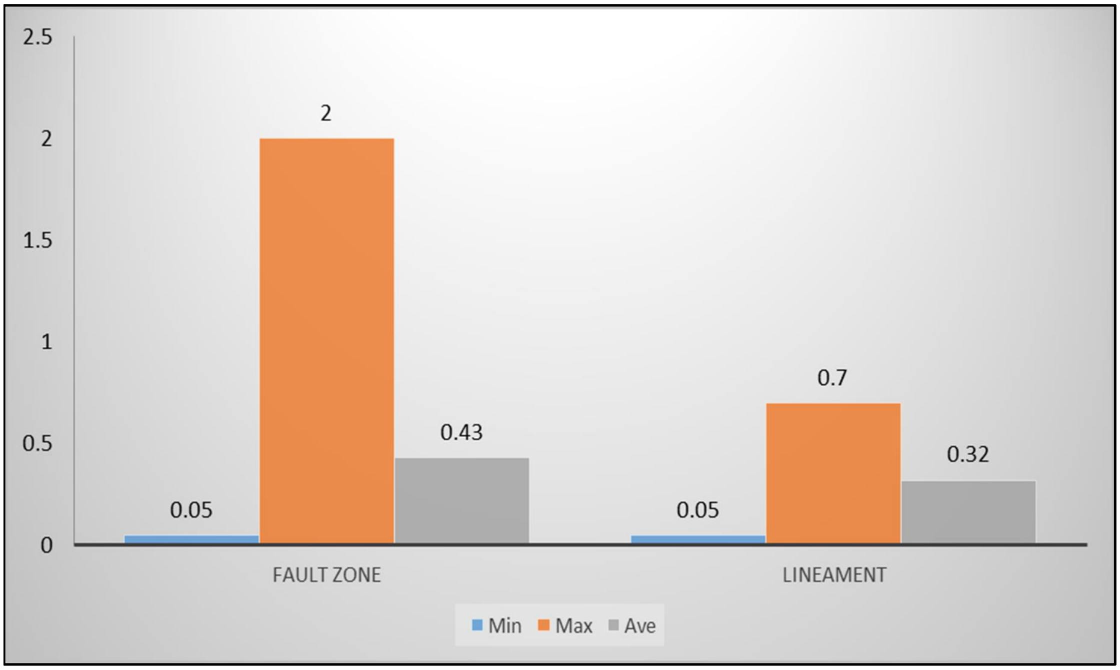


Figure 4-19: Statistical borehole yields (L/s) closer to faults and lineaments.

4.5.2 Orientation influence

The influence of the faults and lineaments orientations on the borehole yields was also assessed. However, the influence of lineaments size, density and degree of intersections were not assessed as part of the study.

The orientation of the faults and mapped lineaments of the area were derived from the published geological maps of Messina (2230), Alldays (2228) and Tzaneen (2330) and the ASTER mapped lineaments by Anke (2008) of topographical maps 2229 DD, 2230 CC and 2230 CD. The orientation of the lineaments in the study area were analysed using rose diagram (Figure 4-20). Even though the rose diagram was not length weighted, it however indicated what the most dominant directions of the lineaments and faults were. The most dominant orientation of the faults and lineaments are northeast ï southwest (NE ï SW), southeast ï northwest (SE ï NW) and west ï east (W ï E).

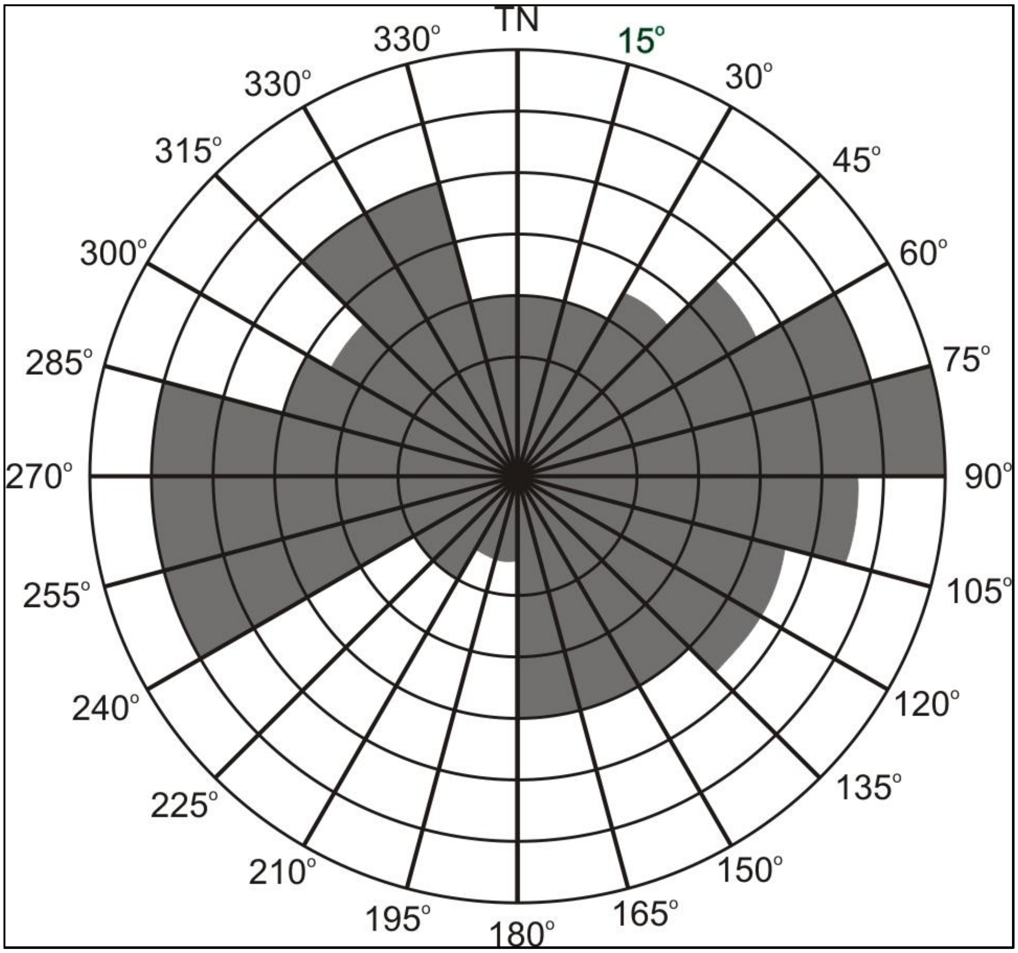


Figure 4-20: Rose diagram of lineaments within the study area.

This analysis is very critical for the study of groundwater flow, as in most cases the orientation of the fractures is identical to the orientation of the preferential groundwater flow path. The statistical analysis of the borehole depth, water level and yields of boreholes drilled closer to lineaments and faults of different orientations are presented in Table 4-7.

Table 4-7: Borehole distribution in lineaments of different orientation within the study area

Lineaments and faults orientation	**Number of boreholes tested**	**Borehole depths in mbgl**			**Borehole Yield in L/s**			**Water level mbgl**		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Fault (NE-SW)	9	10.5	118	51.8	0.05	0.7	0.26	3.89	11.0	7.11
Fault (SE-NW)	10	27.3	66.7	44.3	0.06	2	0.65	0.03	11.3	7.78
Fault (W-E)	6	13.0	90.0	51.4	0.1	0.7	0.3	1.37	18.7	7.37
Lineament (NE-SW)	5	27.8	101	59.8	0.15	0.7	0.41	2.2	6.4	4.01
Lineament (SE-NW)	2	6.1	93.5	49.8	0.05	0.5	0.28	0.25	1.5	0.88
Lineament (W-E)	3	13.0	53	36.9	0.1	0.3	0.20	5.26	8.59	6.47

Lineaments orientation

Majority (50%) of boreholes drilled closer to lineaments were drilled along NE-SW orientated lineaments compared to 30% and 20% of boreholes, which were drilled along W-E and SE-NW, respectively (Figure 4-21).

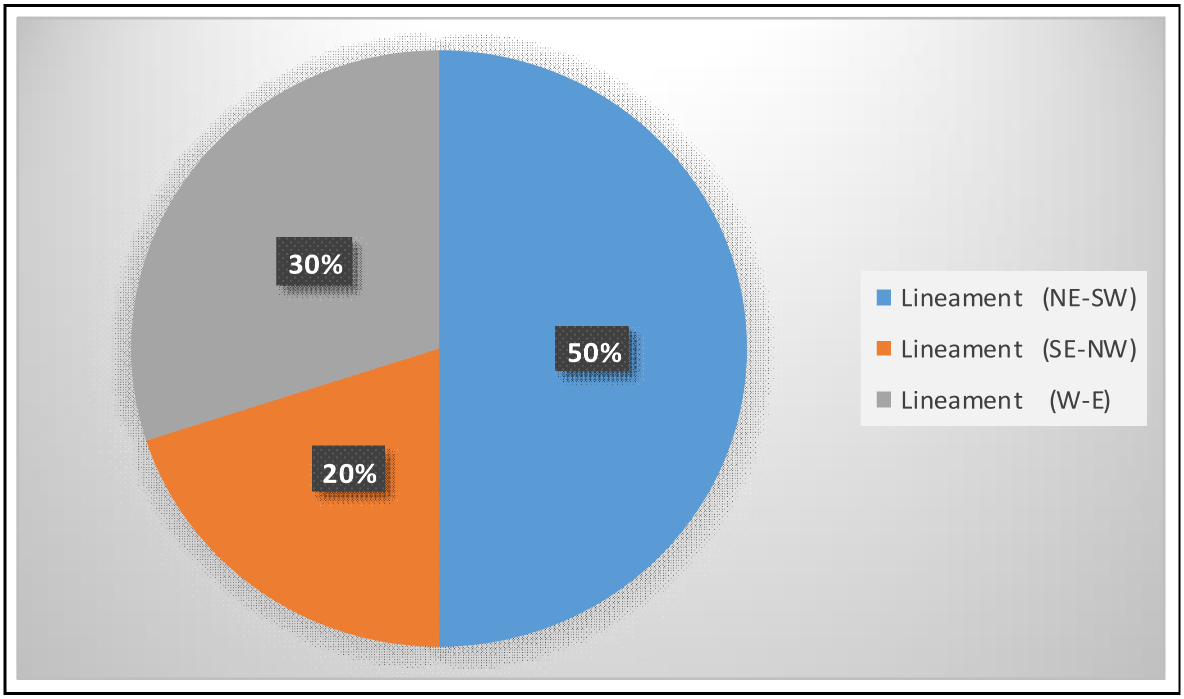


Figure 4-21: Borehole percentage distributions along different lineament orientations.

The depths of boreholes drilled along different orientation of lineaments are shown in Figure 4-22. Shallow boreholes, on average, were drilled along the W-E (36.9 mbgl) orientated lineaments compared to those drilled along SE-NW (49.8 mbgl) and NE-SW (59.8 mbgl) orientated lineaments.

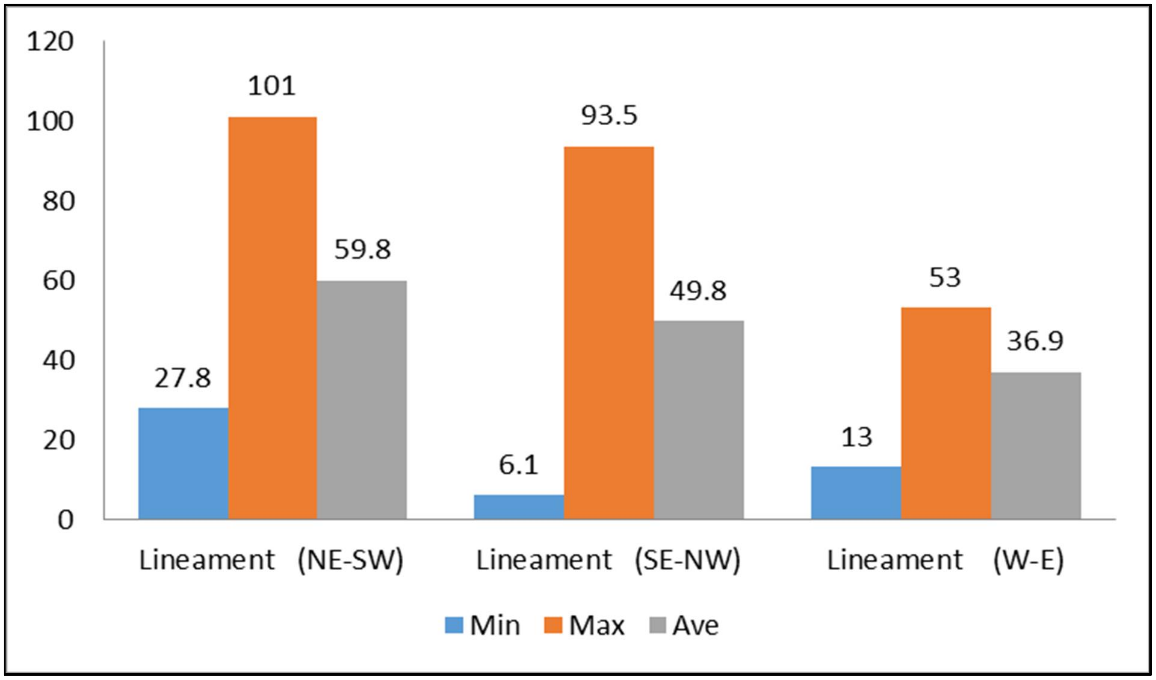


Figure 4-22: Statistical borehole depths (mbgl) along different lineament orientations.

The graphical presentation of the statistical borehole yields along three major lineaments orientations is shown in Figure 4-23.

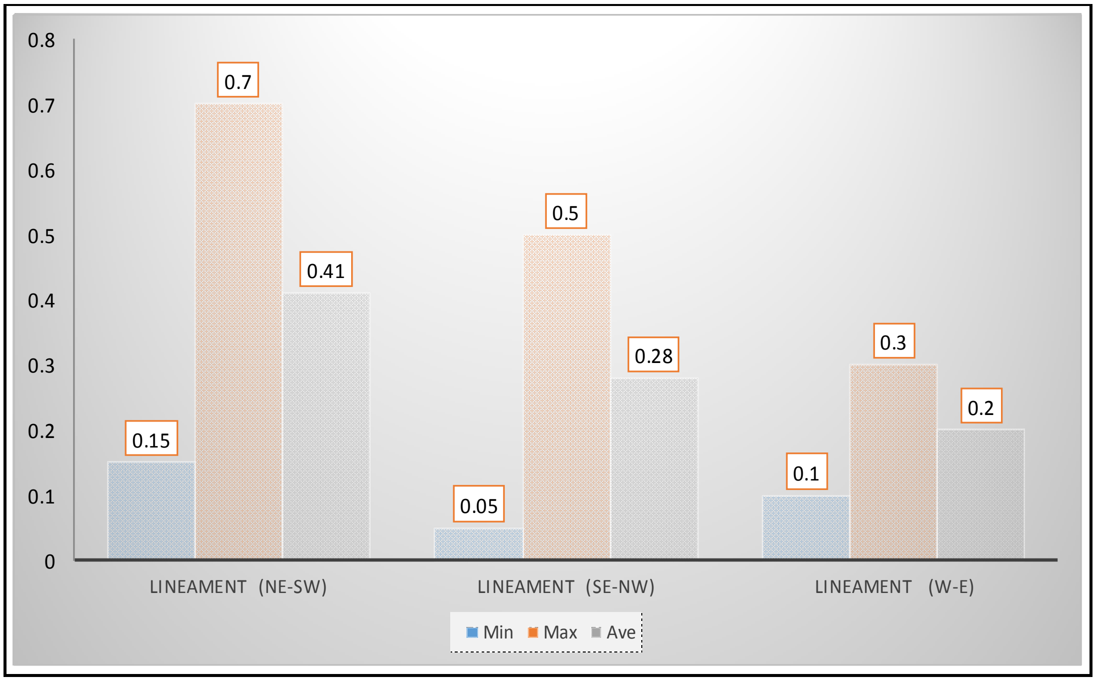


Figure 4-23: Statistical borehole yields (L/s) along different lineament orientations.

The high yielding borehole (maximum) (0.7 L/s) was drilled along NE-SW orientated lineaments compared to boreholes drilled along SE-NW (0.5 L/s) and W-E (0.3 L/s) lineaments. On average, the NE-SW are the most high yielding (0.41 L/s) lineaments, compared to SE-NW (0.28 L/s) and W-E (0.2 L/s) lineaments.

Faults orientation

Most (76%) of the boreholes within the study area were drilled along SE-NW and NE-SW orientated faults (Figure 4-24). Only 24% of the boreholes were drilled along the W-E orientated faults. NE-SW orientated faults are the most dominant fault orientation characterised by older faults, whereas SE-NW and W-E orientated faults are known to be the youngest faults in the area.

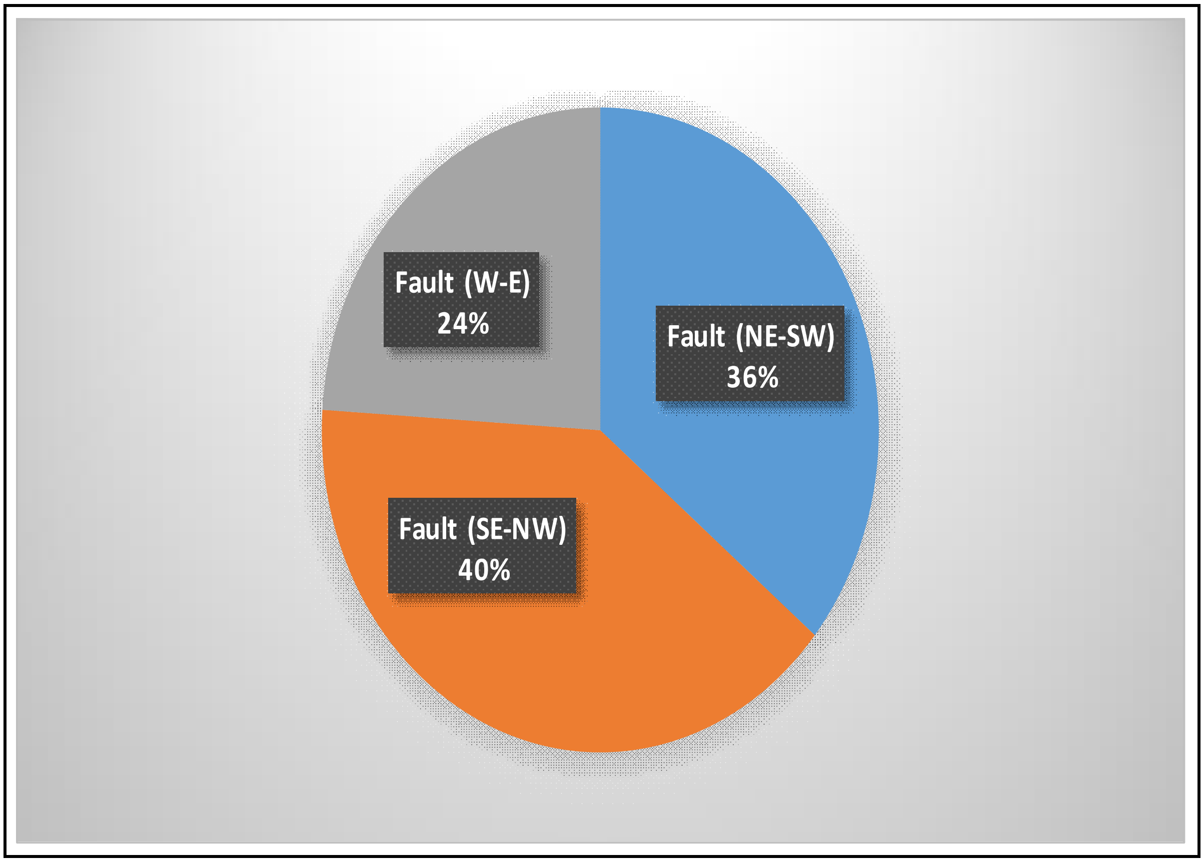


Figure 4-24: Borehole percentage distribution along different fault orientations.

The graphical presentations of the statistical borehole depths (mbgl) along different fault orientations are shown in Figure 4-25. The deepest (118 mbgl) borehole was drilled along NE-SW orientated fault compared to 90 and 66 mbgl in W-E and SE-NW orientated faults, respectively.

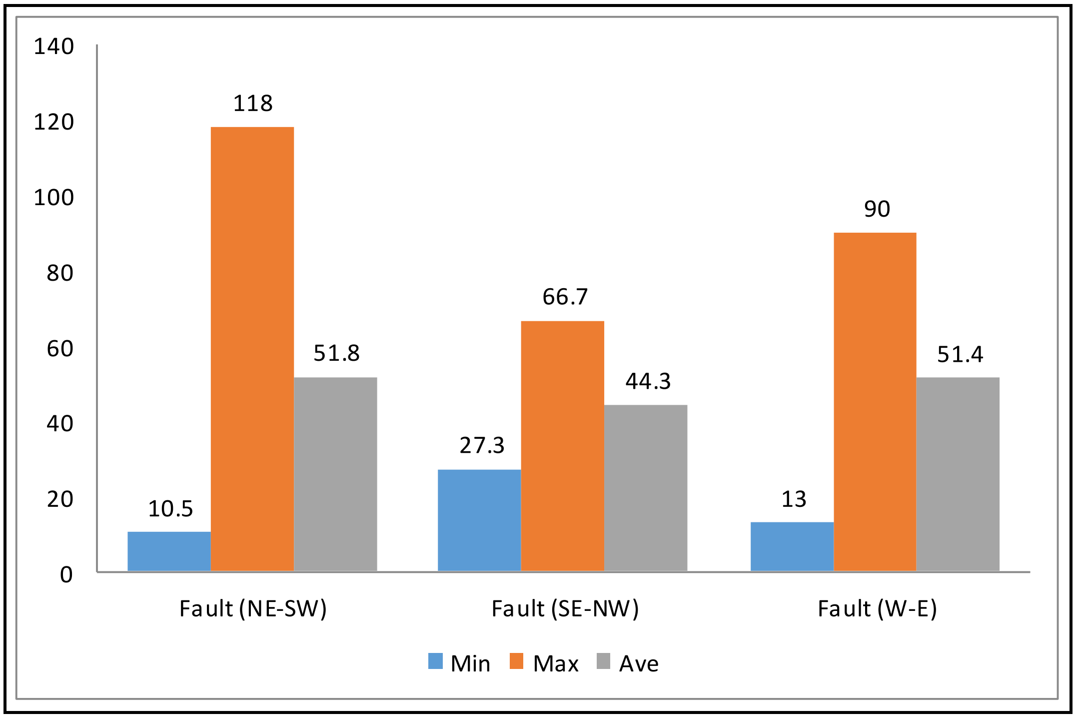


Figure 4-25: Statistical borehole depths (mbgl) along different fault orientations.

The average borehole depths in boreholes drilled along NE-SW and W-E are similar, 51 mbgl, and deeper than the average depths along SE-NW of 44 mbgl.

The statistical borehole yields (l/s) along different fault orientations within the study area are shown in Figure 4-26. The highest yielding borehole within the study area was drilled along the SE-NW (2 l/s) trending fault compared to 0.7 l/s in boreholes drilled along NE-SW and W-E trending faults.

On average, the SE-NW orientated faults are the most (0.65 l/s) high yielding faults compared to W-E (0.3 l/s) and NE-SW (0.26 l/s) orientated faults.

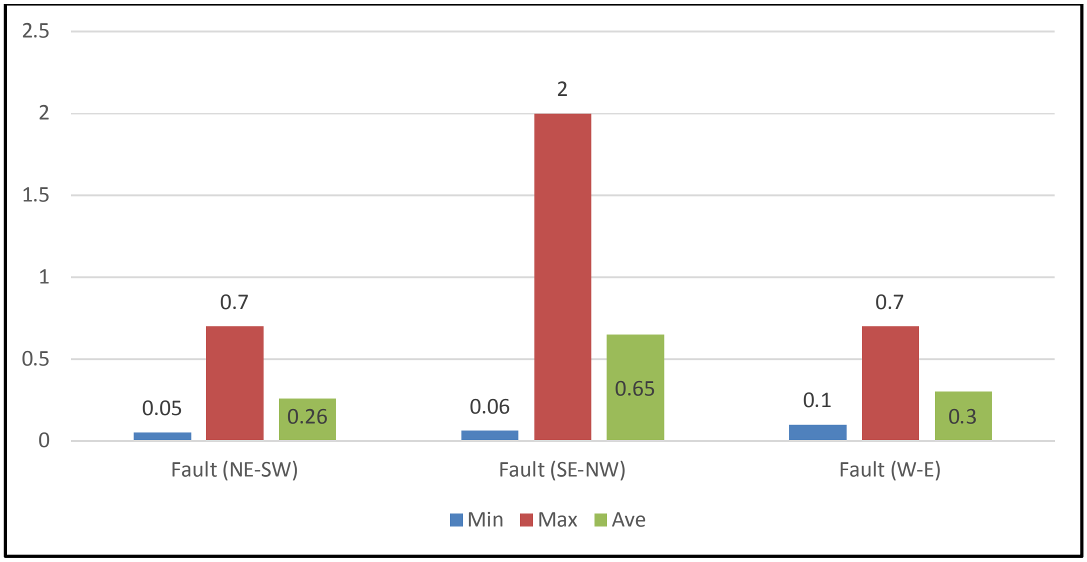


Figure 4-26: Statistical borehole yields (L/s) along different fault orientations.

The NE-SW and W-E orientated faults are considered to be the oldest faults compared to the SE-NW orientated faults which are young. The older faults (NE-SW and W-E orientated) are believed to have been filled up with clay and other materials as well as secondary mineral infilling, reducing the transmissivity, permeability and the groundwater production capacity.

4.6 Drainage influence

The statistical analysis of the borehole depth, water level and yields of boreholes drilled in different drainage environments are presented in Table 4-8. A total of 118 boreholes with pumping test data were considered in assessing the influence of drainage systems in the borehole yields within the study area.

Table 4-8: Borehole distribution in different drainage environments within the study area

Drainage environments	**Number of boreholes tested**	**Borehole depths in mbgl**			**Borehole Yield in L/s**			**Water level mbgl**		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Non-perennial (< 50 m)	40	6.1	115	57.0	0.05	4.4	0.7	1.5	24.8	7.2
Non-perennial (50 - 100 m)	15	13.0	118	51.5	0.05	2.0	0.54	1.4	15.5	6.2
Non-perennial (> 100 m)	50	16.4	181	63.4	0.02	6.0	0.55	0.0	58.0	12.2
Perennial (<50 m)	2	54.1	69.4	61.7	0.2	0.8	0.5	1.5	1.7	9.4
Perennial (50 -100 m)	1	41	41	41	0.7	0.7	0.7	1.4	1.4	1.4
Perennial (> 100 m)	10	30.5	104	60.7	0.05	1.4	0.37	7.4	24.1	13.6

The distribution of boreholes in the identified different drainage settings is shown in Figure 4-27. Half of the (50%) of the boreholes within the study area were drilled closer (within 100 m) to drainage (perennial and non-perennial) systems. Of these boreholes, 5% were drilled closer to perennial rivers and 95% closer to dry channels or non-perennial streams.

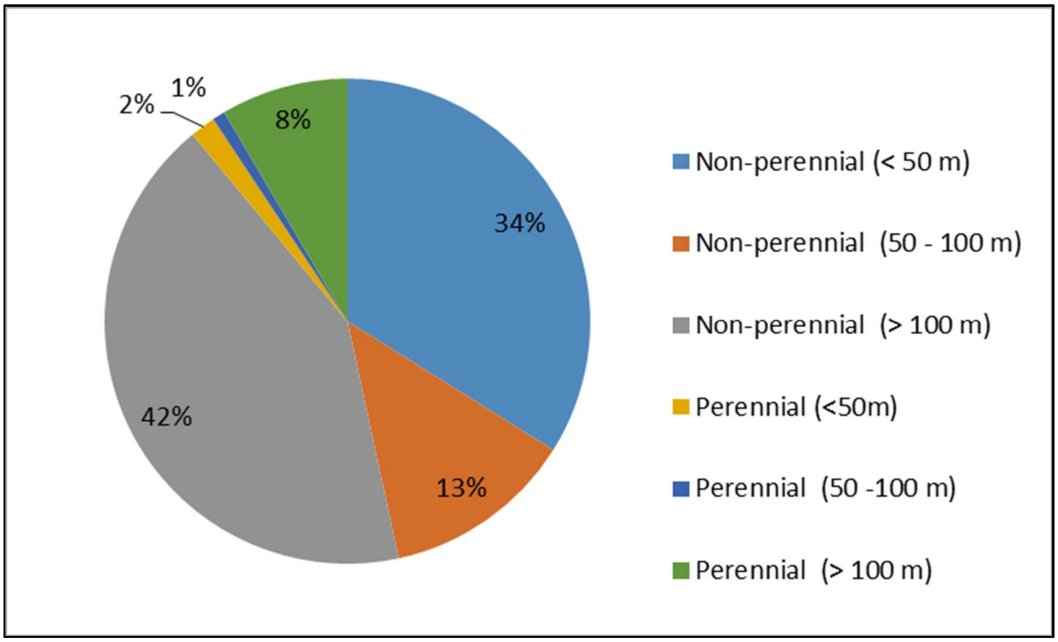


Figure 4-27: Borehole percentage distribution along perennial and non-perennial streams.

Perennial Rivers influence

Very few (3%) boreholes were drilled within 100 m of the perennial streams compared to 47% non-perennial streams. This is expected given the fact that accessibility closer to perennial rivers is always a challenge and these areas are within the floodlines (1:100 years). Only three boreholes were found within the 100 m radius of the perennial rivers and two were within the 50 m zone. A total of 10 boreholes were located closer to perennial rivers but beyond the 100 m radius.

The statistical borehole depths (mbgl) in different distances (radii) from the perennial rivers within the study area are shown in Figure 4-28. The deepest borehole (104 mbgl) was drilled away (>100 m) from the perennial rivers, compared to those drilled within 100 m radius from the perennial rivers, with 41 mbgl (50-100 m) and 69.4 mbgl (< 50 m).

The average borehole depths (mbgl) of boreholes within 50 m radius are almost similar (60.7 and 61.7 mbgl) to those drilled away (>100 m) from the perennial river compared to 41 mbgl of borehole drilled at a distance between 50 and 100 m radius from the perennial rivers.

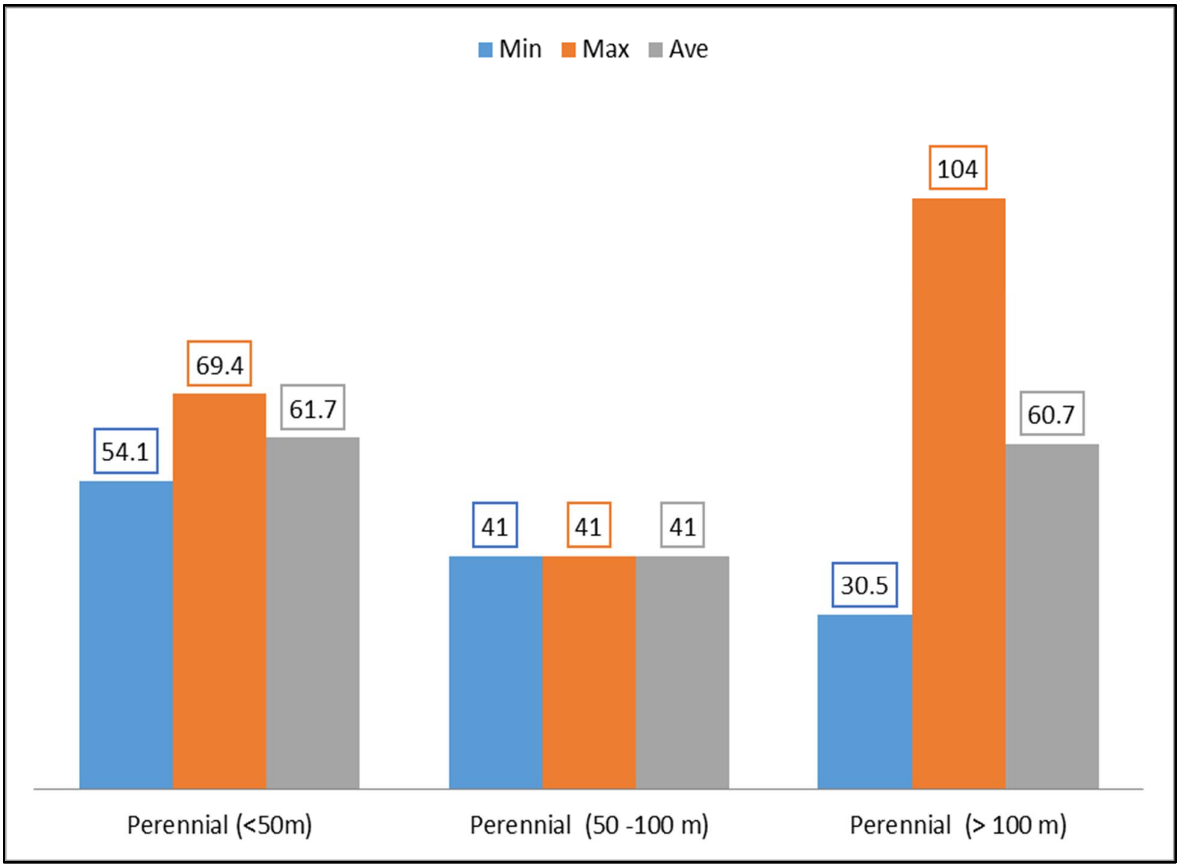


Figure 4-28: Statistical borehole depths (mbgl) in different distances (radii) from the perennial rivers.

The statistical borehole yields (L/s) along different distance zones (radius) from perennial rivers within the study area are shown in Figure 4-29. The results show that the high yielding borehole (1.4 l/s) was drilled away (>100 m) compared to those boreholes drilled within the 100 m radius (0.7 and 0.8 l/s).

However, the average borehole data shows that boreholes in radius between 50 and 100 m are high yielding (0.7 l/s), compared to those located within 50 m radius (0.5 l/s) and those located away (>100 m) from the perennial rivers with average yield of 0.37 l/s.

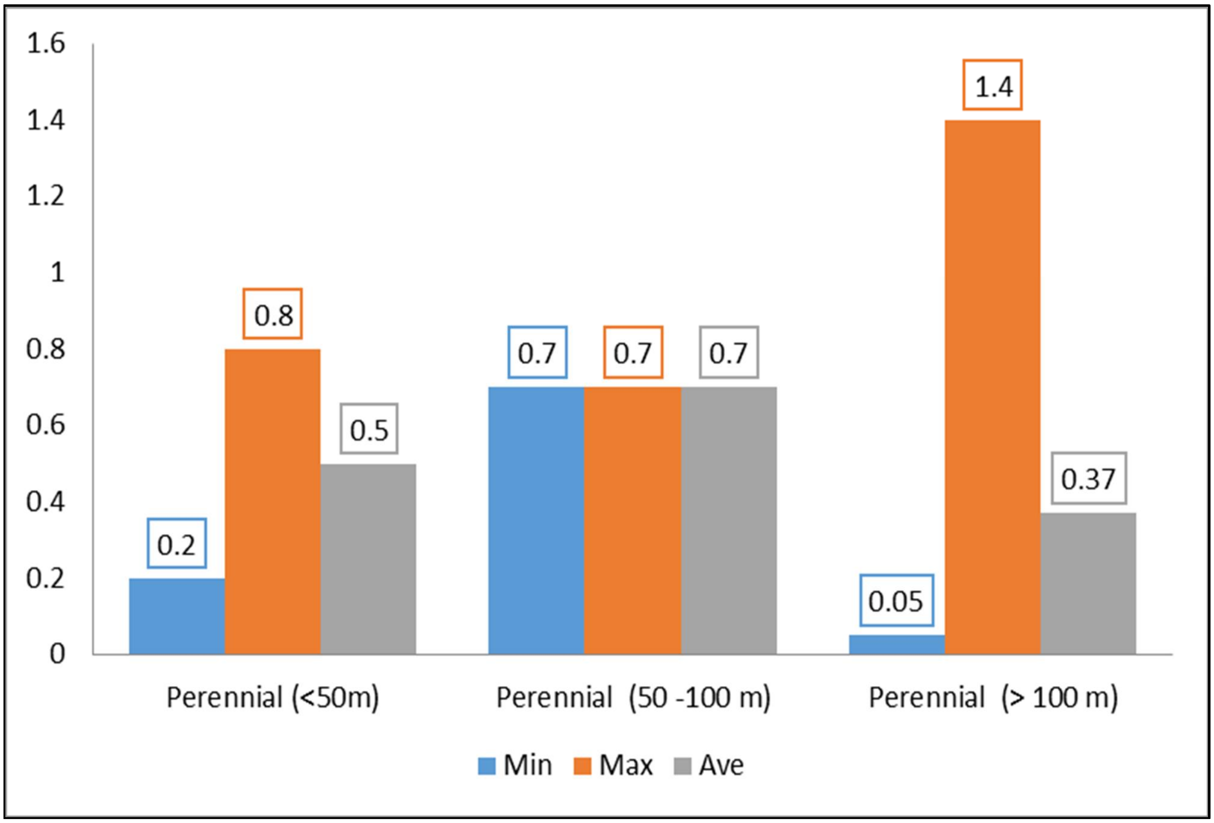


Figure 4-29: Statistical borehole yields (L/s) in different distances (radii) from the perennial rivers.

Non-perennial streams

Of the boreholes located near dry channels, 34% are located within 50 m whereas 13% are located between 50 and 100 m. The statistical borehole depths (mbgl) in different distance (radius) from the non-perennial rivers within the study area are shown in Figure 4-30.

The deepest borehole along the non-perennial boreholes is 181 mbgl and was drilled away (>100 m) from the non-perennial streams. The depths of boreholes drilled within 100 m of the non-perennial streams are almost the same, 115 and 118 mbgl. The average boreholes depths data show that the deepest (63 mbgl) boreholes were drilled away from the non-perennial streams compared to those within 50 and 100 m radius, with average borehole depths of 57 and 51 mbgl, respectively.

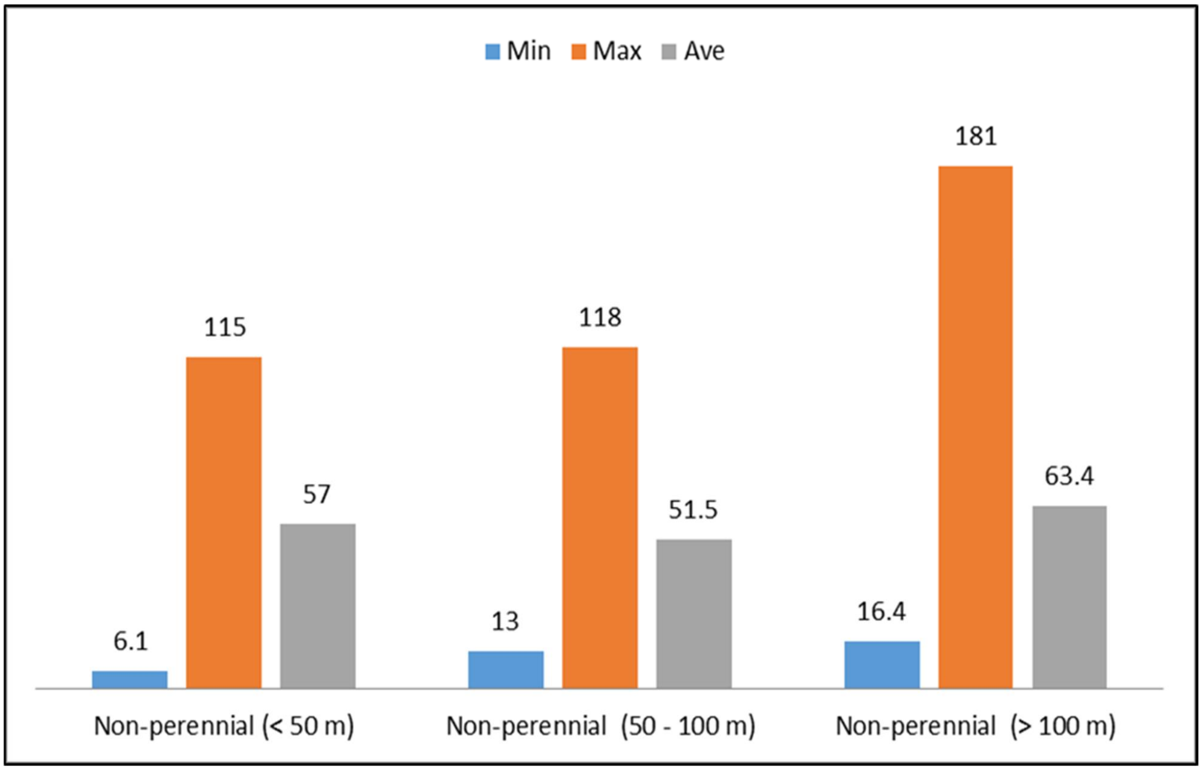


Figure 4-30: Statistical borehole depths (mbgl) in different distances (radii) from the non-perennial streams.

The statistical borehole yields (l/s) along different distance zones (radius) from non-perennial streams within the study area are shown in Figure 4-31. The most high yielding borehole is located away from the non-perennial stream with maximum yield of 6 l/s. Boreholes located within 50 m radius from the non-perennial streams have higher maximum yield (4.4 l/s) compared to those located at a radius of 50-100 m from the non-perennial streams with a maximum yield of 2 l/s.

The boreholes located with 50 m radius of the non-perennial streams are high yielding (0.7 l/s) compared to those located within 50-100 m radius and away (100 m) with average borehole yields of 0.54 and 0.55 l/s, respectively.

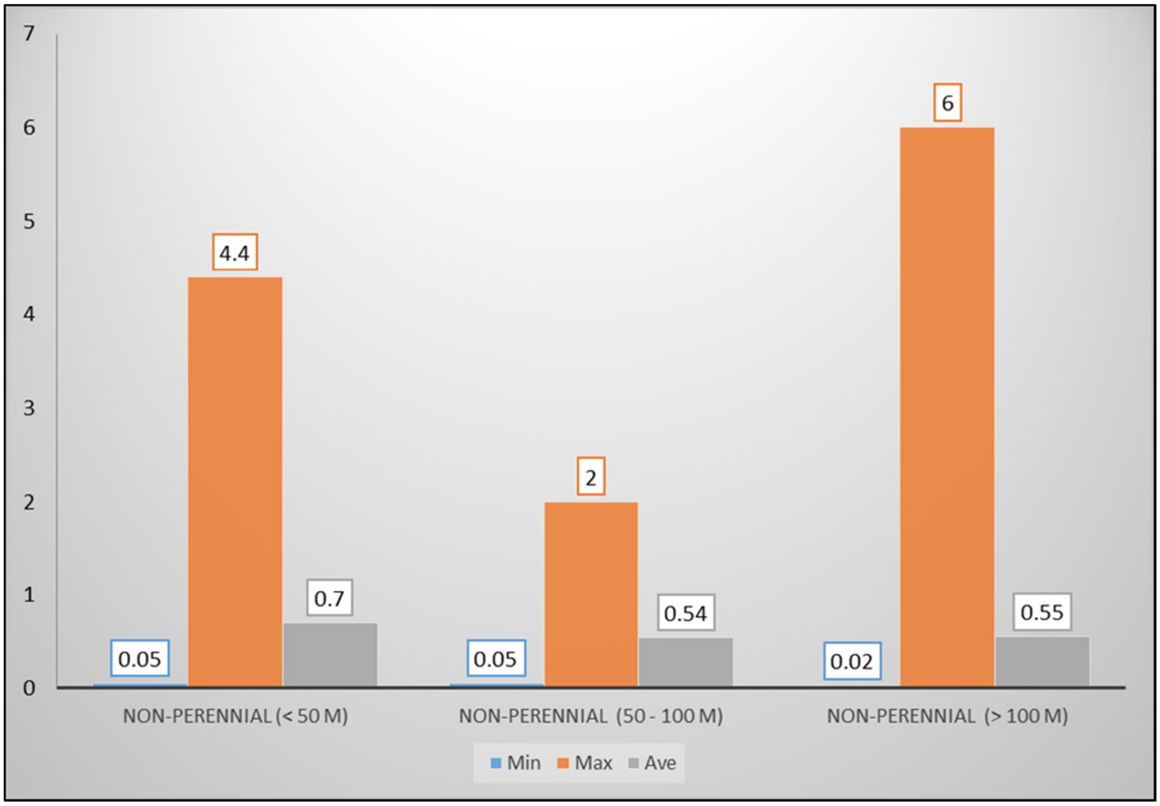


Figure 4-31: Statistical borehole yields (L/s) in different distances (radii) from the non-perennial streams.

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5 Discussion, conclusions and recommendations

5.1 Discussions

The Soutpansberg Group rocks did not attract much scientific attention in the past, since they are almost devoid of any economic mineralisation. However, the existing geological investigations and mapping within and around the study area in trying to understand the geology of the Soutpansberg Group and the structures that affected the group has improved the understanding of the geological and structural settings of the study area. This has enabled the delineation and understanding of different geological formations within the study area.

The area is underlain by five formations of the Soutpansberg Group and quaternary sediments. The formations are comprised of hard rocks and covered the bigger part of the study area, making the area to be classified as hard rock terrain. The hard rocks are known for insufficient primary porosity and conductivity for feasible groundwater extraction. The development of groundwater resource requires thorough scientific approaches, which include thorough understanding of the geology, hydrogeology and structures, which directly or indirectly control the groundwater occurrence and movement.

The understanding of the dynamics of the groundwater resources within hard-rock aquifers in a given area has been seen as necessary and essential steps for assessment or quantification of the groundwater resources in an area. The hydrogeological assessments conducted in the area, in the past, has provided the initial step in understanding the groundwater occurrence within the study area. Even though most of the studies were localised and targeting the development of one or two boreholes for single facility supply, the hydrogeological assessment by Du Toit and Sonnekus (2014) has provided a regional and detailed hydrogeological conditions of the study area, based on the synthesis of the most up-to-date data and hydrogeologists knowledge and understanding of the area. The study by Du Toit and Sonnekus (2014) confirmed the fact that the study area is underlain mostly by fractured hard rock aquifer system with quaternary sediments occupying the low-lying areas next to the rivers.

5.1.1 Existing boreholes

The details of most of the existing boreholes in the area has been captured in the GRIP Limpopo database, which was developed by DWS with an emphasis on groundwater availability and aquifer characteristics assessment. The details of some boreholes in the database (GRIP Limpopo) are not fully populated and the positions of some borehole requires verification because they plot far away from the communities in which they are reported to be in. The hydrocensus in the area provided the groundwater resource baseline conditions and further improved the knowledge regarding the groundwater use in the area.

The borehole distribution in the area followed the settlement pattern within the study area and was largely influenced by the geology and structural settings as well as land use in the area. Most of the settlements are located in flatland and gentle slopes compared to mountainous areas where a few settlements were found. The low-lying areas, especially those closer to perennial rivers (Mutshedzi and Nzhelele) are being used for agricultural purposes and several agricultural irrigations schemes have been developed. Even though the boreholes were drilled closer to the settlements, the distribution of the boreholes within the study area is considered to be good, covering all the geological formations within the study area.

While it is known that borehole installation can be used as a preliminary assessment of the borehole yields, with high yielding boreholes equipped with motorised equipment and low yielding boreholes equipped with hand pumps, this was found not to be true in the current study area. Most of the boreholes in the area were equipped with hand pumps, including those that were found to be high yielding.

In most cases, spring indicate the discharge point of groundwater in an area and some might be associated with major faults or lineaments. Only one spring within the study area was found to be linked to a major fault and other springs are located in perched groundwater systems and are non-perennial.

5.1.2 Yield assessment

Borehole yield assessments also included boreholes that were long abandoned and those that were operational. While the existing information and equipment was used in selecting boreholes for yield assessments, the drilling records and boreholes logs, if present for all boreholes in the area, were going to improve the selection of boreholes for assessment, leading to targeting of high yielding boreholes first.

While transmissivity of the aquifer system measures the rate at which groundwater through the hydrogeologic unit flows, however, the current study focused mainly on the estimated sustainable abstraction rate of each borehole, which was deemed to represent the groundwater potential of the underlying geological formation or nearby structures. In estimating the sustainable abstraction rate, using the FC-Method, the focus was on assessing the relationship between abstraction rate and the drawdown in the borehole. In recommending the abstraction rate, the flow regime was assessed and an average estimated yield on Basic FC, FC Inflection point and Cooper-Jacob was considered the most appropriate abstraction yield. The theoretical inflow, which is an added aspect in the FC-Method, was used as a guide in recommending the final sustainable abstraction rate in a borehole.

The recommended sustainable abstraction rates per day from the tested boreholes are extremely lower compared to the CRDT abstraction values. This is due to fact that the FC-Method sustainable yield calculation is conservative and excludes groundwater recharge of the system for a period of two years. This practice is recommended given the low recharge in the area.

The combined recommended sustainable abstraction daily rate of the tested boreholes is estimated at around 6 ML/day. However, it should be noted that 60% of the tested boreholes are recommended for abstraction below 0.5 L/s and these boreholes are not suitable for motorised abstractions. The recommended abstraction rates from the tested boreholes are skewed towards the low yield with 69% (Figure 4-10) of boreholes in the area being very low yielding (0 ï 0.5 l/s). This is expected given the fact that the study area is mostly underlain by hard rock with limited permeability. The other fact is that most of the boreholes in the area were not scientifically sited.

This results obtained in this study (borehole yields skewed towards low yields) is in agreement with the findings by several authors (Davis and DeWiest, 1966; Cederstrom, 1972; Rohr-Torp, 1987; Banks *et al*., 1992, 1994, 2005, Kaehler and Hsieh,1994; Henriksen 2003) who indicated that the skewness in borehole sustainable yield distribution is common in hard rock terrains.

However, the general assessment of the existing groundwater schemes in health and education facilities as well as the continuous use of groundwater resources in households within the study area is an indication that the aquifer systems underlying the study area are capacious enough to augment the bulk water supply system in the Nzhelele Makhado area. The use of scientific methods and approaches in the development of high yielding and sustainable groundwater sources will be key.

5.1.3 Geology

Most (48%) of the boreholes in the area were drilled into the Nzhelele formation. Nzhelele formation and the Quaternary sediments occupy the low lying areas of the study area whereas other formations, WylliesPoort, Fundudzi and Sibasa formations, occupy the mountainous areas. The Quaternary sediments occupy areas along the Nzhelele and Mutshedzi rivers and these areas have been reserved for agricultural practices and very limited boreholes were drilled in these areas. Most of the settlements are in the Nzhelele valley which is mostly underlined by the Nzhelele formation. Therefore, the siting or drilling of boreholes in the Nzhelele formations is more related to settlement distribution as opposed to any hydrogeological basis.

Different formations are known to be affected by secondary processes differently resulting in different permeabilities of the underlying formations. Depending on the effects of secondary processes, some formations tend to be affected more than others creating a thick layer of the weathered zone with a potential to support high yielding boreholes.

The secondary process in the Fundudzi, WylliesPoort and Nzhelele formations has resulted in fractured aquifer systems whereas in the Sibasa formations a thick layer of clay zone was developed. The average borehole yields in Fundudzi (0.83 l/s) and Nzhelele (0.51 l/s) formations are higher than the average yields of WylliesPoort (0.2 l/s) and Sibasa (0.31 l/s) formations, indicating the effect of the developed fractured aquifers systems in Fundudzi and Nzhelele as compared to the intergranular and fractured system that developed at

Sibasa formations. The low yield in WylliesPoort formation is due to poor location of drilling positions.

The reason for low yield in the intergranular and fractured system of the Sibasa formation is because the weathered zone is mostly clay reducing the vertical recharge of the underlying fracture zone. While Mabee (1999) found that there is a good correlation between the thickness of the weathered zone and the yield of the boreholes, the current study found the contrary in the Sibasa formation. Holland and Witthüser (2009, 2011) stated that the thickness of weathering does not appear to be a major controlling factor on a regional scale, especially in areas of high borehole productivity. According to Poth (1968) and Henry (1992), the depth (thickness) of weathering does not affect the borehole yield, but the weathered zone is an important storage óreservoirô.

The common hydrogeological view point as presented by Holland (2011) is that a deeper weathering profile would be a major controlling factor on the borehole yield due to the enhanced permeability and storage of the weathered zone. However, he further indicated that in semi-arid environment the weathered zones are characterised by thin regolith (with less important water strikes) overlying the fracture aquifer where the main water bearing fractures are encountered.

The average borehole yield in the Quaternary sediments within the study is 0.52 l/s and is similar to the average yield of Nzhelele formation (0.51 l/s) and lower than that of Fundudzi formation (0.83 l/s). This average yield is considered very low given the fact that some of the studies show that Quaternary sediments support high yielding boreholes and increase the transmissivity around the borehole (Krásný, 2002). The low average yield in boreholes drilled through these sediments (Quaternary) within the study area is due to the fact that most of the drilled boreholes were completed within the sediments without reaching the end of the sediment profile, penetrating a very thin layer of the sediments. The findings of this study is in agreement with several studies (Olsson, 1980; Allen and Davidson, 1982) that found a link between the sediments thickness and the yield of boreholes. However, the findings of this study is contrary to the findings by Tennakoon (1990) and Lewis (1990) who found a negative correlation between the thickness of overburden and yield of the boreholes.

The overall thickness of the Quaternary sediments within the study area is not known and the average yield of 0.52 l/s cannot be considered to be the true reflection of the production capacity of Quaternary sediments in the area. Deeper boreholes are required to explore the extent and hydrogeological conditions of these Quaternary sediments.

The difference in lithology of different formations within the study area seems not to have any major influence in the yield of boreholes given the fact that the difference in average yields of different formations (Fundudzi, 0.83 l/s; Nzhelele, 0.51 l/s; Wylliespoort, 0.2 l/s; Sibasa, 0.31 l/s; and Quaternary sediments, 0.53 l/s) is very low. This was also confirmed by the yield potential assessments from previous studies (Du Toit and Sonnekus, 2014; Barnard, 2000), which classified all the lithologies underlying the study area as UNESCO Code a3, b3 and d3, with a borehole yield potential ranging between 0.5 and 2.0 l/s, even though the formations are different. Therefore, lithological difference between hard rock formations and sediments in Makhado-Nzhelele area may be considered insignificant from borehole yield point of view. However, it appears to be possible to drill very low and very high yielding boreholes in both hard rock formations and sediments within the study area.

5.1.4 Topography

As indicated in the previous sections of this document, the borehole distribution within the study area follows the settlement pattern, which was highly influenced by the topographical elevations. The surface elevation has important influence on borehole depths and yields in most cases. Boreholes situated on hilltops are usually very deep and low yielding compared to boreholes in flatlands which are shallow and high yielding. Mäkelä (2012) found that borehole yields decrease as one moves from valleys to hilltops.

The average borehole depth in the study area decreases from flatland (65.3 mbgl) to mountainous areas or hilltops (53.7 mbgl) and this is contrary to the findings by Mäkelä (2012). The average shallow boreholes are located in the hilltops. The average borehole yields in different elevations is almost similar (0.6 and 0.7 l/) suggesting that the surface elevation has no major influence in the borehole yields and this is contrary to the findings by Mäkelä (2012) and Holland (2011). The shallow borehole depth and good yielding boreholes in hilltops within the study area is an indication that there are local groundwater systems that recharges and discharges locally and the boreholes were drilled into these systems.

The presence of boreholes in large percentage in flatland compared to valleys and slopes has more to do with settlements distribution as opposed to any scientific reasons. The depths of boreholes in the area show no correlation with the topography, deepest borehole (181 mbgl) was drilled in the flatland compare to the depth 118 and 115 mbgl in slope and valley areas, respectively. This is contrary to the findings by Mäkelä (2012) who indicated that topographical setting has an important influence in the borehole depths and the deepest boreholes are situated in hilltops, followed by those in slopes and shallow are located in flatlands and valleys.

The average borehole yields is high (0.9 l/s) in the boreholes located in slope areas as compared to those in valleys (0.5 l/s) and flatland (0.5 l/s), and this is contrary to the findings by Mäkelä (2012) in Central Finland. Mäkelä (2012) found that borehole yields decrease as one moves from valleys to hilltops.

The current study found no correlation between borehole yields, borehole depths and different topographical settings and these findings are concordant with Owen *et al*. (2003) who found no significant correlation between borehole yields and the macro-scale topography in crystalline basement aquifers of southern Zimbabwe. Some authors (e.g. Lattman and Parizek, 1964; Cederstrom, 1972; Yin and Brook, 1992a, 1992b; Knopman and Hollyday, 1993) regard topography (statistically) as a minor feature affecting the borehole yield.

5.1.5 Lineaments

Because the geological maps are readily available compared to satellite imagery which shows the mapped lineaments, most of the boreholes were drilled targeting the mapped faults compared to mapped lineaments. High yielding boreholes (2 l/s maximum yield) were drilled closer to faults compared to mapped lineaments (0.7 l/s maximum yield), however, the average borehole yield near lineaments and faults are almost similar, 0.32 and 0.43 l/s, respectively. The findings of this study is similar to the findings by Astier and Paterson (1989) as well as Mabee (1992) who found that the proximity to a fault increases the borehole yields. Holland (2011) concluded that the proximity of the lineaments plays a role in borehole productivity and the intensity of fracturing decrease with increase in distance away from the lineament.

The orientation of the lineaments and faults are known to have influence on the yield of the boreholes. The study found that the average borehole yields drilled along the SE-NW (0.65 l/s) trending faults are double the average of those along NE-SW (0.26 l/s) and W-E (0.3 l/s) trending faults. The SE-NW trending faults are younger and characterised by deep reaching fracture zones which are acting as a zone of preferential flow. The NE-SW are older and believed to have been filled with secondary minerals and impermeable materials reducing the permeability of the fault core zones and affecting the overall borehole yields along these faults. This phenomenon was also suggested by Mäkelä (2012) while assessing the reasons of low yields along lineaments boreholes.

In lineaments, boreholes drilled along the NE-SW trending lineaments support double the yields (0.41 l/s) on average of those along the SE-NW (0.28 l/s) and W-E (0.20 l/s) trending lineaments. The results of the current study show that borehole productivities area is in fact associated with lineaments perpendicular to the current stress regime, more specifically ENE to E. The findings of the current study is similar to the findings by Holland (2011) is his assessment of factors influencing transmissivity in fractured hard rock aquifers of the Limpopo province. This was also noted by the case studies on the Limpopo Mobile Belt by Sami at al. (2002), where lineaments orientated ENE-WSW were regarded as the most favourable hydrogeological features.

This is contrary to the general expectation (as explained by Holland, 2011) given the fact that the borehole influenced by NW-SE (presumed to be under dilation and shear stress caused by the NW-SE maximum horizontal stress direction) should have higher yields than associated with lineaments striking perpendicular to that direction. The possible explanation of high yields in boreholes associated with the NE-SW trending lineaments as explained by Holland (2011) may be a localised compressive stress regime which is inconsistent with the regional maximum horizontal stress regime (NW-SE) as determined by Bird *et al* (2006).

Holland (2011) concluded that it could be generally accepted that lineaments have a positive influence on borehole productivity in Soutpansberg region which includes the current study area. However it can be generally stated that the existence of high yielding boreholes away from the influence of fault and lineaments within the study area could be due to high permeable zones that were not detected in the lineament and geological mapping. These high permeable structures might have gentle dipping structures or less horizontal zones of weakness or fractures that control the flow of groundwater within a certain depth.

5.1.6 Drainage

Drainage system in hard rock terrains represent weak zone or fractured zone which in turn becomes the groundwater flow preferential areas. Valleys and dry streams are seen as good groundwater potential areas. However, due to accessibility by the drill rig most valleys and drainage systems areas are over looked when siting boreholes. This is a similar case in Nzhelele-Makhado area too and as a result; most of the boreholes considered for the assessment were drilled away from any stream or rivers to ease access by the drilling equipments.

Only three boreholes were drilled within 100 m of the perennial rivers compared to 55 boreholes which were drilled within the 100 m radius of the non-perennial streams. This was expected given the fact that no construction or infrastructure should be constructed or developed within 1:100 years floodline or 100 m from the rivers.

Boreholes drilled within 50 m radius of the non-perennial stream supports high yielding borehole (maximum yield of 4.4 l/s) compared to maximum yield (0.8 l/s) in boreholes drilled within 50 m radius of the perennial rivers. This is expected given the fact that non-perennial or dry channels are comprised of thick layer of overburden and therefore support high yielding boreholes. The overburden or sediments along the perennial rivers are washed away during rainy season and floods leaving bedrock exposed or covered with a very thin layer of sediments. As a result, most of the boreholes located along perennial rivers are low yielding because they are located in intact bedrock.

The results of the current study show that the boreholes drilled away (100 m) from the drainage systems (non-perennial) support high yielding boreholes (maximum yield of 6 l/s) compared to those in the vicinity (within 50 m radius) of the non-perennial streams (4.4 l/s). The difference in average yields of boreholes located away (> 100 m); closer (50 ï 100 m) and within (< 50 m) of the perennial and non-perennial streams is very little and insignificant. The results (average yield of the assessed boreholes) of the current study suggests that drainage systems have minor influence on the yield of the drilled boreholes and this is in agreement with the finding by Rosenberry and Winter (1993) and Mabee (1999). The findings of the current study is contrary to the findings by Tam *et al.* (2004) in Vietnam who found that the closer the boreholes to the water course the higher is their specific capacity.

5.2 Conclusions

The investigation of factors that influence the yields of the drilled boreholes in Nzheleleï Makhado area was a culmination of integrating the geological and hydrogeological evidence within and around the study area. The extensive geological and hydrogeological work completed in previous studies conducted within and around the study area helped in understanding the geological and hydrogeological settings of the area, and further improved the understanding and knowledge with regard to potential and borehole yields within the study area. Based on assessment and findings of the current study, the following conclusions were made:

- The study area is underlain by the ôhard rockô formations (Fundudzi, Nzhelele, WylliesPoort and Sibasa), of the Soutpansberg Group, as well as the Quaternary sediments. The hard rock formations practically have no primary porosity and unweathered and un-fractured rocks of these formations are virtually impermeable. The unweathered and un-fractured rocks of different formations in the study area are virtually impermeable and seems not to have any major influence in the yield of boreholes. The secondary processes such as weathering and fracturing have improved the permeabilities of the underlying formations throughout the area creating fractured aquifer systems in other formations and intergranular aquifer systems capable of supporting both low and high yielding boreholes.
- The groundwater in the area is residing mainly within the weathered and fractured or discontinuities, considered being secondary porosities. The underlying aquifer systems in the area are capable of supporting borehole yields between 0.5 and 2.0 l/s. However, the boreholes yields potential of the Sibasa hydrostratigraphic unit decreases towards the east.
- The hydrocensus in the area provided the baseline groundwater resource conditions and further improved the knowledge regarding the groundwater use in the area. The borehole distribution in the area followed settlement pattern which was largely influenced by the geology and structural settings as well as land use in the area. Even though the boreholes were drilled closer to the settlements, the distribution of the boreholes within the study area is considered to be good, covering all the geological formations within the study area.
- The dominance of very low yielding boreholes in the area is due to limited permeability of the hard rock formations which underlain most of the study area. The fact that most of the drilled boreholes were not scientifically sited also contributed to the dominance of very low yields in boreholes within the study area.
- A combined estimated abstraction volume of 6 ML/day can be abstracted from the existing tested boreholes within Makhado-Nzhelele area. However, it should be noted that 60 % of the tested boreholes are recommended for abstraction below 0.5 L/s and might not be suitable for motorised abstractions.
- The existence of sustainable groundwater schemes in health and education facilities as well as the continuous use of groundwater resources in households within the study area is an indication that the aquifer systems underlying the study area are capacious enough to augment the bulk water supply system. However, the use of scientific methods and approaches will be key in the siting and development of high yielding and sustainable groundwater sources within the study area.
- The presence of most boreholes in Nzhelele formation is due to the formationôs locality, occupies the central part of the study area and Nzhelele valley, and not geological or

hydrogeological basis. The limited number of boreholes drilled into the Quaternary sediments is due to agricultural practices which targeted these sediments.

- The secondary processes in the Fundudzi, WylliesPoort and Nzhelele formations have resulted in fractured aquifer systems whereas in the Sibasa formations a thick layer of clay zone was developed. The developed fractured aquifers systems in Fundudzi and Nzhelele formations are high yielding compared to the intergranular and fractured systems that developed at Sibasa and WylliesPoort formations, respectively. The low yield in WylliesPoort formation is due to poor location of drilling positions, whereas the low yield in Sibasa formation is due to the developed thick layer of clay which reduces the vertical recharge of the underlying fractured system.
- While it is known that Quaternary sediments support high yielding boreholes, the low yields in the sediments within the study area is due to the fact that most of the drilled boreholes were completed within the sediments without reaching the end of the sediment profile, only penetrating a very thin layer of the sediments. The overall thickness of the Quaternary sediments within the study area is not known and the estimated average yield cannot be considered to be the true reflection of the production capacity of Quaternary sediments in the area.
- The difference in lithology of different formations within the study area seems not to have any major influence in the yield of boreholes given the fact that the difference in average yields of different formations and Quaternary sediments is very low. Therefore, lithological difference between hard rock formations and sediments in Makhado-Nzhelele area may be considered insignificant from borehole yield point of view. However, it appears to be possible to drill very low and very high yielding boreholes in both hard rock formations and sediments within the study area.
- The topographical settings of the area do not have any influence in the borehole depth and yields in the area. The high borehole yields in shallow boreholes located in mountainous areas is due to local groundwater systems, which recharges and discharges locally. While it is understood that topographical setting has important influence on borehole depths and yields, with boreholes on hilltops usually being very deep and low yielding compared to boreholes in flatlands, the current study failed to establish any correlation between the borehole yields and different topographical settings of the area.
- Mapped lineaments are low yielding compared to the faults within the study area. The higher yielding boreholes closer to younger faults compared to older once indicate that the older faults have been filled up with fine materials reducing the permeability of these faults. The SE-NW trending faults are younger and characterised by deep reaching fracture zones which are acting as a zone of preferential flow. Boreholes drilled along the NE-SW trending lineaments support double the yields on average of those along the SE-NW and W-E trending lineaments because the boreholes are drilled in lineaments which are perpendicular to the current stress regime. The presence of high yielding

boreholes away from the faults or lineaments is due to high permeable zone that were not detected in the lineament and geological mapping.

- The limited number of boreholes closer to the perennial rivers compared to non-perennial streams is due observation of the 1:100 years floodline requirement which prohibits the development of infrastructures within the 100 m radius of the river. The high yields in boreholes closer to non-perennial stream compared to perennial river is due to the fact that non-perennial streams are comprised of thick layer of overburden capable of supporting high yielding boreholes, whereas the overburden along the perennial rivers are washed away during rainy season leaving bedrock exposed or covered with thin layer of sediments. The difference in average yield in boreholes located closer to drainage systems is low and insignificant indicating that drainage systems have minor influence on the yield of the drilled boreholes.
- The proximity to the young faults trending NW-SE and dry non-perennial streams has proved to be the most favourable areas for development of high yielding boreholes in the study area, compared to lithological difference and topographical settings of the area. However, it should be noted that there are no simple relationships between various factors that control the overall occurrence, movement of groundwater and the yield of the boreholes in the area.
- It can therefore be concluded, as in so many hard rock aquifer system investigations (Holland, 2011; Wright, 1992), that, despite the similarities in some factors that influence borehole productivity on a regional scale such as faults and drainage systems, the complexity of the weathered-fractured aquifer system suggests an over-riding influence of local features, which results in significant variations in yield and response to abstraction.

5.3 Recommendations

Most of the boreholes used in this thesis to assess the groundwater yields were developed during the drought relief and very little, if any, of the geological and hydrogeological information were considered in siting these boreholes. Where geological and hydrogeological information were considered, the focus was on a very small scale and aimed at developing a single borehole for a single facility. It is therefore, recommended that the following studies and programmes should be undertaken within the study area:

- A regional hydrogeological study which involves remote sensing, geological structure mapping, geophysical (airborne and ground) survey, drilling and testing of boreholes as well as assessment of hydraulic parameters of the penetrated aquifer systems. This will enhance the understanding of groundwater resources in different aquifer systems within the study area.
- A hydrogeological investigation to assess the groundwater carrying capacity of the younger fault zones and contact zones between different formations.

- A hydrogeological investigation to assess the hydrogeological conditions of the Quaternary sediments as well as the groundwater carrying capacity. The study should also include mapping of the extent and distribution of the quaternary sediments within the study area.
- Due to the complexity of the fractured or hard rock aquifer system underlying the study area, any groundwater development in the area should be done using scientific methods and approaches. This should include remote sensing, geological and hydrogeological assessment, geological structure mapping, geophysical (ground) survey, drilling and testing of boreholes as well as assessment of hydraulic parameters of the penetrated aquifer systems.

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Appendices

Appendix A: Hydrocensus Data

Summary of the existing groundwater sources in the study area

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshithuthuni	H27-0001	30.19333	-22.87580	Borehole	Handpump
Tshithuthuni	H27-0002	30.19417	-22.87500	Borehole	Mono-type pump
Tshithuthuni	H27-0003	30.19222	-22.87440	Borehole	No equipment
Tshithuthuni	H27-0004	30.1985	-22.87290	Borehole	Handpump
Thonoda Lusidzana	H27-0005	30.20945	-22.86300	Borehole	Handpump
Ha-Manngo	H27-0006	30.16208	-22.88290	Borehole	Handpump
Ha-Manngo	H27-0007	30.16170	-22.88300	Borehole	Handpump
Ha-Makatu	H27-0008	30.16139	-22.86940	Borehole	Handpump
Ha-Mapila	H27-0009	30.04840	-22.91120	Borehole	No equipment
Luvhalani	H27-0010	29.96186	-22.90550	Borehole	No equipment
Luvhalani	H27-0011	29.96013	-22.90250	Borehole	Handpump
Tshikuwi	H27-0012	29.95623	-22.8980	Borehole	Handpump
Tshikuwi	H27-0013	29.95265	-22.90480	Borehole	Handpump
Tshikuwi	H27-0014	29.93887	-22.90120	Borehole	Handpump
Tshikuwi	H27-0015	29.94710	-22.89950	Borehole	Handpump
Matsa A	H27-0016	29.96223	-22.88680	Borehole	Handpump
Manyii	H27-0017	29.94510	-22.86820	Borehole	No equipment
Manyii	H27-0018	29.94270	-22.86540	Borehole	Handpump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Mamvuka	H27-0019	29.92408	-22.86110	Borehole	Handpump
Ha-Mphaila	H27-0020	30.15194	-22.89800	Borehole	Handpump
Ha-Maphaha	H27-0021	30.10631	-22.88800	Borehole	Handpump
Raliphaswa	H27-0022	30.11670	-22.88910	Borehole	No equipment
Raliphaswa	H27-0023	30.12644	-22.89050	Borehole	Handpump
Makungwi	H27-0024	30.12258	-22.91470	Borehole	Handpump
Mavhunga	H27-0025	30.11531	-22.92180	Borehole	Handpump
Divhani	H27-0026	30.08491	-22.91550	Borehole	Handpump
Maname Paradise	H27-0027	29.93136	-22.89670	Borehole	Handpump
Maname Paradise	H27-0028	29.92896	-22.89640	Borehole	Handpump
Matsa A	H27-0029	29.96395	-22.87880	Borehole	No equipment
Matsa A	H27-0030	29.96171	-22.86580	Borehole	Handpump
Matsa A	H27-0031	29.97429	-22.86610	Borehole	Handpump
Matsa A	H27-0032	29.97642	-22.87230	Borehole	Handpump
Matsa B	H27-0033	29.99406	-22.86810	Borehole	Handpump
Matsa B	H27-0034	29.99746	-22.87430	Borehole	Handpump
Matsa B	H27-0035	29.99472	-22.87520	Borehole	Handpump
Luvhalani	H27-0036	29.98216	-22.89800	Borehole	No equipment
Maname Paradise	H27-0037	29.92877	-22.90470	Borehole	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Maname Paradise	H27-0038	29.92820	-22.90370	Borehole	No equipment
Tshikuwi	H27-0039	29.93972	-22.89760	Borehole	No equipment
Matsa	H27-0040	29.99739	-22.87900	Borehole	Handpump
Ha Matsa	H27-0041	29.99779	-22.88610	Borehole	No equipment
Tshituni Tshantha	H27-0042	30.05349	-22.85780	Borehole	No equipment
Tshituni Tshantha	H27-0043	30.05588	-22.85590	Borehole	No equipment
Ha-Rabali	H27-0044	30.10277	-22.87050	Borehole	Handpump
Lutomboni	H27-0045	30.21063	-22.87140	Borehole	Handpump
Lutomboni	H27-0046	30.21069	-22.87140	Borehole	No equipment
Luvhalani	H27-0047	29.98288	-22.90620	Borehole	Handpump
Malamba	H27-0050	30.26179	-22.89500	Borehole	Handpump
Siloam	H27-0051	30.19139	-22.90250	Borehole	No equipment
Siloam	H27-0052	30.18973	-22.9002	Borehole	Handpump
Ha-Matshareni	H27-0053	30.18889	-22.90580	Borehole	No equipment
Divhani	H27-0054	30.07010	-22.91570	Borehole	Handpump
Tshituni B	H27-0055	30.03235	-22.90960	Borehole	Handpump
Tshituni Tshantha	H27-0057	30.05675	-22.85730	Borehole	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshituni Tshantha	H27-0058	30.04872	-22.85710	Borehole	Mono-type pump
Tshituni Tshantha	H27-0059	30.04863	-22.8570	Borehole	No equipment
Divhani	H27-0060	30.07902	-22.91430	Borehole	Handpump
Divhani	H27-0061	30.07902	-22.91430	Borehole	No equipment
Dzanani	H27-0063	30.03025	-22.89740	Borehole	Submersible pump
Dzanani	H27-0064	30.03136	-22.89660	Borehole	Mono-type pump
Mamvuka	H27-0074	29.92397	-22.86080	Borehole	No equipment
Tshikuwi	H27-0078	29.94109	-22.89800	Borehole	No equipment
Tshikuwi	H27-0079	29.95012	-22.90220	Borehole	Submersible pump
Tshirolwe Ext 2	H27-0080	30.01033	-22.88700	Borehole	No equipment
Dopeni	H27-0100	30.20944	-22.91380	Borehole	Mono-type pump
Mandala Tshantha	H27-0101	30.21839	-22.91230	Borehole	Handpump
Mandala Tshantha	H27-0102	30.22177	-22.89600	Borehole	Handpump
Mudunungu	H27-0103	30.22879	-22.89150	Borehole	Handpump
Fondwe	H27-0104	30.22567	-22.91880	Borehole	No equipment
Mandala B	H27-0105	30.25394	-22.91940	Borehole	Handpump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshitasini	H27-0106	30.25889	-22.91630	Borehole	Handpump
Makhavhani	H27-0107	30.22584	-22.93230	Borehole	Handpump
Dopeni	H27-0108	30.20639	-22.91610	Borehole	No equipment
Dzumbathoho	H27-0109	30.17378	-22.94220	Borehole	No equipment
Dzumbathoho	H27-0110	30.17736	-22.94250	Borehole	Handpump
Mazhazhani	H27-0111	30.20017	-22.95380	Borehole	Handpump
Tshitavha	H27-0112	30.19545	-22.95900	Borehole	Handpump
Murunwa	H27-0113	30.15766	-22.98070	Borehole	Handpump
Matshavhawe	H27-0114	30.10250	-22.97260	Borehole	Handpump
Piesanghoek	H27-0115	30.09850	-22.98020	Borehole	Mono-type pump
Vuvha	H27-0116	30.20914	-22.99210	Borehole	Submersible pump
Vuvha	H27-0117	30.20708	-22.99150	Borehole	Mono-type pump
Vuvha	H27-0118	30.20736	-22.99190	Borehole	Handpump
Gudumabama	H27-0119	30.12634	-22.99180	Borehole	Mono-type pump
Gudumabama	H27-0120	30.12678	-22.99240	Borehole	Mono-type pump
Tshilimbane	H27-0123	30.18861	-22.82360	Borehole	Handpump
Tshiendeulu	H27-0124	30.16944	-22.82820	Borehole	Handpump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshiendeulu	H27-0125	30.16778	-22.83150	Borehole	Handpump
Dzata Ruins	H27-0126	30.15158	-22.83200	Borehole	No equipment
Thononda	H27-0127	30.23778	-22.86440	Borehole	Handpump
Thononda	H27-0128	30.24689	-22.85940	Borehole	Mono-type pump
Mudunungu	H27-0129	30.23304	-22.88380	Borehole	Handpump
Thononda	H27-0130	30.23945	-22.86750	Borehole	Handpump
Tshiheni	H27-0131	30.26862	-22.88190	Borehole	Handpump
Tshiheni	H27-0132	30.27203	-22.87950	Borehole	No equipment
Khalavha	H27-0133	30.29594	-22.91530	Borehole	No equipment
Thonoda Lusidzana	H27-0135	30.21106	-22.86090	Borehole	Mono-type pump
Lutomboni	H27-0136	30.21604	-22.87130	Borehole	Handpump
Lutomboni	H27-0137	30.21584	-22.87130	Borehole	No equipment
Siloam	H27-0138	30.19233	-22.89430	Borehole	Mono-type pump
Tshikuwi	H27-0139	29.93702	-22.90150	Borehole	No equipment
Tshikuwi	H27-0140	29.93782	-22.90070	Borehole	No equipment
Tshikuwi	H27-0141	29.93717	-22.90380	Borehole	No equipment
Tshikuwi	H27-0142	29.93961	-22.89770	Borehole	Mono-type pump
Tshirolwe Ext 2	H27-0145	30.00433	-22.89460	Borehole	Handpump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshituni	H27-0146	30.00903	-22.87920	Borehole	Handpump
Tshirolwe Ext1	H27-0147	30.00486	-22.90480	Borehole	Handpump
Ha Matsa	H27-0148	29.98981	-22.88700	Borehole	No equipment
Dzanani	H27-0149	30.01917	-22.89750	Borehole	Handpump
Dzanani	H27-0150	30.02102	-22.89540	Borehole	Handpump
Mapakophele	H27-0151	30.04100	-22.89110	Borehole	No equipment
Dzanani	H27-0152	30.0362	-22.89850	Borehole	Handpump
Thembaluvhilo	H27-0153	30.05056	-22.89030	Borehole	Handpump
Tshithuni Tshafhasi	H27-0154	30.04700	-22.88170	Borehole	Windpump
Tshituni Tshantha	H27-0155	30.05031	-22.85580	Borehole	Mono-type pump
Tshituni Tshantha	H27-0156	30.04952	-22.85670	Borehole	No equipment
Ha-Rabali	H27-0157	30.08562	-22.88020	Borehole	Handpump
Posaito	H27-0158	30.08449	-22.88450	Borehole	Handpump
Ha-Rabali	H27-0159	30.10380	-22.88080	Borehole	Handpump
Mamuhohi	H27-0160	30.07186	-22.86380	Borehole	Handpump
Mamuhoyi	H27-0161	30.10016	-22.86610	Borehole	No equipment
Mamuhoyi	H27-0162	30.11076	-22.87110	Borehole	Handpump
Mamuhoyi	H27-0163	30.12312	-22.86460	Borehole	Handpump
Ha-Manngo	H27-0164	30.16936	-22.88470	Borehole	Handpump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshavhalovhedzi	H27-0165	30.18024	-22.88500	Borehole	Handpump
Siloam	H27-0166	30.17944	-22.90500	Borehole	Powerhead
Tshavhalovhedzi	H27-0167	30.17500	-22.89440	Borehole	Handpump
Ha-Matshareni	H27-0168	30.18750	-22.90440	Borehole	Mono-type pump
Ha-Mapila	H27-0169	30.04977	-22.91020	Borehole	No equipment
Ha-Mapila	H27-0170	30.04956	-22.91160	Borehole	No equipment
Siyawoadza	H27-0171	30.03870	-22.91180	Borehole	No equipment
Tshituni B	H27-0172	30.03972	-22.90810	Borehole	No equipment
Ha-Mapila	H27-0173	30.04019	-22.90960	Borehole	No equipment
Manyii	H27-0174	29.94801	-22.87870	Borehole	No equipment
Manyii	H27-0175	29.94795	-22.87640	Borehole	No equipment
Manyii	H27-0176	29.95342	-22.87340	Borehole	No equipment
Manyii	H27-0177	29.94884	-22.87060	Borehole	No equipment
Manyii	H27-0178	29.94861	-22.87090	Borehole	No equipment
Matsa A	H27-0179	29.94845	-22.86320	Borehole	No equipment
Tshitasini	H27-0189	30.25937	-22.91680	Borehole	Submersible pump
Tshikhudo	H27-0190	30.15617	-22.86900	Borehole	No equipment
Phadzima	H27-0191	30.18908	-22.94700	Borehole	Submersible pump
Matsa A	H27-0195	29.95473	-22.86750	Borehole	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshiendeulu	H27-0199	30.16945	-22.82600	Borehole	Mono-type pump
Thononda	H27-0204	30.23695	-22.86610	Borehole	No equipment
Thononda	H27-0205	30.23417	-22.86860	Borehole	Handpump
Tshitangani	H27-0210	30.29730	-22.87500	Borehole	No equipment
Tshiheni	H27-0212	30.27500	-22.87880	Borehole	No equipment
Tshiheni	H27-0214	30.26973	-22.87970	Borehole	No equipment
Tshilimbane	H27-0216	30.18528	-22.82190	Borehole	No equipment
Siloam	H27-0228	30.17944	-22.90500	Borehole	No equipment
Siloam	H27-0232	30.19472	-22.89410	Borehole	No equipment
Matshavhawe	H27-0275	30.10369	-22.97130	Borehole	No equipment
Ha-Funyufunyu	H27-0287	30.11329	-22.90890	Borehole	No equipment
Raliphaswa	H27-0290	30.12736	-22.90680	Borehole	No equipment
Khunda	H27-0291	30.11849	-22.95840	Borehole	No equipment
Posaito	H27-0298	30.07725	-22.89390	Borehole	Handpump
Ha-Matidza	H27-0305	30.07519	-22.86510	Borehole	Handpump
Posaito	H27-0306	30.0755	-22.89850	Borehole	Handpump
Mamvuka	H27-0307	29.90002	-22.86450	Borehole	No equipment
Ha-Manngo	H27-0313	30.16135	-22.88070	Borehole	No equipment
Ha-Maphaha	H27-0314	30.09305	-22.88100	Borehole	Mono-type pump

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Dopeni	H27-0316	30.20789	-22.92510	Borehole	No equipment
Tshithuthuni	H27-0321	30.19148	-22.87260	Borehole	No equipment
Matsa A	H27-0323	29.95464	-22.86920	Borehole	No equipment
Ha Matsa	H27-0324	29.99608	-22.88300	Borehole	No equipment
Mamvuka	H27-0325	29.92999	-22.86820	Borehole	Submersible pump
Mazuwa	H27-0326	30.18314	-22.95610	Borehole	No equipment
Matsa A	H27-0327	29.95372	-22.85290	Borehole	No equipment
Vuvha	H27-0328	30.19903	-22.99080	Borehole	No equipment
Matsa A	H27-0329	29.95377	-22.86700	Borehole	No equipment
Matsa A	H27-0330	29.95425	-22.86530	Borehole	No equipment
Mamuhoyi	H27-0336	30.11971	-22.86740	Borehole	No equipment
Khalavha	H27-0337	30.29594	-22.91530	Borehole	Submersible pump
Siloam	H27-0372	30.18423	-22.90000	Borehole	No equipment
Dzanani	H27-0373	30.03528	-22.89930	Borehole	No equipment
Tshavhalovhedzi	H27-0393	30.17261	-22.88490	Borehole	No equipment
Mauluma	H27-0394	30.11872	-22.92150	Borehole	Submersible pump
Mauluma	H27-0395	30.11878	-22.92150	Borehole	No equipment
Dzanani	H27-0398	30.03936	-22.89880	Borehole	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Piesanghoek	H27-0399	30.09425	-22.98020	Borehole	Mono-type pump
Piesanghoek	H27-0400	30.09839	-22.98030	Borehole	No equipment
Luvhalani	H27-0401	29.97422	-22.90180	Borehole	No equipment
Murunwa	H27-0403	30.14761	-22.97900	Borehole	No equipment
Murunwa	H27-0404	30.14836	-22.97920	Borehole	No equipment
Thembaluvhilo	H27-0405	30.07761	-22.88210	Borehole	No equipment
Thembaluvhilo	H27-0407	30.07767	-22.88210	Borehole	No equipment
Tshikuwi	H27-0410	29.95011	-22.90230	Borehole	No equipment
Dzanani	H27-0411	30.14836	-22.88660	Borehole	No equipment
Tshikuwi	H27-0412	29.95260	-22.90470	Borehole	No equipment
Tshikuwi	H27-0422	29.95637	-22.89860	Borehole	No equipment
Luvhalani	H27-0423	29.97393	-22.90390	Borehole	No equipment
Luvhalani	H27-0424	29.97407	-22.90270	Borehole	No equipment
Ha-Matidza	H27-0427	30.07750	-22.87070	Borehole	No equipment
Ha-Matidza	H27-0428	30.07749	-22.87040	Borehole	No equipment
Posaito	H27-0429	30.08427	-22.88750	Borehole	Mono-type pump
Dzanani	H27-0430	30.03008	-22.89600	Borehole	Submersible pump
Ha-Maphaha	H27-0433	30.09333	-22.88080	Borehole	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Dzanani	H27-0434	30.03433	-22.90100	Borehole	Submersible pump
Mavhunga	H27-0437	30.10906	-22.92610	Borehole	No equipment
Mauluma	H27-0438	30.11785	-22.92220	Borehole	No equipment
Tshitasini	H27-0439	30.25906	-22.91760	Borehole	No equipment
Siloam	H27-0440	30.19455	-22.89980	Borehole	No equipment
Siloam	H27-0441	30.19299	-22.89670	Borehole	No equipment
Tshitasini	H27-0442	30.25919	-22.9176	Borehole	No equipment
Tshirolwe Ext1	H27-0478	30.00383	-22.89930	Borehole	No equipment
Ha-Makatu	H27-0479	30.16197	-22.86980	Borehole	No equipment
Tshirolwe Ext 2	H27-0480	30.00842	-22.88520	Borehole	No equipment
Matsa A	H27-0481	29.96031	-22.87170	Borehole	No equipment
Matsa B	H27-0482	29.99781	-22.87560	Borehole	No equipment
Matsa B	H27-0483	29.99717	-22.87510	Borehole	No equipment
Maname Paradise	H27-0497	29.92747	-22.90120	Borehole	No equipment
Matserere	H27-0134	30.26359	-22.92420	Borehole	Recorder
Fondwe	H27-0338	30.22569	-22.91880	Borehole	Recorder
Dzanani	H27F0070	30.01919	-22.89710	Spring	No equipment
Matsa A	H27F0071	29.95915	-22.87880	Spring	No equipment
Mamvuka	H27F0075	29.92224	-22.86510	Spring	No equipment

Village	Borehole Number	GPS Coordinates (WGS 84)		Site type	Equipment type
		Longitude	Latitude		
Tshiswenda	H27F0083	30.06316	-22.92320	Spring	No equipment
Khalavha	H27F0227	30.29473	-22.92350	Spring	No equipment
Siloam	H27F0229	30.17861	-22.90580	Spring	No equipment
Domboni	H27F0230	30.27084	-22.91580	Spring	No equipment
Ha-Matshareni	H27F0244	30.18439	-22.90760	Spring	No equipment
Matshavhawe	H27F0273	30.10352	-22.97070	Spring	No equipment
Maelula	H27F0279	30.14745	-22.98500	Spring	No equipment
Maelula	H27F0282	30.14747	-22.98500	Spring	No equipment
Tshithuthuni	H27W0203	30.19194	-22.87580	Spring	No equipment
Lutomboni	H27W0206	30.22584	-22.87110	Spring	No equipment
Tshiheni	H27W0213	30.26485	-22.87960	Spring	No equipment
Malamba	H27W0215	30.26140	-22.89690	Spring	No equipment
Tshilimbane	H27W0217	30.19130	-22.82540	Spring	No equipment
Tshivhilidulu	H27W0219	30.26333	-22.92990	Spring	No equipment
Tshiheni	H27W0222	30.28333	-22.88930	Spring	No equipment
Makanga	H27W0231	30.26431	-22.90630	Spring	No equipment

Appendix B: CRDT Drawdown and Recovery Data

CRDT drawdown and Recovery data for the tested boreholes within the study area

Time (in minutes)	H27-0006		H27-0016		H27-0021		H27-0119		H27-0023		H27-0024		H27-0025		H27-0027		H27-0033		H27-0050		H27-0060		H27-0107		H27-0110		H27-0111		H27-0113	
	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT
0		1.94		27.3		15.79		15.65		47.9		5.79		27.7		26.49		55.00				26.5		27.80		10.57		15.20		8.05
1	0.36	1.48	2.44	24.32	1.59	13.12	3.96	13.56	4.08	37.90	0.66	4.20	3.03	25.48	3.33	16.87	3.39	46.92			1.43	25.45	1.71	26.86	2.29	10.20	0.09	14.58	0.63	8.40
2	0.49	1.41	2.89	22.42	2.37	11.49	5.90	12.01	5.91	34.82	1.21	3.47	5.42	23.34	5.02	13.57	6.06	42.08			2.00	23.68	2.29	25.55	2.66	9.80	0.40	13.20	0.65	7.78
3	0.60	1.37	3.13	21.76	2.78	9.89	7.53	11.13	6.70	31.32	1.46	2.91	6.71	21.42	5.75	9.62	8.55	37.17			3.78	21.47	2.85	23.95	3.22	9.53	0.50	11.82	0.66	7.16
5	0.71	1.34	4.52	19.70	3.48	8.79	9.88	9.48	7.61	24.66	2.30	2.56	7.80	18.03	8.47	9.27	11.46	26.17			6.23	16.03	3.17	21.80	3.53	9.16	0.93	7.56	0.66	5.77
7	0.77	1.30	5.00	18.43	3.73	6.87	11.62	7.52	8.66	19.79	2.46	2.37	8.30	15.92	9.85	7.36	13.45	18.23			8.94	11.85	3.86	20.15	3.75	8.94	1.29	4.48	0.67	4.70
10	0.80	1.27	6.23	17.43	4.04	4.90	12.46	5.29	9.88	12.19	2.94	2.17	8.97	13.45	11.80	5.93	16.21	10.13			10.44	7.02	4.96	18.78	4.04	8.63	2.79	1.92	0.68	3.91
15	0.86	1.20	6.32	16.79	4.56	2.43	12.83	2.60	11.97	7.62	3.03	1.92	9.06	10.31	13.92	4.32	19.26	5.84			11.45	4.88	6.95	16.52	5.09	8.26	3.96	1.28	0.69	2.95
20	0.89	1.15	6.89	15.62	5.68	1.44	12.98	1.35	13.21	5.88	3.33	1.76	9.31	7.95	16.48	3.89	21.76	4.61			12.01	4.10	8.19	14.58	5.46	8.00	4.03	1.21	0.72	2.34
30	0.93	1.12	7.68	14.22	9.00	1.22	13.12	0.63	16.33	3.11	3.55	1.55	9.74	5.73	19.98	2.75	24.28	3.84			12.92	3.38	11.19	11.65	5.97	7.69	4.27	1.02	0.80	1.67
40	0.99	1.08	8.47	13.01	9.81	1.10	13.28	0.30	19.79	2.82	3.76	1.42	10.39	4.39	21.35	2.29	27.37	3.48			13.57	3.00	12.50	9.85	6.79	6.96	4.39	0.88	0.86	1.40
60	1.07	0.98	8.95	11.17	10.66	0.93	13.45	0.21	21.94	2.41	3.90	1.35	12.31	3.39	23.27	1.45	29.89	3.12			14.30	2.47	14.08	6.62	7.41	4.96	5.75	0.63	1.05	1.34
90	1.13	0.90	10.23	9.36	10.87	0.80	13.61	0.10	25.32	2.02	4.03	1.19	13.68	2.75	23.93	1.09	32.47	2.86			15.32	2.26	15.45	4.49	7.69	3.49	6.63	0.48	3.69	1.22
120	1.20	0.86	12.23	8.47	10.99	0.65	13.87	0.00	28.45	1.81	4.40	0.95	15.20	2.23	24.00	0.96	33.26	2.64			16.10	1.88	18.98	3.61	7.89	2.12	7.03	0.39	8.05	1.15
150	1.28	0.83	13.82	7.66	11.08	0.52	14.05		34.21	1.65	4.43	0.81	16.92	2.01	24.15	0.85	35.26	2.47			16.76	1.64	20.28	3.12	8.18	1.33	7.14	0.28		1.07
180	1.34	0.80	14.90	6.93	11.35	0.47	14.39		38.01	1.50	4.53	0.65	18.14	1.90	24.27	0.80	36.94	2.35			17.26	1.41	21.80	2.64	8.46	0.89	7.40	0.24		1.03
210	1.38	0.76	16.08	6.37	11.69	0.33	14.62		39.09	1.41	4.60	0.52	19.99	1.50	24.39	0.70	38.80	2.23			17.77	1.25	26.10	2.30	9.07	0.67	8.41	0.20		0.98
240	1.41	0.72	17.02	5.93	11.75	0.19	14.85		40.19	1.32	4.84	0.40	21.34	1.18	24.57	0.65	40.24	2.13			17.95	1.12	27.76	2.08	9.15	0.56	9.41	0.17		
300	1.48	0.68	27.30	5.17	11.95	0.08	14.99		44.04	1.19	4.96	0.33	22.01	1.00	24.89	0.62	41.88	1.97			18.95	0.93			10.20	0.34	10.06	0.11		
360	1.55	0.64			12.20	0.00	15.12		44.98	1.08	5.00	0.21	24.20	0.94	25.19	0.60	43.31	1.84			19.45	0.79			10.34	0.29	11.08	0.07		
420	1.60	0.60			12.65		15.25		45.03	0.97	5.15	0.14	25.90	0.82	25.35	0.59	46.10	1.77			19.86	0.70			10.45	0.18	11.27	0.05		
480	1.68	0.56			12.89		15.32		45.82	0.89	5.23	0.08	27.65	0.79	25.70	0.55	48.45	1.66			19.99	0.65			10.57	0.12	12.06	0.05		
540	1.76	0.51			13.45		15.41		47.88	0.79	5.34	0.05			25.97	0.48	51.33	1.52			20.27	0.60					12.75			
600	1.85	0.49			14.56		15.57				5.44	0.03			26.37	0.47	53.81	1.46			20.89	0.53					13.35			
720	1.94	0.47			15.79		15.65				5.79	0.02			26.49	0.44	55.00	1.27			21.75	0.49					13.48			
840		0.45																			22.38	0.28					15.22			
960		0.43																			24.07	0.22								
1080																					24.77	0.17								
1200																					25.52	0.12								
1320																					25.93	0.08								
1440																					26.45	0.00								

CRDT drawdown and Recovery data for the tested boreholes within the study area

Time (in minutes)	H27-0115		H27-0119		H27-0126		H27-0131		H27-0136		H27-0145		H27-0.148		H27-0149		H27-0153		H27-0154		H27-0157		H27-0158		H27-0160		H27-0161	
	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT
0		24.10		15.65		24.17		3.10		5.23		12.27		32.45		13.4		31.02		22.38		17.25		32.49		35.10		24.45
1	2.84	21.02	3.96	13.56	1.03	21.20	0.10	2.67	1.00	4.85	2.10	2.36	1.93	30.15	1.60	9.00	1.98	29.98	7.90	11.94	1.66	15.08	2.10	22.57	1.11	30.51	5.66	20.72
2	3.63	18.16	5.90	12.01	1.55	20.09	0.12	2.15	1.17	4.74	2.66	1.27	3.08	26.92	2.40	7.15	3.71	27.52	8.20	6.07	1.92	13.25	3.85	18.62	1.12	26.27	6.10	18.56
3	5.12	15.89	7.53	11.13	1.85	18.98	0.14	1.89	1.32	4.66	2.88	0.85	3.95	19.46	2.70	5.40	5.09	25.03	9.33	2.10	2.11	10.13	4.50	15.42	1.16	22.34	7.80	17.20
5	6.02	12.90	9.88	9.48	2.59	17.04	0.16	1.63	1.47	4.54	3.64	0.54	8.39	13.73	4.61	3.43	6.47	23.17	10.14	0.71	3.50	4.30	5.21	10.20	2.11	12.65	10.27	15.90
7	6.62	10.84	11.62	7.52	2.93	15.25	0.20	1.40	1.66	4.32	6.00	0.51	9.63	10.23	5.90	1.67	7.58	21.70	11.65	0.59	5.54	3.62	6.15	6.85	2.12	7.45	10.98	14.68
10	7.04	9.28	12.46	5.29	3.77	13.26	0.23	1.26	2.28	4.02	7.76	0.50	10.92	7.78	6.63	1.10	8.44	18.45	12.34	0.56	8.38	3.30	6.30	2.97	2.17	1.35	11.69	13.54
15	7.70	9.00	12.83	2.60	4.75	12.13	0.28	1.13	2.47	3.64	7.81	0.47	11.03	5.08	7.16	0.82	9.42	14.36	13.10	0.52	9.97	3.04	8.49	1.00	2.47	0.70	12.66	12.28
20	8.25	8.64	12.98	1.35	5.98	10.98	0.33	0.99	2.71	2.91	7.88	0.45	12.95	4.38	7.40	0.69	9.92	12.56	14.80	0.48	10.78	2.95	8.57	0.80	2.67	0.51	13.06	11.77
30	8.88	8.23	13.12	0.63	7.92	8.78	0.40	0.86	3.18	1.33	7.97	0.41	14.70	3.95	7.62	0.60	12.40	11.13	15.68	0.43	11.34	2.66	9.12	0.68	5.92	0.42	13.73	11.09
40	9.65	7.90	13.28	0.30	8.96	7.14	0.48	0.70	3.52	1.25	8.08	0.39	16.46	3.45	7.95	0.51	16.98	10.62	15.98	0.40	11.70	2.51	9.47	0.60	7.62	0.37	14.26	10.89
60	10.81	7.62	13.45	0.21	11.15	6.00	0.60	0.57	3.72	0.83	8.14	0.37	18.32	2.80	8.24	0.47	19.93	9.30	16.24	0.36	12.05	2.32	10.59	0.50	9.34	0.32	14.98	10.34
90	10.97	7.02	13.61	0.10	14.24	2.88	0.82	0.42	4.20	0.39	8.22	0.32	20.03	1.43	8.50	0.44	21.90	8.18	16.82	0.34	12.28	1.97	12.66	0.46	10.51	0.27	15.38	9.65
120	11.05	6.69	13.87	0.00	15.75	1.64	1.08	0.33	4.48	0.25	8.31	0.30	21.32	1.22	8.60	0.40	23.76	7.42	16.99	0.31	12.59	1.67	12.94	0.40	11.45	0.25	16.79	8.49
150	11.55	6.09	14.05		16.68	1.36	1.34	0.26	4.61	0.19	8.37	0.28	25.69	1.00	8.75	0.37	24.05	6.57	17.10	0.29	12.74	1.45	13.57	0.36	12.04	0.23	17.66	7.86
180	11.86	5.78	14.39		18.24	1.20	1.61	0.23	4.70	0.10	8.50	0.27	26.18	0.90	9.27	0.35	25.28	6.00	17.24	0.28	12.90	1.29	14.42	0.32	12.22	0.21	18.20	6.71
210	12.66	3.01	14.62		18.68	1.12	1.97	0.21	4.75	0.08	8.63	0.25	26.18	0.78	9.55	0.34	26.04	5.44	17.37	0.25	12.98	1.16	15.86	0.29	12.38	0.20	18.77	6.24
240	12.98	2.76	14.85		19.30	1.06	2.17	0.18	4.80	0.06	8.77	0.23	27.40	0.77	9.82	0.32	26.83	5.05	17.48	0.23	13.03	0.91	16.37	0.27	12.64	0.19	19.89	5.88
300	13.09	2.66	14.99		20.17	1.02	2.95	0.13	4.96	0.04	8.82	0.19	28.50	0.74	10.23	0.30	27.65	4.39	17.80	0.18	13.69	0.87	17.43	0.25	12.88	0.16	21.06	4.56
360	13.27	2.43	15.12		20.81	0.95	3.10	0.08	5.08	0.00	8.90	0.17	29.93	0.65	10.48	0.29	28.35	3.85	17.92	0.12	13.87	0.69	17.84	0.24	12.95	0.12	21.70	3.79
420	13.38	2.07	15.25		21.26	0.80			5.18		8.99	0.15	30.15	0.43	10.91	0.28	29.40	3.41	18.07	0.09	14.15	0.41	18.13	0.20	13.08	0.07	22.42	1.83
480	13.75	1.97	15.32		21.80	0.54			5.23		9.08	0.14	31.35	0.38	11.40	0.23	31.02	3.06	18.31	0.07	14.61	0.27	19.06	0.16	13.86	0.03	22.79	1.14
540	14.00	1.70	15.41		22.43	0.33					9.16	0.13	32.45	0.38	11.72	0.20			18.87	0.05	14.87	0.00	19.65	0.10	14.24	0.00	23.58	0.86
600	14.18	1.31	15.57		22.98	0.27					9.76	0.11			11.98	0.19			19.02	0.03	15.00		21.34	0.05	15.68		23.92	0.25
720	14.48	1.18	15.65		24.17	0.12					10.84	0.04			13.40	0.17			19.55	0.00	15.68		22.10		16.88		24.27	0.12
840	14.89	1.00									10.97								20.00		16.09		23.00		19.14		24.45	0.08
960	15.15	0.91									11.12								20.18		16.25		25.64		26.85			
1080	15.37	0.77									11.22								21.77		16.85		27.43		31.47			
1200	15.79	0.66									11.36								21.97		17.05		28.09		35.10			
1320	16.24	0.58									11.88								22.14		17.20		30.22					
1440	16.56	0.56									12.27								22.38		17.25		32.49					
1560	17	0.50																										
1680	17.2	0.47																										
1800	17.5	0.41																										

CRDT drawdown and Recovery data for the tested boreholes within the study area

Time (in minutes)	H27-0163		H27-0165		H27-0191		H27-0199		H27-0102		H27-0103		H27-0105		H27-0290		H27-0316		H27-0321		H27-0337		H27-0338		H27-0022	
	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT	CRDT	RT
0		30.10		30.39		43.53		51.75		51.40		67.00		14.12		41.02		5.12		1.76		50.98		91.1		20.97
1	2.78	26.60	4.69	24.11	1.69	39.89	2.07	47.79	1.03	39.70	3.10	63.50	2.00	11.80	6.60	33.21	0.38	3.86	0.52	0.80	3.53	45.19	2.79	81.76	8.47	10.60
2	3.15	18.15	6.84	18.72	2.43	38.08	2.66	43.63	2.27	28.80	5.92	60.52	2.91	10.67	7.61	22.48	0.59	3.14	0.89	0.62	3.97	39.96	4.90	78.80	9.58	9.82
3	3.74	16.20	8.97	13.26	3.24	36.57	3.09	42.47	4.16	20.50	7.37	57.69	3.74	9.93	8.73	12.70	0.80	2.60	1.00	0.56	4.86	35.77	9.03	77.03	10.60	9.44
5	4.90	13.33	9.60	9.88	4.54	33.70	3.90	39.97	6.58	17.71	8.95	52.10	4.92	8.91	10.48	4.30	0.89	1.86	1.26	0.49	6.17	32.50	11.34	75.35	11.22	8.91
7	5.14	13.12	10.48	6.78	5.72	30.92	4.56	38.64	8.07	15.01	10.54	46.18	5.87	8.05	12.64	2.70	0.96	1.40	1.27	0.42	6.98	30.87	11.82	74.21	11.62	8.57
10	5.76	12.23	10.99	4.15	7.38	27.10	5.36	36.06	10.44	13.13	12.92	36.51	6.67	6.50	16.15	1.91	1.00	1.08	1.29	0.37	7.69	27.40	14.75	73.35	11.96	8.24
15	6.70	11.07	11.53	2.26	9.33	21.49	6.89	30.45	11.11	9.09	14.30	24.04	8.06	4.19	19.55	1.73	1.30	1.01	1.35	0.33	9.35	19.48	21.05	72.82	12.42	7.81
20	7.33	9.52	12.98	1.66	10.90	16.72	8.26	26.05	13.30	7.05	16.28	17.27	8.82	2.70	22.74	1.11	2.08	0.92	1.45	0.31	10.52	15.26	26.32	71.13	12.80	7.47
30	8.12	8.33	13.09	1.33	12.94	12.56	13.29	20.71	15.70	5.04	18.50	10.37	9.25	1.77	26.55	0.98	2.90	0.80	1.50	0.27	11.51	11.96	35.20	70.91	13.15	7.01
40	8.85	7.82	13.27	1.10	14.25	9.18	18.03	15.26	17.27	2.26	20.01	8.59	9.63	1.25	27.28	0.92	3.22	0.74	1.50	0.23	12.00	9.66	43.06	69.38	14.05	6.60
60	9.33	6.78	13.43	0.97	16.90	5.45	23.07	10.07	19.80	1.60	22.54	6.02	10.27	0.83	27.83	0.80	3.40	0.47	1.54	0.19	13.29	7.64	55.65	67.11	14.52	5.99
90	10.25	5.96	13.63	0.81	19.17	3.20	28.09	5.95	22.20	1.13	25.44	4.51	11.56	0.67	28.26	0.65	3.52	0.39	1.58	0.16	14.43	6.62	67.18	63.14	15.02	5.25
120	12.38	5.27	13.75	0.70	22.27	2.69	30.63	4.69	22.89	0.93	27.40	3.29	12.00	0.44	29.30	0.60	3.76	0.35	1.60	0.13	15.03	6.18	74.14	60.03	15.24	4.87
150	14.46	4.80	13.86	0.65	25.81	2.42	31.67	3.34	23.15	0.72	29.40	3.12	12.12	0.31	30.20	0.54	3.88	0.32	1.60	0.11	16.08	5.72	76.54	58.08	15.48	4.36
180	15.83	4.28	13.95	0.53	29.20	2.25	33.04	2.98	23.25	0.67	30.05	2.87	12.26	0.25	36.74	0.49	4.10	0.29	1.61	0.10	18.48	5.39	78.05	56.11	15.83	3.91
210	16.86	3.93	14.03	0.46	31.53	1.97	34.16	2.51	23.41	0.60	32.30	2.52	12.49	0.18	30.27	0.46	4.15	0.25	1.63	0.09	20.56	4.92	82.21	54.46	15.95	3.65
240	18.10	3.70	14.38	0.34	33.31	1.72	36.48	2.03	23.58	0.53	34.61	2.23	12.66	0.14	29.20	0.39	4.19	0.22	1.63	0.09	21.93	4.64	83.31	52.61	16.34	3.51
300	20.21	3.15	14.63	0.22	35.82	1.36	38.70	1.57	23.78	0.43	38.89	1.83	13.01	0.10	31.25	0.32	4.23	0.19	1.61	0.08	24.28	4.23	85.89	48.35	16.57	3.41
360	23.17	2.79	14.89	0.17	38.90	1.18	43.40	1.33	23.94	0.38	49.90	1.46	13.39	0.08	32.35	0.25	4.25	0.17	1.63	0.08	25.80	3.80	88.36	43.10	16.87	3.15
420	25.00	2.45	15.02	0.08	40.27	0.99	48.70	1.19	24.10	0.18	55.98	1.12	13.78	0.06	33.08	0.19	4.30	0.15	1.65	0.06	27.07	3.36	90.03	36.53	17.13	2.97
480	29.58	2.24	15.17	0.06	43.53	0.84	51.75	1.15	24.48	0.12	65.45	0.99	14.12	0.04	33.86	0.13	4.45	0.12	1.67	0.06	29.09	3.17	91.05	36.35	17.26	2.80
540	30.10	1.92	15.39	0.04					26.82	0.10	67.00	0.80			34.21	0.07	4.55	0.09	1.68	0.04	30.50	3.00			17.45	2.67
600		1.00	15.50	0.00					28.14	0.08					35.36	0.04	4.70	0.07	1.74	0.04	34.76	2.88			17.76	2.52
720			15.77						33.40	0.07					36.54	0.00	5.12	0.01	1.76	0.02	39.09	2.70			17.89	2.46
840			16.11						46.94	0.06					37.44						46.35	2.53			17.98	2.34
960			17.07						51.40	0.05					37.63						50.98	2.31			18.17	2.21
1080			17.83												37.77										18.33	1.93
1200			18.72												38.10										18.42	1.75
1320			19.60												39.41										18.55	1.66
1440			20.41												41.02										18.58	1.55
1560			21.33																						18.7	1.5
1680			23.01																						18.8	1.44
1800			23.95																						19	1.36

Appendix C: Recommended Abstraction Rates

Recommended abstraction rates

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0001	-22.87578	30.19333	Tshithuthuni	27.8	6.4	24	0.30	24	25.92
H27-0002	-22.87495	30.19417	Tshithuthuni	43.4	2.83	18	0.70	24	60.48
H27-0004	-22.87294	30.19850	Tshithuthuni	17.58	10.25	16	0.30	24	25.92
H27-0006	-22.88290	30.16208	Ha-Manngo	36	5.06	12	0.20	24	17.28
H27-0007	-22.88295	30.16170	Ha-Manngo	58.22	2.45	18	1.60	24	138.24
H27-0008	-22.86937	30.16139	Ha-Makatu	57.04	15.82	26	0.70	24	60.48
H27-0011	-22.90250	29.96013	Luvhalani	59.83	15.12	28	0.40	24	34.56
H27-0013	-22.90480	29.95265	Tshikuwi	61.68	27.76	36	0.40	24	34.56
H27-0014	-22.90124	29.93887	Tshikuwi	60.24	4.26	16	0.40	24	34.56
H27-0015	-22.89949	29.94710	Tshikuwi	98.92	20.26	36	0.20	24	17.28
H27-0016	-22.88681	29.96223	Matsa A	37	6.65	24	0.23	24	19.872
H27-0019	-22.86112	29.92408	Mamvuka	60.65	4.95	18	0.10	24	8.64
H27-0021	-22.88796	30.10631	Ha-Maphaha	36.4	12.23	24	0.33	24	12.96
H27-0022	-22.88913	30.11670	Raliphaswa	28.8	3.4	24	4.00	24	345.6

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0023	-22.89046	30.12644	Raliphaswa	73.23	19.3	42	0.23	24	21.6
H27-0024	-22.91465	30.12258	Makungwi	16.36	6.49	14	0.26	24	17.28
H27-0025	-22.92176	30.11531	Mavhunga	43.5	11	21	0.04	24	4.32
H27-0027	-22.89669	29.93136	Maname Paradise	48.43	18.72	42	0.21	24	12.96
H27-0032	-22.87228	29.97642	Matsa A	50.37	14.52	40	0.20	24	17.28
H27-0033	-22.86806	29.99406	Matsa B	72.23	12.69	54	0.28	24	25.92
H27-0040	-22.87900	29.99739	Matsa	79.7	13.17	28	0.05	24	4.32
H27-0047	-22.90621	29.98288	Luvhalani	104.25	57.96	72	0.15	24	12.96
H27-0050	-22.89498	30.26179	Malamba	14.7	5.7	0	0.10	24	8.64
H27-0051	-22.90245	30.19139	Siloam	55.1	6.13	0	0.10	24	8.64
H27-0052	-22.90022	30.18973	Siloam	60.9	3.38	21	0.30	24	25.92
H27-0053	-22.90578	30.18889	Ha-Matshareni	115	3.35	27	0.30	24	25.92
H27-0054	-22.91570	30.07010	Divhani	31.85	1.64	27	0.10	24	8.64
H27-0060	-22.91428	30.07902	Divhani	35.68	1.2	24	0.60	24	51.84
H27-0063	-22.89742	30.03025	Dzanani	61.3	16.91	42	0.62	24	25.92

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0079	-22.90217	29.95012	Tshikuwi	90	29.79	48	0.05	24	4.32
H27-0101	-22.91234	30.21839	Mandala Tshantha	35.1	9.1	18	0.16	24	13.824
H27-0102	-22.89597	30.22177	Mandala Tshantha	66.7	11.33	36	0.55	24	21.6
H27-0103	-22.89147	30.22879	Mudunungu	75.61	2.88	36	0.08	24	12.96
H27-0104	-22.91881	30.22567	Fondwe	84	3.8	36	0.31	24	26.784
H27-0105	-22.91935	30.25394	Mandala B	23.57	1.99	18	0.10	24	6.912
H27-0107	-22.93231	30.22584	Makhavhani	48.38	15.5	32	0.03	24	6.912
H27-0110	-22.94247	30.17736	Dzumbathoho	30.5	13.3	24	0.06	24	4.32
H27-0111	-22.95378	30.20017	Mazhazhani	31.8	12.25	21	0.15	24	12.96
H27-0112	-22.95900	30.19545	Tshitavha	68	22.83	42	0.25	24	21.6
H27-0113	-22.98074	30.15766	Murunwa	18.42	7.99	12	0.08	24	6.912
H27-0115	-22.98022	30.09850	Piesanghoek	38.95	6.56	27	1.03	24	95.04
H27-0116	-22.99206	30.20914	Vuvha	35.7	5.81	21	1.00	24	86.4
H27-0117	-22.99148	30.20708	Vuvha	62.65	10.19	24	1.60	24	138.24

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0119	-22.99181	30.12634	Gudumabama	23.65	2.9	21	0.35	24	21.6
H27-0123	-22.82357	30.18861	Tshilimbane	72.21	9.44	30	0.10	24	8.64
H27-0124	-22.82823	30.16944	Tshiendeulu	108.38	4.67	30	0.10	24	8.64
H27-0125	-22.83148	30.16778	Tshiendeulu	64.3	15.53	43	0.10	24	8.64
H27-0126	-22.83197	30.15158	Dzata Ruins	53	5.57	28	0.19	24	17.28
H27-0127	-22.86440	30.23778	Thononda	27	12.44	18	0.22	24	19.008
H27-0128	-22.85940	30.24689	Thononda	61.2	3.51	18	4.40	24	380.16
H27-0130	-22.86745	30.23945	Thononda	81.84	17.08	0	0.02	8	1.728
H27-0131	-22.88190	30.26862	Tshiheni	6.1	1.5	5	0.04	10	4.32
H27-0135	-22.86088	30.21106	Thonoda Lusidzana	90.37	17.68	30	0.50	24	43.2
H27-0136	-22.87126	30.21604	Lutomboni	13.03	5.26	12	0.09	24	8.64
H27-0138	-22.89428	30.19233	Siloam	93.5	0.25	24	0.50	24	43.2
H27-0139	-22.90152	29.93702	Tshikuwi	101	3.3	28	0.40	10	34.56
H27-0140	-22.90065	29.93782	Tshikuwi	89.2	24.77	30	0.50	24	43.2
H27-0142	-22.89773	29.93961	Tshikuwi	90	3.81	42	0.50	24	43.2
H27-0145	-22.89459	30.00433	Tshirolwe Ext 2	26.6	7.16	18	0.39	24	30.24

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0146	-22.87921	30.00903	Tshituni	27.3	7.27	21	0.60	24	51.84
H27-0148	-22.88700	29.98981	Ha Matsa	52.46	17.61	46	0.15	24	17.28
H27-0149	-22.89753	30.01917	Dzanani	28	8.4	18	0.17	24	12.96
H27-0153	-22.89028	30.05056	Thembaluvhilo	42.51	9.96	33	0.25	24	12.96
H27-0154	-22.88167	30.04700	Tshithuni Tshafhasi	51.7	21.44	42	1.96	24	138.24
H27-0155	-22.85583	30.05031	Tshituni Tshantha	40.22	1.54	14	2.50	24	216
H27-0157	-22.88020	30.08562	Ha-Rabali	26.14	2.85	18	1.19	24	51.84
H27-0158	-22.88446	30.08449	Posaito	82.28	2.28	22	0.36	24	30.24
H27-0160	-22.86376	30.07186	Mamuhohi	42.53	2.6	18	0.27	24	17.28
H27-0161	-22.86612	30.10016	Mamuhoyi	36.68	10.96	27	2.11	24	172.8
H27-0163	-22.86458	30.12312	Mamuhoyi	44.51	8.59	21	0.38	24	25.92
H27-0165	-22.88503	30.18024	Tshavhalovhedzi	51.17	15.62	30	0.82	24	77.76
H27-0168	-22.90439	30.18750	Ha-Matshareni	82.68	1.68	18	1.00	24	86.4
H27-0171	-22.91184	30.03870	Siyawoadza	41	1.37	18	0.70	24	60.48
H27-0176	-22.87337	29.95342	Manyii	118	6.75	0	0.10	2	8.64
H27-0177	-22.87060	29.94884	Manyii	46	7.17	26	0.30	24	25.92
H27-0179	-22.86321	29.94845	Matsa A	101	2.2	30	0.30	24	25.92

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0190	-22.86897	30.15617	Tshikhudo	59.25	21.54	42	0.10	4	8.64
H27-0191	-22.94701	30.18908	Phadzima	69.79	24.09	44	0.05	24	4.32
H27-0199	-22.82597	30.16945	Tshiendeulu	76.9	4.85	42	0.06	24	4.32
H27-0290	-22.90677	30.12736	Raliphaswa	53.22	6.97	45	0.75	24	60.48
H27-0306	-22.89847	30.07550	Posaito	10.55	3.89	9	0.10	2	8.64
H27-0313	-22.88065	30.16135	Ha-Manngo	51.53	7.43	18	0.06	24	5.184
H27-0314	-22.88101	30.09305	Ha-Maphaha	80	0	40	0.10	8	8.64
H27-0316	-22.92511	30.20789	Dopeni	76.3	13.75	21	0.40	24	43.2
H27-0321	-22.87256	30.19148	Tshithuthuni	55.35	5.83	12	0.95	24	69.12
H27-0323	-22.86920	29.95464	Matsa A	69.33	7.19	30	0.25	24	21.6
H27-0324	-22.88303	29.99608	Ha Matsa	62.12	13.54	24	0.10	24	8.64
H27-0325	-22.86821	29.92999	Mamvuka	51.02	13.95	30	0.05	24	4.32
H27-0326	-22.95614	30.18314	Mazuwa	50.04	7.4	12	0.50	24	43.2
H27-0327	-22.85292	29.95372	Matsa A	88.85	2.64	59	0.10	2	8.64
H27-0328	-22.99081	30.19903	Vuvha	98.27	6.07	24	0.15	24	12.96
H27-0330	-22.86528	29.95425	Matsa A	68.27	3.04	18	0.05	24	4.32
H27-0336	-22.86738	30.11971	Mamuhoyi	117.9	10.7	36	0.20	24	17.28
H27-0337	-22.91533	30.29594	Khalavha	69.39	17.29	36	0.41	24	17.28

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0372	-22.89999	30.18423	Siloam	55.79	3.82	18	1.00	24	86.4
H27-0373	-22.89930	30.03528	Dzanani	59.87	9.41	30	0.40	24	34.56
H27-0393	-22.88494	30.17261	Tshavhalovhedzi	51.02	5.74	18	0.60	24	51.84
H27-0394	-22.92150	30.11872	Mauluma	39.8	4.04	30	0.50	24	43.2
H27-0398	-22.89881	30.03936	Dzanani	78.9	7.7	42	6.00	24	518.4
H27-0399	-22.98017	30.09425	Piesanghoek	37.3	5.84	30	0.25	24	21.6
H27-0400	-22.98025	30.09839	Piesanghoek	71	7.13	28	1.80	24	155.52
H27-0403	-22.97900	30.14761	Murunwa	100.3	25.47	95	0.20	24	17.28
H27-0407	-22.88214	30.07767	Thembaluvhilo	141	11.55	60	0.40	24	34.56
H27-0410	-22.90231	29.95011	Tshikuwi	181	43.04	86	0.30	24	25.92
H27-0411	-22.88658	30.14836	Dzanani	82	5.34	24	0.20	24	17.28
H27-0412	-22.90474	29.95260	Tshikuwi	111	21.67	48	3.00	24	259.2
H27-0427	-22.87068	30.07750	Ha-Matidza	77.6	8.85	24	1.40	24	120.96
H27-0428	-22.87044	30.07749	Ha-Matidza	104	8.5	48	0.50	6	43.2
H27-0429	-22.88751	30.08427	Posaito	32	6.73	18	2.20	24	190.08
H27-0433	-22.88081	30.09333	Ha-Maphaha	64.55	12.25	30	0.20	24	17.28
H27-0434	-22.90103	30.03433	Dzanani	52.15	7.35	36	1.60	24	138.24
H27-0438	-22.92224	30.11785	Mauluma	101	7.25	21	0.10	24	8.64

Borehole No.	GPS coordinates		Village name	Borehole depth (mbgl)	Static water level (mbgl)	Recommendations			
	Latitude	Longitude				Pump setting (mbgl)	Abstraction rate (l/s)	Pumping duration (hrs)	Daily abstractions (m3/day)
H27-0440	-22.89983	30.19455	Siloam	65.75	0.34	41.9	0.32	24	27.648
H27-0441	-22.89672	30.19299	Siloam	33.42	0.03	29.3	0.10	24	8.64
H27-0478	-22.89925	30.00383	Tshirolwe Ext1	59.8	3.58	30	2.80	24	241.92
H27-0479	-22.86981	30.16197	Ha-Makatu	61.2	18.71	36	0.90	24	77.76
H27-0480	-22.88517	30.00842	Tshirolwe Ext 2	78.3	7.69	36	0.40	24	34.56
H27-0481	-22.87169	29.96031	Matsa A	47.82	6.34	30	0.10	24	8.64
H27-0482	-22.87564	29.99781	Matsa B	70.42	3.22	24	0.80	24	69.12
H27-0483	-22.87508	29.99717	Matsa B	79.35	3.86	24	0.40	24	34.56
H27-0497	-22.90122	29.92747	Maname Paradise	121.42	27.72	42	0.10	24	8.64
H27-0134	-22.92417	30.26359	Matserere	54.06	1.53	36	0.80	24	69.12
H27-0338	-22.91881	30.22569	Fondwe	104.7	3.72	36	0.73	24	25.92