School of Environmental Sciences

Department of Mining and Environmental Geology

Investigation of sustainable groundwater resource supply in the crystalline basement aquifers at Relela Village, Greater-Tzaneen Municipality, Limpopo province, South Africa.

By

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A masters dissertation in fulfilment of a Masters of Earth Sciences in Mining and Environmental Geology Degree submitted at the University of Venda, School of Environmental Sciences, Department of Mining and Environmental Geology

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DECLARATION

I, **Ramathieledza Ronald**, declare that this research submitted for a Masters of Earth Science in Mining and Environmental Geology at the Department of Mining and Environmental Geology, University of Venda, has not previously been done or submitted for a degree at any Institution or University and that this is my own work that has been designed and performed by me in confidence, honesty and that all reference material contained therein has been duly acknowledged.

Student’s Signature: Date: 30/03/2021

ACKNOWLEDGEMENTS

My first gratitude goes to God for always being there for me, his mercy and honour, made it possible for me through this great journey.

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ABSTRACT

South Africa is one of the countries in the world having challenges on the untreated surface and groundwater. In arid and semi-arid areas groundwater is the main source of supply, these areas consist of crystalline basement aquifers which store water either in rock fractures, geological structures (i.e dykes), and contact zones. The water supply crisis is caused by the combination of low rainfall, high evaporation rates, and population growth whose geographical demand for water supply cannot conform to the distribution of exploitable water. The current study aims to evaluate groundwater resource supply in the crystalline basement aquifers at Relela villages, in South Africa, Limpopo province.

Based on the literature review, two geophysical techniques were used for groundwater exploration. The proton precession G856 magnetometer was used in magnetic data collection which covered six profiles in four villages. PQWTC-300 (resistivity) was used to study the resistivity of the subsurface lithologies. The traverse lines were set perpendicular to the geological structures trending in the NW-SE direction. The magnetic results presented in x-y graphs showed the variation in magnetic intensities, with the maximum magnetic intensity of 1431 nT and the minimum magnetic intensity of -3561 nT. High magnetic intensity indicated the presence of subsurface geological structures and the low magnetic intensity indicated the presence of weathered subsurface lithologies. The resistivity results indicated low, medium to high (1.2-8.6 ohms) resistivity values throughout the study area. Low resistivity values indicated the presence of weathered subsurface lithologies whereas high resistivity values indicated solid/hard subsurface lithologies. The drilling targets were selected based on the magnetic and resistivity results gathered during groundwater exploration.

A drilling machine was used to exploit groundwater resources, several lithologies which were encountered during drilling are; clay soil, dolerite dykes, gneiss, and granites. The blow yield values ranged from 0.1-2.0 l/s. After the completion of the drilling pump testing was conducted to determine the aquifer parameters which had safe yields ranging from 0.01 l/s – 0.5 l/s; transmissivity ranging from 1 m^2/day-2.9 m^2/day and the specific capacity ranging from 0.01 l/s per m- 0.15 l/s per m. Low transmissivity values indicated low-yielding borehole whereas high transmissivity values indicated high-yielding borehole. Water samples were collected and sent to the laboratory for chemical analysis. Hydrochemical processes were also evaluated using the Durov diagram. The laboratory results suggested class 0 (good water quality) in borehole H07-2016 and H07-1685, class 1 (good water quality) in borehole H07-2023, class 2 (marginal water quality) in borehole H07-2015 and H07-2022, and class 3 (poor water quality) in borehole H07-2014. The pH values were in a range of 6.8 to 7.5, the electric conductivity of 30.2 – 332 µS/cm, Total alkalinity of 88.8 to 690.4 mg/l, and Total hardness of 94.48-776.79 mg/l. All metals (in boreholes H07-2015, 2022, 2016, 1685 and 2023) including As, Ca, Mg, Mn, K, Na, and Zn, had concentrations in a range of 0 mg/l -0.03 mg/l, 24.36 mg/l -155.90 mg/l, 8.19 mg/l – 94.40 mg/l, 0.01 mg/l – 0.76 mg/l, 0.71 mg/l – 4.80 mg/l, 21.75 mg/l – 418.45 mg/l, and 0.29 mg/l – 1.06 mg/l, respectively. All constituents were within the South African National Standards 241 (SANS): 2011 except borehole H07-2014 with a sodium concentration of 418.45 mg/l.

The Durov specified the dominance of dynamic water within the study area, this can be attributed to the fresh recent recharge water exhibiting Mg and HCO_3 dominance. In conclusion, all recently drilled boreholes, as well as the existing boreholes, can supply groundwater that meets the water needs of the current population (of about 6 500 people). It was estimated that all boreholes can supply about 325 000 l/day.

LIST OF ACRONYMS

AMSL	Above Mean Sea Level
CMB	Chloride Mass Balance
CSIR	Council for Scientific and Industrial Research
DOI	Depth of Investigation
DWS	Department of Water and Sanitation
FAO	Food and Agriculture Organization
GRA	Groundwater Resource Assessment
GRIP	Groundwater Resource Information Project
IGRF	International Geomagnetic Reference Field: the 12th generation
IPCC	Intergovernmental Panel on Climate Change
MRT	Mean Residence Time
NW	North-West
SANS	South African National Standards
SE	South-East
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Funds
USGS	United States Geological Survey
WHO	World Health Organization
WRC	Water Research Commission

DEDICATION

I would like to dedicate this work to my family, especially my grandmother Mrs. Nyadza Maria and my grandfather Mr. Nyadza Ratshilumela Phineas who always believes in me. They encouraged me not to give up until I achieve all my goals throughout my life. They always say I should create or make something out of nothing.

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CHAPTER 1: INTRODUCTION

This chapter describes the background on water challenges around the globe, more specifically on the groundwater system. This includes water shortage and water quality problems in Limpopo, South Africa. The problem statement, research aim, specific objectives, research questions, justifications of the study, and description of the study area were also presented.

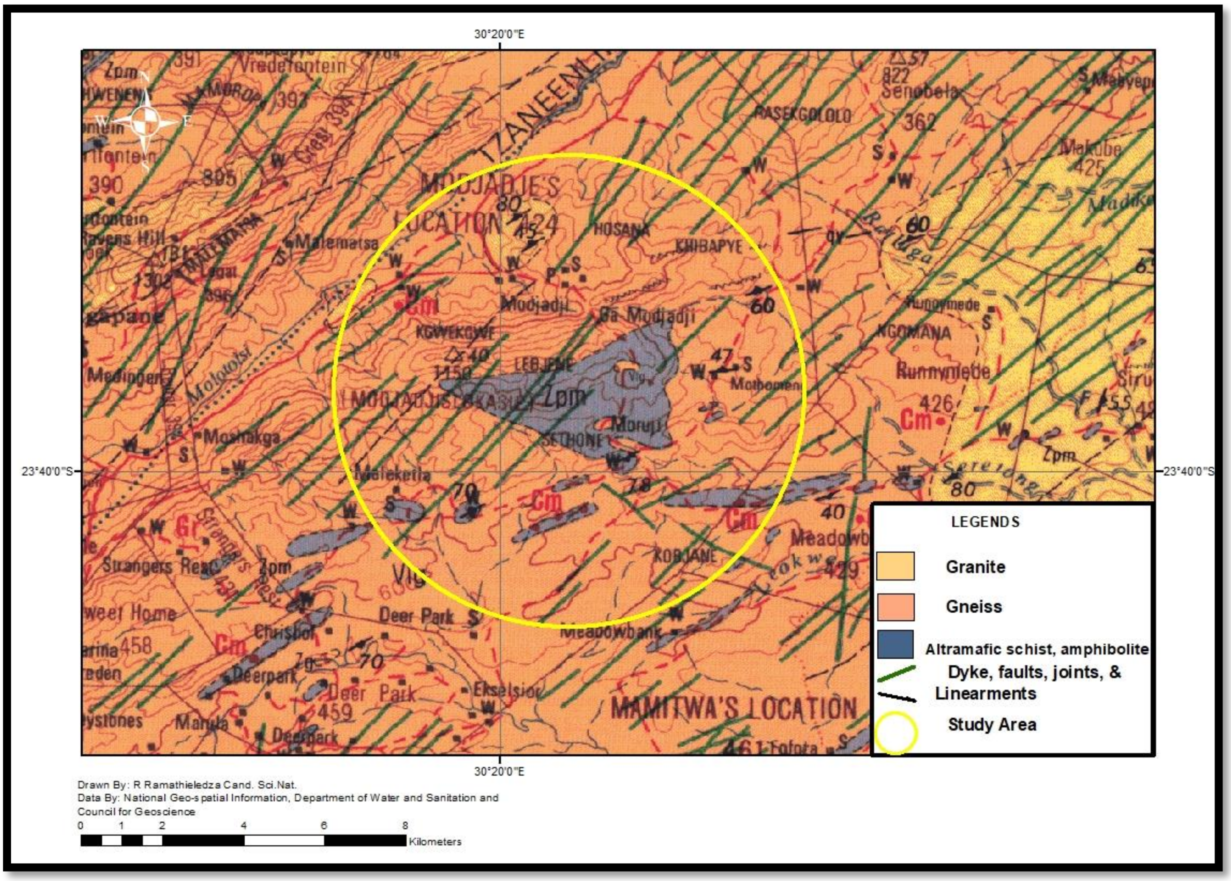
1.1 Background

Water is the cornerstone of life, without it living things on earth cannot survive. It is essential for livelihood (humans, animals, and plants). Safe drinking water and sufficient water available are some of our human rights (WHO, 2011). However, in most of the countries around the globe, this is still not a reality. According to WHO over 1.1 billion people do not have access to safe and sufficient water and more than 1 billion people are living in water-stressed areas. The water scarcity is extreme in developing countries and people struggle to get safe and sufficient water supply (Rosen and Vincent, 1999).

Southern Africa is one of the countries around the globe having challenges on water scarcity where people receive untreated surface or groundwater sources for their daily water uses (Monyatsi *et al*., 2012). On a global scale, groundwater is an essential resource for socio-economic and environmental systems, however it requires chemical analysis before use (UNEP/WHO, 1996). Studies conducted by the CSIR in 2010 shows that South Africa is facing a water supply crisis caused by a combination of low rainfall, high evaporation rates, an expanding economy, and a growing population whose geographical demands for water do not conform to the distribution of exploitable water supplies. Most parts of the country are semi-arid and consist of crystalline basement rocks which are distributed extensively throughout the country including Limpopo Province (Wright, 1992; Martin, 2011).

People who live in arid or semi-arid areas receive most of their water that is stored in crystalline rocks for a long time (Wright, 1992). In arid and semi-arid regions where the climate is prone to long periods of below world average rainfall, the requirements for sustainable sources of water that can withstand these low recharge periods are essential (Macdonald *et al.,* 1995). Groundwater resources is found in varying quantities depending in the underlying geological units, Limpopo province is one the areas which relies on groundwater rsources for domestic uses (Martin, 2011).

Crystalline aquifers are known as secondary aquifers, due to the low porosity and permeability of the underling rocks, they have a low storage capacity and water quality problems (Clark, 1985). The crystalline basement aquifers are categorized into two aquifer types, namely: weathered zone aquifers and fractured rock aquifers, and this is where the groundwater resources are stored in this type of aquifers (Shafick *et al.,* 2004). Relela villages are is located within the crystalline basement rocks in the Greater-Tzaneen Municipality, Mopani District, Limpopo Province in South Africa. The available information from geological studies indicates that the study area is underlined by igneous rocks; namely, gneisses and granite of the Archean greenstone belt (Brandl, 1987) see Figure 1.1.



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Data By: National Geo-spatial Information, Department of Water and Sanitation and Council for Geoscience

Figure **1.1**: Geological map of the study area

1.2 Location of the study area

The study area is located within the Mopani district, in the Greater-Tzaneen Municipality at the coordinates S 23°40ˈ45ˈˈ and E 30°19ˈ35.69ˈˈ and is accessed via R 529 road from Tzaneen town. The study area is located about 25 km northeast of Tzaneen town (Figure 1.2).

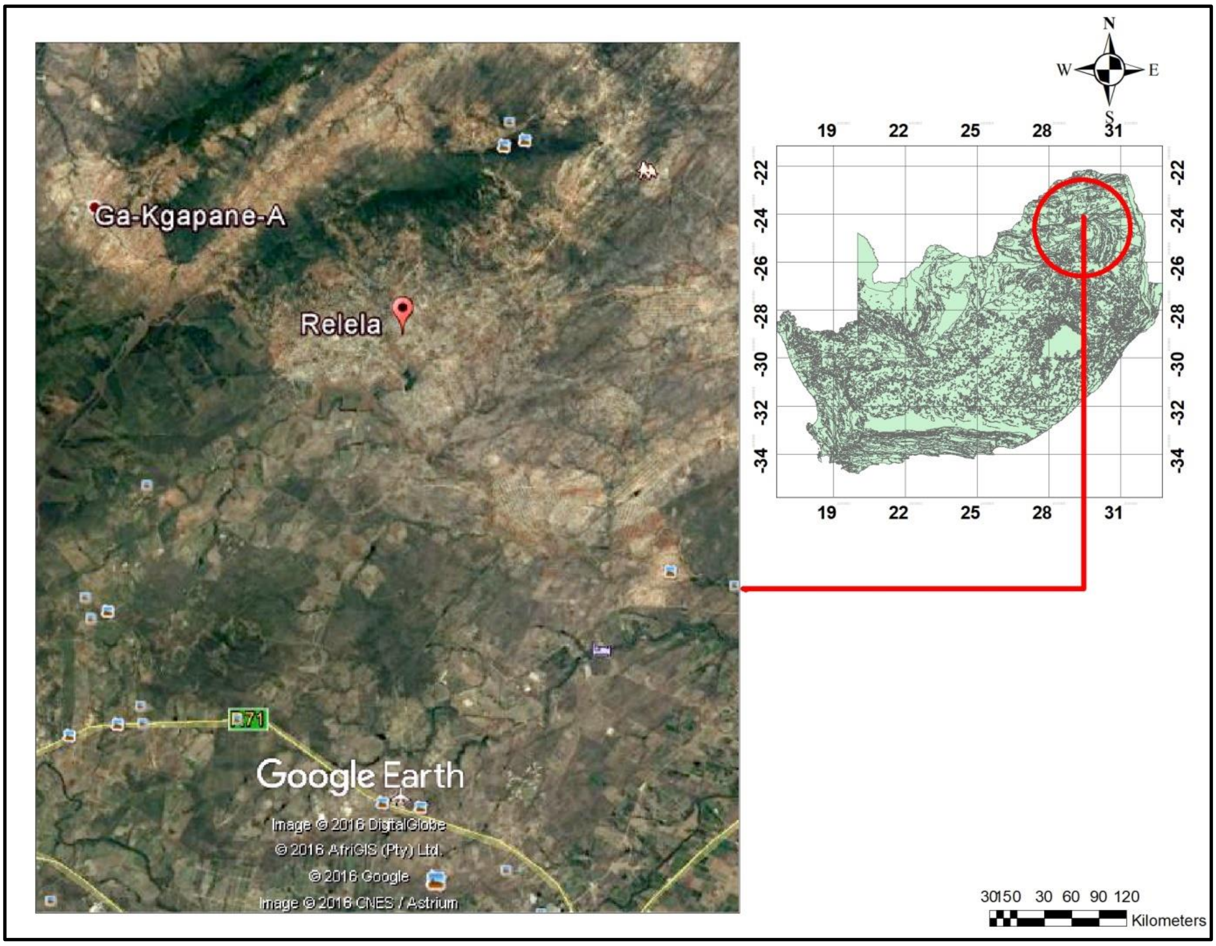


Figure **1.2**: Satellite image showing the study area

1.3 Climate

The climate in Tzaneen is warm tropical. It has two main climate seasons; winter and summer seasons. There is less rainfall in winter than in summer. The Köppen-Geiger climate classification (2006) suggested Cwb (C- warm temperature, w- winter dry, b- warm summer). Tzaneen has an average annual temperature of about 20.4 °C, with the average rainfall of about 965 mm per annum according to GRA II, 2003. The driest month is July with an average precipitation of 10 mm per month. The data gathered by kottek *et al*., (2006) shows that high precipitation falls in February, with the average of 213 mm per annum.

1.4 Topography

The study area is situated at an average elevation of 827 m to 587 m above the mean sea level (AMSL). The site is located on slightly steeping land, whilst the general area is situated in the easterly direction, flowing to the Nwanedzi River (Figure 1.3).

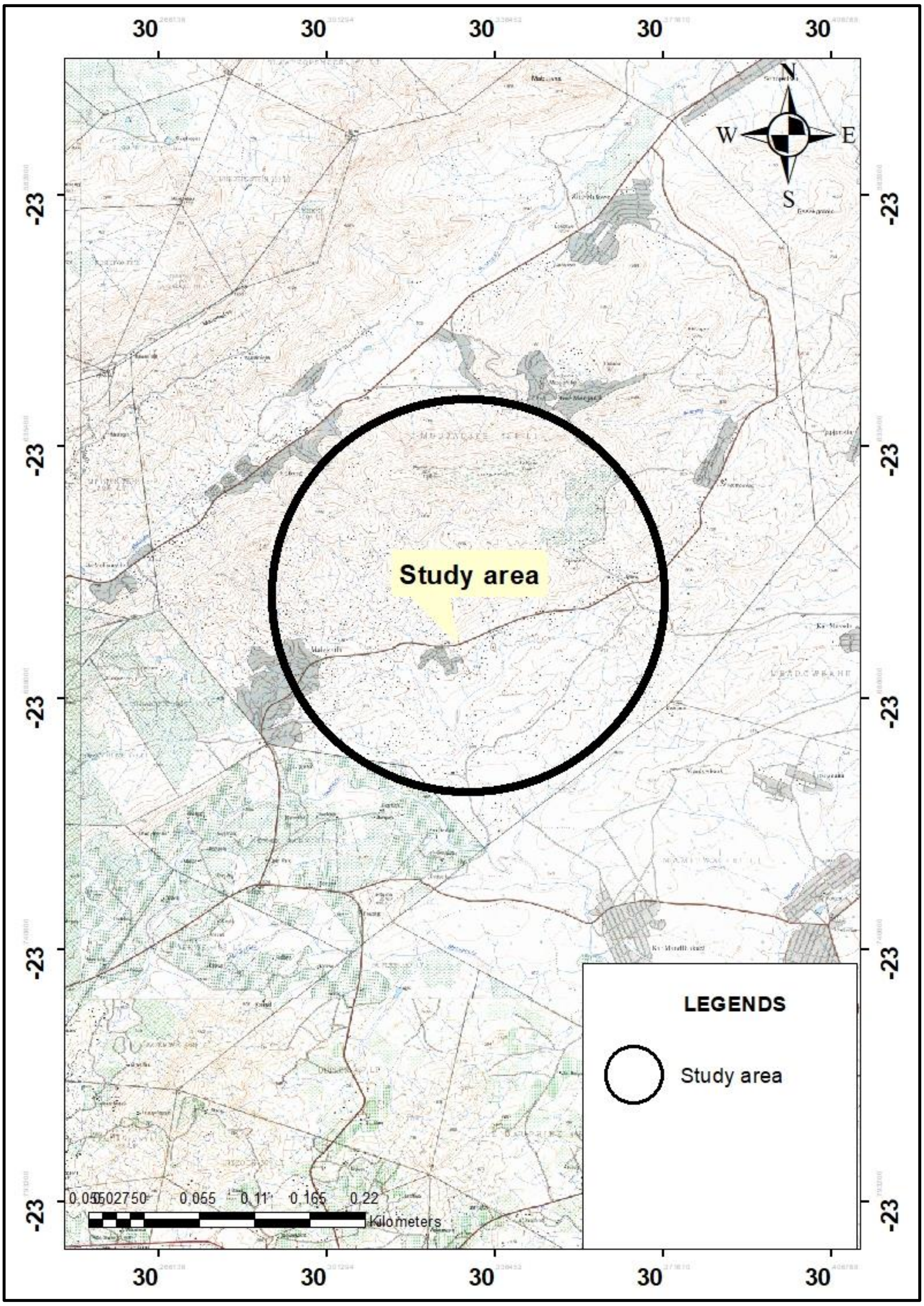


Figure **1.3**: Topographical map showing the study area

1.5 Pedology

The underlying rocks within the study area are covered by various soil types, described as Chromic Luvisols (FAO code: Lc65-1/2ab) which are sandy, loam, and clay soil (FAO, 1980). The bulk density is estimated to be 1.50 g/cm^3 and the available water content is approximately 0.18 mm/mm (Charles *et al.,* 2016).

1.6 Problem statement

Limpopo Province is one of the water-scarce regions of South Africa and the situation is worsened by climate change, population growth, and economic development (Matshidiso et al., 2014). Sarbeswar et al., (2015) stated that every geographical area should have some inborn causes of water scarcity related to its origin, structure, geographical location, and setup. Relela villages are found in Limpopo province, which falls under Greater-Tzaneen Municipality in the Mopani District and these are poverty-stricken villages that are currently faced with many problems including sustainable water supply. These villages rely mostly on the boreholes as their main source of water however, most of the drilled boreholes are low-yielding producing 0.2 l/s to 1.4 l/s (GRIP, 2010). This yield cannot meet the current population demand and the demand from the growing economic sector. Relela villages are underlined by the crystalline basement aquifers.

Crystalline basement aquifers are known for their low porosity and permeability. These aquifers require a good understanding of hydrogeology if the groundwater resource will be exploited and managed on a sustainable basis. Weathered-fractured aquifers which are the most likely to be found in these villages are known for their low storage capacity, low recharge potential, and low borehole yields (McFarlane et al., 1992; Clark, 1985; Jones, 1985). Other challenges the Relela community face are broken down water infrastructures (taps & pipelines), vandalism of existing borehole pumps, lack of electricity to pump water from the existing drilled boreholes, and illegal connections of piped water supplies by communities resulting in a huge water loss in the system. In most cases some members of the community walk for long distances to fetch water from rivers and streams.

1.7 Justification of the study

According to UNESCO, (1984) groundwater resources with good water quality can meet the water needs of the growing population if they are managed sustainably and effectively. The water scarcity and water quality problems are the major challenges in securing adequate water to meet human, environmental, social, and economic needs to support the developing countries. Poor water quality around the globe is a major concern threatening human health and the ecosystem’s integrity but also represents a serious problem for groundwater resources sustainability. This research will investigate the underlying aquifers of the Relela community by determining the aquifer characteristics. These will help to determine or evaluate the scientific use (safe yield) of groundwater resources, to meet the water demands for the growing population within the study area and its surroundings.

The groundwate resources contains different types of chemical constituens. Some of the chemical elements are harmless and they can results into acute health effects in some sensitive groups. This research will analyse groundwater quality from the investigated aquifers. In Relela community groundwater is used for domestic purposes, this research will classify the groundwater quality according to the Deprtment of Water and Sanitation (DWS) water quality standards to determine its sustainability.

The information from this research will be used to guide DWS, researchers, world organizations like WHO, to improve water management plans and clause. This study will also be used to create awareness about water scarcity and water quality in the Greater Tzaneen Municipality, Mopani District, in Limpopo province.

1.8 Objectives

1.8.1 Main objective

The main aim is to study groundwater availability, quality, and sustainability for human consumption to meet the demand associated with population growth at Relela community.

1.8.2 Specific objectives

- To determine the groundwater potential zones using geophysical exploration.
- To identify characteristics of the aquifer systems based on the lithological analysis.
- To evaluate the hydraulic characteristics Transmissivity (T), Specific capacity (Cs), Safe yield (Q) of aquifers through pump testing
- To determine the exploitable groundwater resource and determine whether the resources are sufficient for the current and future water demands to supplement the municipal water supply.

1.9 Research questions

What are the major uses of the extracted groundwater?

Where are the groundwater occurrences in Relela villages?
What are the geological characterizations of the aquifer?
What are the characterizations of aquifer hydraulics and storage properties?
What is the groundwater quality at Relela villages and is it suitable for human consumption?
Can the available groundwater be used as a water supply to the Relela villages sustainably?
What are the possible groundwater resource supply challenges and strategies for resolving them?

1.10 Hypothesis

- Groundwater occurs within geological structures, fractured and weathered zones.
- The groundwater is fit for human consumption before treatment.
- The groundwater can be used sustainably if the borehole is managed and abstracted efficiently.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

This chapter outlines the literature related to the occurrence of groundwater, groundwater resources, and the associated risks, both from natural and anthropogenic activities, regional and local geology of the study area, an overview of crystalline aquifers, hydraulic characteristics of aquifers, major factors on the availability or potentiality of groundwater resources, sustainable groundwater supply, and case studies on sustainable groundwater resource supply.

2.1 Regional geology

The geological description of the study area was referred to the studies conducted by (Brandl and kroner, 1993), which indicate the occurrences of various granitoid of highly crystallized basement rocks in the Northeastern Kaapvaal Craton (Figure 2.3). The granitoid was formed through intrusions such as Palaeoarchean intrusions (3600-3200 Ma), Mesoarchaean intrusions (3200-2800 Ma), and Neoarchaean intrusions (2800-2500 Ma). The surrounding lithologies such as dyke intrusions within the study area will also be considered, because lot of the post-Archaean geological structures are not limited to the basement rocks alone (Konstant, 2009). Figure 2.1 and Table 1.1 show a geological map and a geological timeline of emplacement events of granitoid intrusions in the northeastern Kaapvaal Craton.

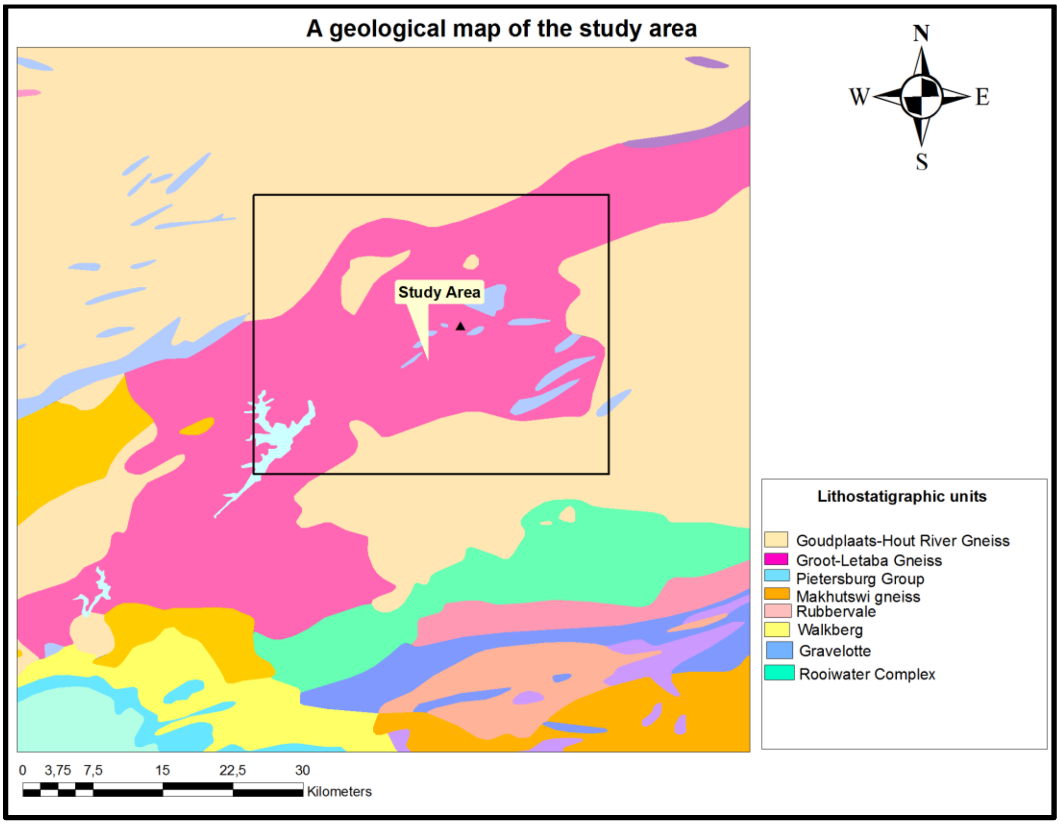


Figure **2.1**: Geological map of the study area (adapted from the Council of Geosciences)

Table **1.1**: The emplacement events of granitoid intrusions in the northeastern Kaapvaal Craton (adopted from Brandl and Kroner, 1993).

Rock Unit	**Sample characteristics**	**Age (years)**	**Method**
Goudplaats-Hout River Gneiss (GHRG)	Migmatitic tonalite gneiss	3333 ± 5 (C)	C = Pb-Pb zircon evaporation
GHRG	Tonalite gneiss (Tg)	3282.6 ± 0.4 (C)	C = Pb-Pb zircon evaporation
GHRG	Tg	3274 +56/-45 (A)	A = U-Pb ID-TIMS
Makhutswi-Gneiss	Trondhjemite & tonalite gneiss	3228 ± 12 (A)	A = U-Pb ID-TIMS
Harmony-Granite	Trondhjemite gneiss	3091 ± 5 (A)	A = U-Pb ID-TIMS
Makhutswi-Gneiss	Tonalite gneiss	3063 ± 12 (A)	A = U-Pb ID-TIMS
Baderoukwe Granite	Trondhjemite	3018 ± 15 (A)	A = U-Pb ID-TIMS
Maranda Granite	Granite	2969 ± 17 (A)	A = U-Pb ID-TIMS
Melkboomfontein granite	Granite	2853 +19/-18 (A)	A = U-Pb ID-TIMS
Gravelotte area	Pegmatite	2848 ± 58 (A)	A = U-Pb ID-TIMS

Willie Granite	Porphyritic granite	2820 ± 38 (A)	A = U-Pb ID-TIMS
Turfloop Granite (TG)	Porphyritic granodiorite	2777 ± 10 (A)	A = U-Pb ID-TIMS
TG	Monzogranite	2765 ± 7 (A)	A = U-Pb ID-TIMS
TG	Porphyritic granodiorite	2763 ± 15 (A) (T)	A = U-Pb ID-TIMS
Rooiwater Complex	Hornblende tonalite	2740 ± 4 (A)	A = U-Pb ID-TIMS
Mashishimale suite	Peraluminous granite	2698 ± 21 (A)	A = U-Pb ID-TIMS
Lekkersmaak Granite	Porphyritic granite	2690 ± 65 (A)	A = U-Pb ID-TIMS
Uitloop Granite	Granite	2687 ± 2 (A)	A = U-Pb ID-TIMS
Matok Granite	Charno-enderbite	2671 ± 2 (C)	C = Pb-Pb zircon evaporation

2.1.1 Kaapvaal Craton

The kaapvaal Craton is particularly well endowed with large areas of granitoid gneisses containing several infolded greenstone belts or their remnants, ranging in age from 3 500 Ma to 2 700 Ma (Brandl *et al.*, 1993). The Craton covers an area of about 1.2 x 10^6 km^2 and is made up of strongly deformed early Archean (de Wit *et al.,* 1992). The Craton formed and stabilizes when major granitoid batholith intruded, and deformation thickened the crust. At the same time a thick, stable harzburgitic keel formed the lower part of the lithosphere (Muriel, 2011).

Relela villages are located in the northeastern sector of the Kaapvaal Craton. The Mesoarchean intrusions (3200-2800 Ma) are in the vicinity of the study area (Relela villages in Tzaneen) and they consist of highly metamorphic basement rocks such as porphyritic granitoid and Groot-Letaba Gneiss (Poujol et al., 1996). The study area consists of various Archaean subdomains which are Palaeoarchean intrusions, Mesoarchaean intrusions and Neoarchaean intrusions.

2.1.2 Palaeoarchean intrusions

Palaeoarchean intrusions are distinguished by the widespread occurrence of G-H-R Gneiss suite, Klaserie Gneiss, and Makhutswi Gneiss which comprises the wide spectrum of granitoids gneisses of various types and composition (figure 2.1).

These gneissic bodies ranges from homogeneous to strongly layered, from leucocratic gneiss to dark-grey gneiss, and from fine-grained to pegmatoidal varieties (Brandl, 1986, 1987; Dutoit et al., 1983; Anhaeusser, 1992; Brandl and Kroner, 1993). They underlie both the high-grade (Southern Marginal Zone, Limpopo Belt) and low-grade terranes of the northern part of the Kaapvaal Craton, mainly to the north of Pietersburg and Giyani Greenstone Belts (Figure 2.2). The gneisses typically form flat ground with poor exposure. The previous subdivision into a leucocratic, strongly migmatised gneiss (Hout River) and a grey, layered, but less well-magmatised gneiss (Goudplaats) is no longer regarded as tenable (Brandl, 1993).

2.1.3 Mesoarchaean intrusions

The study area falls under the Mesoarchean intrusions (3200 – 2800 Ma. The Mesoarchaean intrusions consist of various greenstone belts as well as the surrounding granitoid rocks (gneisses, granites, and pegmatites). Vearncombe, (1991) and Vearncombe et al., (1992) interpreted the Murchison Greenstone Belt as a volcanic arc which was formed millions of years ago, between *c*.3090 and 2970 Ma (Brandl *et al*., 1996; Poujol et al., 1996). Six main magmatic events have been identified within the Murchison Greenstone Belt, five of which are of Mesoarchaean age at *c*. 3090, 3060, 3020, 2970, and 2680 Ma, and the sixth being Neoarchaean in age (*c*. 2680).

The Groot-Letaba Gneiss consist different granitoid gneisses which were formed between the Murchison and the Pietersburg- Giyani greenstone belts (Brandl and Kroner, 1993; figure 2.2). The Groot-Letaba Gneiss extends from a point southeast of Polokwane towards the Lowveld in the east, where it is overlain by karoo rocks. It encompasses different types of gneisses, such as minor banded and linear gneisses, fine to medium-grained tonalite and coarse-grained trondhjemite.

2.1.4 Neoarchaean intrusions

During the Early Neoarchaean times (2800-2500 Ma) magmatic activity caused tectonic granitoid movements in the Pietersburg and Murchison areas. The granites from Neoarchaean granites are found in the study area, and they are relative to the older granitoid gneisses (Robb et al., 2006). The ages estimated for these intrusions ranges from 2800 Ma and 2650 Ma (Kröner *et al.,* 2000).

The Turfloop Granite is the most underlying lithology and best-researched group of granite bodies and it forms an elongate north-east trending batholith (Figure 2.2). The Turfloop granite consists of different mineral compositions ranging from granodioritic to monzogranitic, which might be an indication that this granitic body is composed of a small number of plutons of similar age and origin (Henderson *et al.,* 2000). Some of the minerals that made up this rock are plagioclase, quartz, orthoclase, biotite, and muscovite (Kroner *et al.,* 2000).

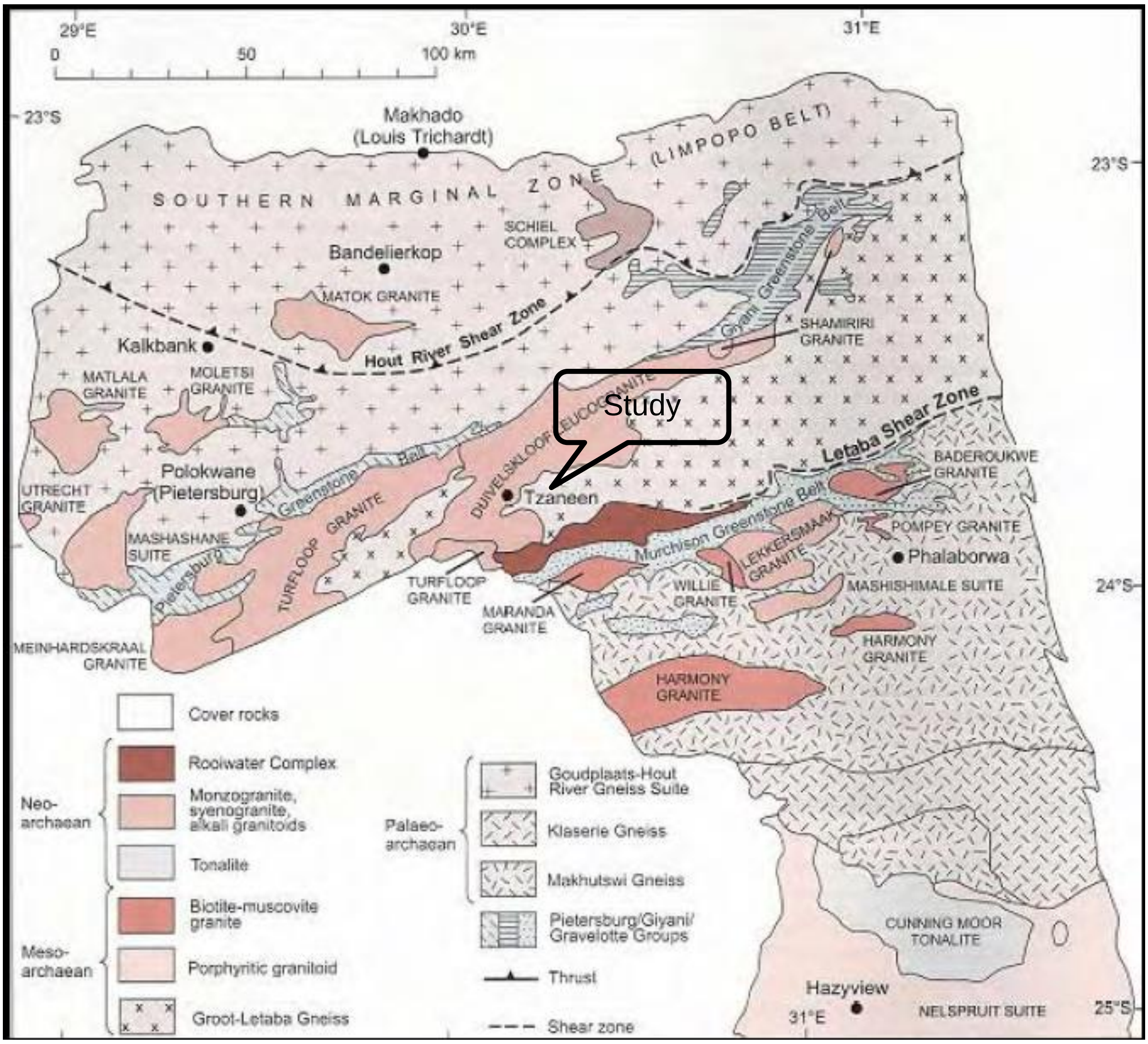


Figure **2.2**: The map of the study area in the northern and northeastern sector of the Kaapvaal Craton showing the various granitoid occurrences (Robb *et al*., 2006).

2.2 Sustainable groundwater resource supply

Groundwater is one of the most crucial natural resources. According to William *et al.,* (1999) it provides about 40 percent of South Africa’s public water supply. More than 40 million people, including most of the rural population, supply their drinking water from groundwater resources (William *et al*., 1999). Alley *et al.,* (1999); Leake, (2004) described sustainable groundwater resources as the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. The concept of sustainability includes the consideration of issues such as ecology, water quality, and environmental welfare (Delvin and Sophocleous, 2005).

Two terms that are associated with groundwater sustainability are safe yield and overdraft (US Water Resource Council, 1980). The term safe yield is defined as the sufficient good quality water withdrawn from a well without producing undesired results, and the term overdraft refers to borehole water extraction at an excessive rate (Todd, 1959,).

2.3 Risks involved with Groundwater resources, natural and anthropogenic activities

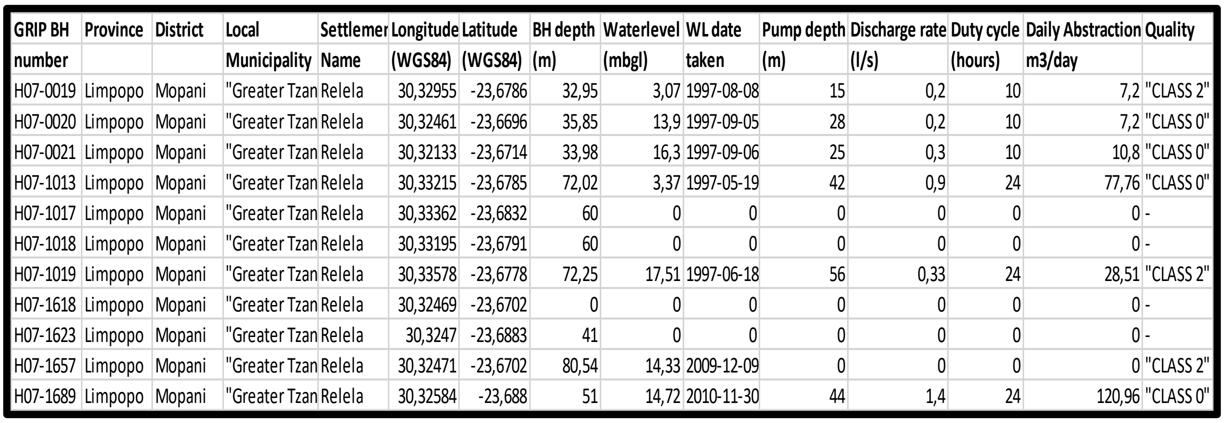
People around the world depend on groundwater for domestic use, such as drinking, washing, and bathing. Recently there has been high stress on the groundwater due to massive groundwater abstraction and the ever-increasing demand for water around the world due to factors like population growth and climate change (Kathrin, 2011). Most of the countries around the world depend on groundwater for survival but there is a need to use it sustainably. Furthermore, many aquifers worldwide and have been put at risk due to high extraction rates and anthropogenic activities that lead to the contamination of groundwater include; agriculture, mining activities, operating filling stations, etc. This results in long-term negative environmental impacts. Some of the factors affecting groundwater resources are discussed below. These include groundwater quantity problems,water quality problems, and the impacts caused by climate change.

2.3.1 Groundwater Quantity problems

Water scarcity is experienced in many parts of the world, population growth, socio-economic development, and climate change are considered to be the main contributing factors. Thus people who depend on groundwater for survival are overexploiting the underlying aquifers, resulting in the drying up of boreholes, decrease in water tables, groundwater contamination, and impacts the biodiversity (Sophocleous, 2009). Danielopol *et al*., (2003) stated groundwater overexploitation will results in water shortarge and water demand in the next 25 years. Thus societies must recognize the significance of groundwater resource use and scientific water use when there is a high demand for groundwater.

According to Groundwater Information Project (GRIP), the available data of the water quantity and quality at Relela villages shows the borehole yields range from 0.2 l/s to 1.4 l/s and the water quality is classified as class 0 to class II. Class 0 to Class I can be consumed without health effects but Class II can be sensitive to some other groups (DWAF, 1998) see Table 2.2 below.

Table **2.2**: Grip for Relela villages showing the existing borehole information such as borehole depth, pump depth, discharge rate, water quality, and recommended abstraction rate.



GRIP BH number	Province	District	Local Municipality	Settlemer Name	Longitude (WGS84)	Latitude (WGS84)	BH depth (m)	Waterlevel (mbgl)	WL date taken	Pump depth (m)	Discharge rate (l/s)	Duty cycle (hours)	Daily Abstraction m3/day	Quality
H07-0019	Limpopo	Mopani	"Greater Tzan	Relela	30,32955	-23,6786	32,95	3,07	1997-08-08	15	0,2	10	7,2	"CLASS 2"
H07-0020	Limpopo	Mopani	"Greater Tzan	Relela	30,32461	-23,6696	35,85	13,9	1997-09-05	28	0,2	10	7,2	"CLASS 0"
H07-0021	Limpopo	Mopani	"Greater Tzan	Relela	30,32133	-23,6714	33,98	16,3	1997-09-06	25	0,3	10	10,8	"CLASS 0"
H07-1013	Limpopo	Mopani	"Greater Tzan	Relela	30,33215	-23,6785	72,02	3,37	1997-05-19	42	0,9	24	77,76	"CLASS 0"
H07-1017	Limpopo	Mopani	"Greater Tzan	Relela	30,33362	-23,6832	60	0	0	0	0	0	0	-
H07-1018	Limpopo	Mopani	"Greater Tzan	Relela	30,33195	-23,6791	60	0	0	0	0	0	0	-
H07-1019	Limpopo	Mopani	"Greater Tzan	Relela	30,33578	-23,6778	72,25	17,51	1997-06-18	56	0,33	24	28,51	"CLASS 2"
H07-1618	Limpopo	Mopani	"Greater Tzan	Relela	30,32469	-23,6702	0	0	0	0	0	0	0	-
H07-1623	Limpopo	Mopani	"Greater Tzan	Relela	30,3247	-23,6883	41	0	0	0	0	0	0	-
H07-1657	Limpopo	Mopani	"Greater Tzan	Relela	30,32471	-23,6702	80,54	14,33	2009-12-09	0	0	0	0	"CLASS 2"
H07-1689	Limpopo	Mopani	"Greater Tzan	Relela	30,32584	-23,688	51	14,72	2010-11-30	44	1,4	24	120,96	"CLASS 0"

2.3.2 Groundwater Quality problems

The chemical and biological characteristics of groundwater must meet some minimum requirements that are acceptable for the intended use. However, groundwater may contain natural heavy metals, semi-metals, metalloids, and halogen concentrations, and this is predominantly referred to as water quality characteristics (Raiswell, 1980). The groundwater quality particularly in shallow aquifers, are contaminated as a result of human activities such as mining, urban development, industry, and agricultural activities. According to the World Health Organisation (WHO), The tested water with dissolved minerals exceeding 1 000 mg/L IS considered as poor water quality for human consumption. Figure 2.3 shows a schematic diagram representation of groundwater pollution through human activities.

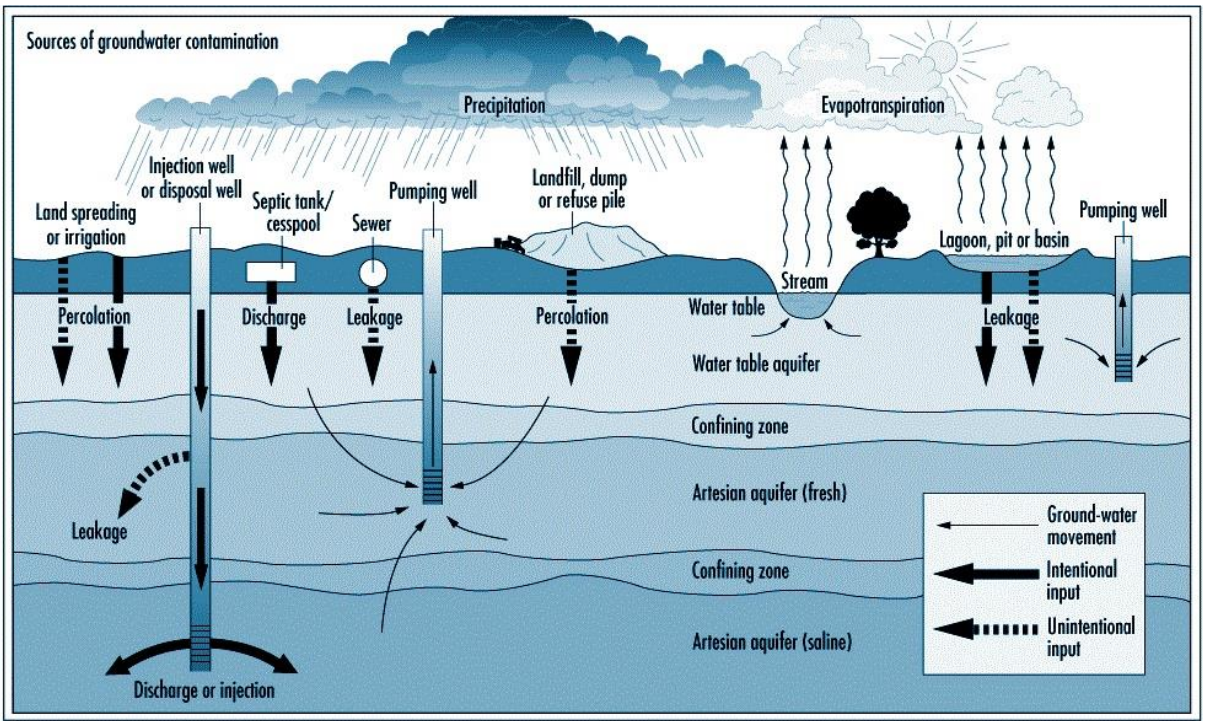


Figure **2.3**: A schematic representation of the processes leading to groundwater pollution (Preul and Schroepfer, 1968).

2.3.3 Climate change impacts

Contemporary global and regional climate change poses an immense challenge to the groundwater resources, this includes unexpected natural disasters such as heavey flooding resulting in groundwater contamination and frequent periods of drought (Shrestha, 2015). The groundwater sustainability can affected by the climate in several ways. The groundwater sustainability can be affected by climate change in several ways these includes changes in groundwater recharge, changes in evapotranspiration, and the increase in demands of groundwater use as a backup source for water supply (William *et al*., 1999). Unscientific groundwater withdrawal during drought seasons could cause overexploitation of aquifers, which can result in water shortage throughout the dry seasons.

2.4 The occurrence of groundwater

Most of the groundwater occurs mainly through the process called the hydrological cycle. Pidwirmy, (2006) defined the hydrologic cycle as conceptual model that describes the storage and continuous movement of water between the biosphere, atmosphere, lithosphere, and hydrosphere. Evaporation is the first stage of the hydrologic cycle, water evaporates from all surface water bodies. The water vapour is lifted and condenses to form clouds. The water returns to the surface in the form of precipitation (rain fall). When the precipitation reaches the eartgh's surface, infiltration, surface runn off and percolation occur, thus the water will move through the soil particles from the surface to the subsurface forming undergroundwater. The undergroundwater is released back into the atmosphere through evaporation and transpiration (Figure 2.4).

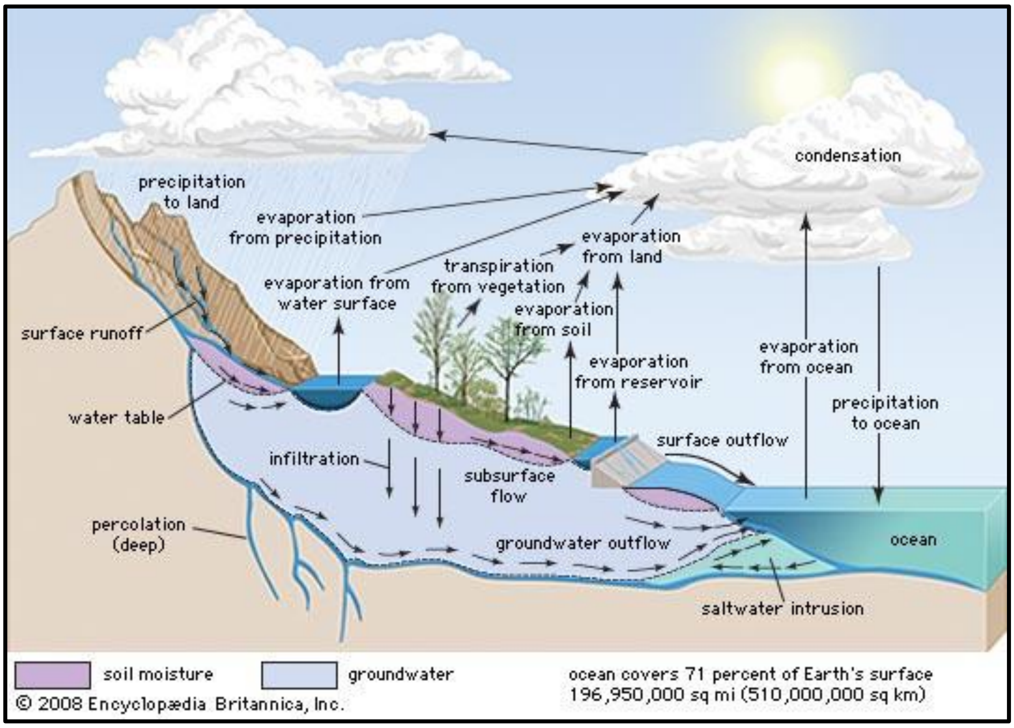


Figure **2.4**: A diagram showing the hydrologic cycle (Cheng & Reid, 2001).

2.5 The overview of crystalline aquifers

The term crystalline aquifers (hard rock) is defined as the rocks with ninor intergranular pore spaces and these are mostly igneous or metamorphic rocks. The groundwater flow through cracks and fractures in the underlying aquifers such as granites, basalts, metaquartzites, or gneisses (Banks and Robbins, 2002). The development of sustainable groundwater supply in a crystalline basement aquifer is complex and the groundwater occurrence is highly variable (Chilton and Foster, 1995). Crystalline basement rocks mostly underlies large parts of Africa and South Africa is also underlined by the crystalline basement rocks (Martin, 2011). It is estimated that South Africa constitute about 55 % of the crystalline basement aquifers land area (WRC, 2009). Braune and Mutheiwana, (2009) indicated that about 60 to 90% of rural areas in southern Africa mostly uses groundwater originating from crystalline basement aquifers.

2.6 Characterisation of Crystalline Basement Aquifers

Crystalline basement aquifers are made of hard rocks such as granites, basalts, metaquartzites, or gneisses with minor porosity and permeability (Gustafson,1994). In general, South Africa is underlain by crystalline bedrocks, and in other places overlaid by a thick sedimentary cover. The crystalline bedrocks in South Africa are divided into three main suites:

I. Ancient rocks such as granites, gneisses, and greenstones.

II. Metamorphic rocks like gneisses of the Limpopo Mobile Belt

III. The intrusions rocks of various ages, like the Bushveld Igneous Complex and Cape veldGranite Suite.

The groundwater potential in this areas are found in weathered or crystalline basement rocks

2.6.1 Weathered-fractured rocks

The traditional weathering-fracturing concept proposed in the 1980s and 1990s (i.e. Jones, 1985; Acworth, 1987; Chilton and Foster 1995) still applies to most crystalline basement terrains and recently (e.g., Dewandel et al., 2003). The “classical” model of a basement aquifer refers to the following layers which have specific hydraulic properties (Figure 2.5):

a) Unconsolidated material derived from regolith, with a thickness extending to a greater depth.

b) Weathered material wherin the porosity decreases with depth, all together with soft soil, up until the fresh bed rock is reached.

c) The fractured-weathered layer is generally characterized by a fracture density that decreases with depth, mostly controlled by cooling stresses in the magma and subsequent tectonic activity (Houston and Lewis, 1988).

d) Consolidated basement rocks, permeable only in weak zones such as cracks.

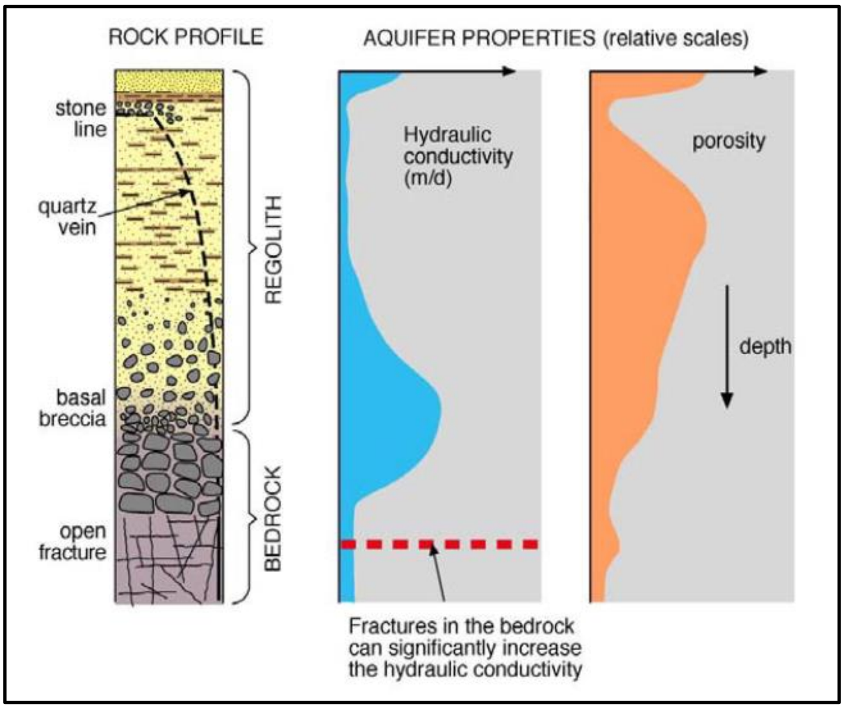


Figure **2.5**: Crystaline basement aquifers (Foster, 1995).

The observed variations in different crystalline aquifers are attributed to two main factors: 1) the degree of weathering and the saturation and 2) the extent of fracturing. These are the factors which influence the potentila of groundwater. The water quantity in crystalline basement aquifers depends on the degree of weathered material and the fracturing of overlying and underlying rock (Burgess, 1992). These aquifers are of great interest in arid crystalline terrain which usually lacks enough surface water resources and where in most cases poses a thin weathered overburden. The focus in such areas is usually on groundwater flow in the fissures/fractures within the underlying bedrock (Titus *et al.,* 2009).

2.6.2 The groundwater flow behaviour

The water flow in hard rock is controlled by hydraulic gradient and the hydraulic conductivities making it very complex. Wright (1992) developed a model for the groundwater flow and the groundwater recharge systems in the crystalline basement regions of sub-Saharan Africa. Tóth (1963) showed that the groundwater flow systems can be placed over one another within a groundwater basin, using two-dimensional flow in vertical section. This contrasts the general groundwater flow behaviour in crystalline aquifers and this suggests that groundwater flow is shallow, mainly occur in the weathered and fractured zones, generally limited to 50 mbgl level (Howard, 2011).

In general, the regional flow occurs within the major interconnected fracture systems, which is linked/interrelated with the main groundwater flow systems localized to the zones between recharge from watersheds to discharge by run-off or evaporation at valley bottoms (Figure 2.6). Fractures such as contact zones which are exposed on the Earth's surface act as the path way to the underlying lithologies (Howard, 2011). High porosity of the underlying rocks increases the storativity that slowly percolates into bedrock. However, the groundwater recharge into the bedrock becomes difficult to estimate as it is controlled by the hydraulic characteristics at the regolith–bedrock interface.

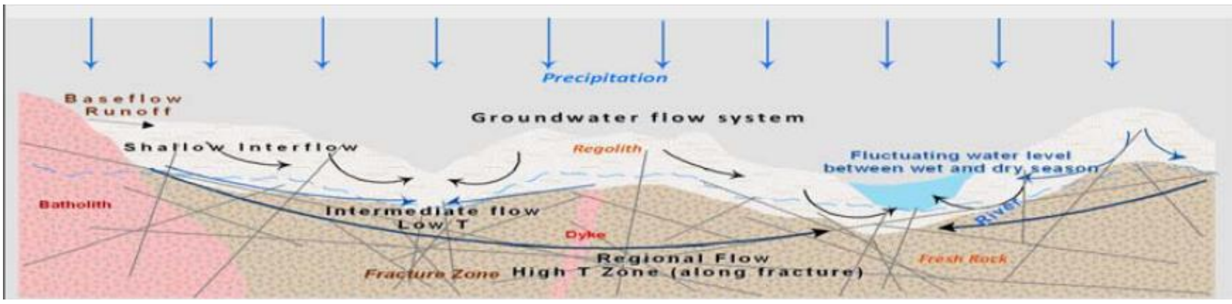


Figure **2.6**: groundwater flow in the crystalline basement aquifers (Adapted from Tóth, 1963; Chilton and Foster, 1995).

2.7 Groundwater Recharge

Groundwater recharge is the amount of rainfall that penetrates deep into the bedrock, driven by downward infiltration and percolation through the unsaturated zone (Shafick *et al.,* 2004). Lerner *et al*., (1990) indicated that in crystalline basement rocks groundwater recharge can results in weathering and fracturing of the underlying lithologies. According to Winter, (1996) the relief of land and bedrock surface above groundwater discharge areas, lateral trends in bulk-rock horizontal conductivity, local topographic features, and local drift stratigraphy are the main factors which contribute to the recharge pattens into the groundwater system. Figure 2.7 below shows the relationship between groundwater recharge in relation to rainfall. Deep weathering in bedrocks is dominated by high infiltration rates, and land wearing of terrestrial surface is dominated by high runoff (Taylor and Howard, 1999). GRA II (2003) studies showed that the B81E quaternary catchment of about 665 km^2 area in which Relela villages are located, has an average annual precipitation of 667.08 mm and a recharge value of about 4.26 %.

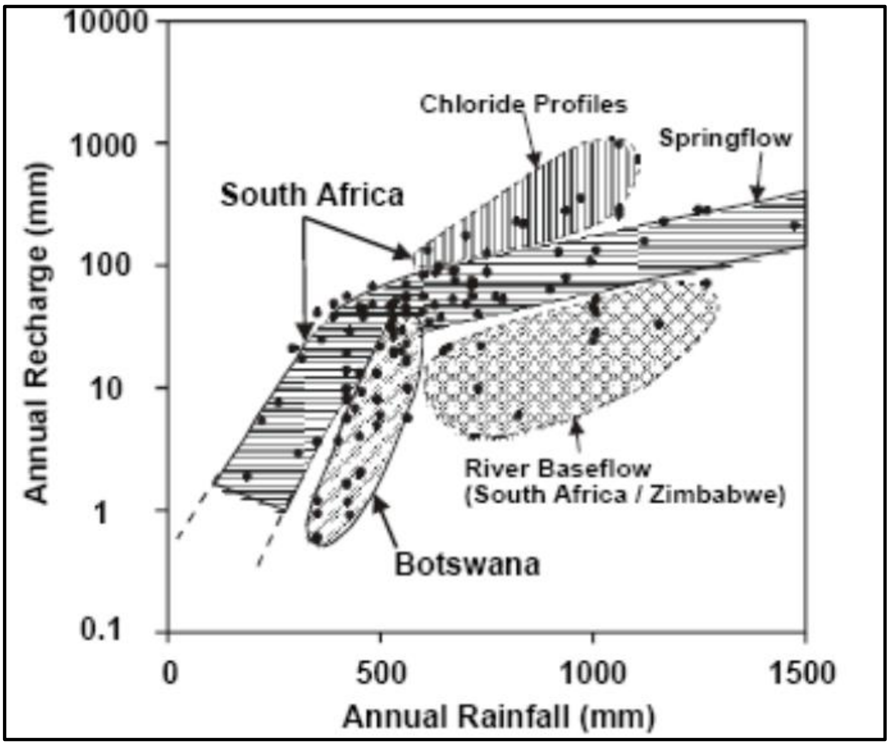


Figure **2.7**: The groundwater recharge estimates for southern Africa (Adams et al., 2004).

The evaporation rate is higher than average annual rainfall, and groundwater recharge is likely to be low more especially in arid environment like south Africa (Howard, 2011). The recharge from direct infiltration is likely to be small mostly when the annual rainfall is less than 400 mm (Wright, 1992). However, quantification of groundwater recharge values is an important element in geohydrology, especially in semi-arid areas such as the Limpopo Province for groundwater sustainability. The estimation of recharge is subject to significant uncertainty in crystalline basement terrain, because of the heterogeneity and discontinuity of the aquifers and the associated complexities in the groundwater flow systems (Chilton and Foster, 1995). Several conventional methods of groundwater recharge estimation can be applied in semi-arid environment (Xu and Beekman, 2003).

The CMB method is one of the methods which is commonly used for determining recharge rates in fractured underlying aquifers (Cook, 2003). The chloride present in groundwater must be taken into consideration when estimating the recharge rate by using CMB method (Banks et al., 2009). The CMB-method alone cannot give an accurate account of recharge estimations and should be used in conjunction with other recharge methods. The groundwater level fluctuations and rainfall correlation methods can be used in conjunction with CMB to improve the recharge results (Adams et al., 2004). The analyses of water-level fluctuations are useful for determining the magnitude of long-term changes in recharge as a result of climate change or land use. The water fluctuation method usually includes the use of static water level data from existing boreholes.

2.8 Groundwater quality

The groundwater quality shows the state at which the water is consumable or not. In most basement terrains the groundwater quality is generalized as good (Foster, 1995), with low salinities and neutral to slightly acid pH values. High salinities values are elevated in areas of low groundwater recharge. The chemical elements which exceed the maximum allowed limit can results in acute health effects if they are used without any treatment (Marais, 1999). High concentrations of nitrates, fluorides, and sulphates can cause harm to human health (Clark, 1985). Crystalline basement aquifers are prone to groundwater contamination since groundwater movement is through rock fractures and weathered zones. It is important to test water quality from a newly developed borehole before utilization. In rural areas most of the boreholes are sited close to pit latrines, and this results in microbial contamination.

2.8.1 Geochemical studies

There are many geochemical techniques and methods in use for the interpretations of hydrochemical processes in groundwater systems, and an improved understanding of how structural, geological, and hydrological features affect flow and chemistry (Glynn and Plummer, 2005). With the current technology, there exist several equipments for water quality studies. The data obtained can be benched marked with international and national standards to determine if the water meets the minimum standard requirements. Several methods are used to determine the relationship between different chemical parameters (McNeil et al., 2005). The relationship from the statistically defined clusters of samples to the geographic location can portray the variations in regional distribution.

The isotopes and hydrochemical studies give more information on the structure of the underlying aquifers (McFarlane, 1992). The depth (shallow or deep) of the aquifers can be distinguished using the hydrochemical and isoptope data (Praamsa *et al.,* 2009). These data are also used to identify the zones of interaction and groundwater recharge processes (Jayasena *et al.,* 2007).

2.9 Groundwater exploration using Geophysics

Geophysics is defined as the physics of the earth and its surrounding atmosphere (Telford, 1990). Geophysical applications for different studies involve taking measurements of the behavior of the physical properties of the earth. The vertical and horizontal variations in geophysical data or information are important in the sciences of geophysics. When planning for groundwater development or acquiring the information on subsurface hydrogeology, geophysical investigations is widely used because it’s cost effective (Brooks, 1991).

The groundwater exploration and water quality evaluation using geophysical techniques has increased over the last years due to rapid advances in electronic technology and the development of numerical modelling solutions (Metwaly *et al.,* 2009). The most used geophysical technique for groundwater exploration is the electrical resistivity method because it’s cost-effective, simple to operate, and more efficient in areas with high contrasting resistivities, such as between the weathered overlying and underlying lithologies (Sheriff, 1990).

The hydrogeological properties such as porosity and permeability make it possible for the geoelectrical methods to work perfectly when doing groundwater exploration, this is because these properties can easily be correlated to the electrical resistivity values. Geoelectrical techniques such as the resistivity method can provide information on the different subsurface lithological layers, underground geological structures, and the associated occurrence of groundwater (Van Overmeeren, 1989, Dahlin *et al.,* 1999, Nowroozi *et al.,* 1999). The resistivity is also related to various geological parameters such as weathering, fluid content, unsaturated zones, and saturation zones.

Another method that is widely used in groundwater surveying is the electromagnetic method. The magnetic exploration technique for groundwater is focused on finding anomalous measurements of the earth’s magnetic field which is the measurement of the property called: Magnetic susceptibility which is the amount of magnetization in a substance exposed to a magnetic field. The magnetic method detects horizontal variations in susceptibility (Gadallah and Fisher, 2009). Most igneous or metamorphic rocks contain magnetic minerals, the amount of magnetism in most of the crystalline rocks has two-component which are induced, and the remnant magnetic field formed during geologic history (Kayode *et al.,* 2013).

2.10 The hydraulic characteristics of aquifers

An aquifer is defined as the underlying geologic formation that is sufficiently permeable to allow water to be stored in a sufficient volume (Rae, 1988). There are two different types of aquifers, namely: confined and unconfined aquifers. A confined aquifer is a saturated layer found between two impermeable layers. This type of aquifer has high pressure due to the overburden, when a weak zone or a well is created in the confined layer the water level will rise to the well tube. An unconfined aquifer is an aquifer whose water strike or the upper water table is exposed to atmospheric pressure. When a weak zone or a well is developed in this type of aquifer, the water level can rise and fall in the well (DeWiest, 1965).

2.10.1 The groundwater hydraulics

Crystalline basement aquifers can be considered to fall on a continuum between porous media and conduit systems (Cook, 2003). The unconsolidated weathered rock represents a porous medium, while the consolidated fractured bedrock represents a fractured porous media and groundwater flows in the conduit network and water is stored in the aquifer matrix between the conduits. Aquifer or pump testing is usually conducted to understand the aquifer hydraulic parameters. The pumping test is the study of aquifer characteristics, it suffers from non-uniqueness as the pump testing data observed can be fitted with the other sets of aquifer parameters, boundaries, and initial conditions that differ completely from one another (Van Tonder et al., 2001). The hydraulic parameters, boundary, and initial conditions are used to develop a conceptual model. However, it is still difficult to identify the model that represents reality.

2.10.2 The Aquifer response evaluation

The aquifer is stressed with various discharge rates until the pump suction is reached, to determine the hydraulic properties of an aquifer. Mathematical solutions were developed to estimate the aquifer characteristics (Thiem, 1906). This includes the derived equations to interpret the aquifer pump testing data of either a single or multiple wells (observation well). In single well pumping testing, various discharge tests are conducted and this includes step tests and constant discharge tests while measuring and monitoring the changes in water levels during pumping and recovery. Pump testing is conducted to calculate the transmissivity and hydraulic conductivity (de Ridder, 1991).

Grady (1997) conducted a study in Nevada (United States) to analyze the aquifer characteristics such as transmissivity and borehole yields in a single borehole test. The aquifer test was conducted in three existing boreholes in the Yucca Mountain area between March 1995 and January 1996 to determine the aquifer parameters such as specific capacity and aquifer transmissivity. Pump testing data was analyzed using the Cooper and Jacob straight-line method, two modified Theis non-equilibrium equation solutions, and a modified reservoir-limit solution.

The Thiem equation can be used to estimate T (transmissivity):

$$T = \frac{43.08Q}{Sw} \quad \text{......} 1$$

Where:

Q = the constant discharge in m^3/day.

S_w = the drawdown inside the well at steady flow in m.

T = the transmissivity.

The Cooper-Jacob method can also be used to estimate the transmissivity as follows:

$$T = \frac{2.3Q}{4\pi\triangle S} \quad \text{......} 2$$

Where: $\triangle S$ = Change in drawdown over one logarithmic cycle

Transmissivity can be defined as the rate of flow under a unit hydraulic gradient through a unit width of the aquifer of a given saturated thickness. The transmissivity of an aquifer is related to its hydraulic conductivity (K) as follows:

$$T = Kb \quad \text{......} 3$$

Where:

T = Transmissivity

K= Hydraulic Conductivity

b = Aquifer thickness

Multiple well tests are implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping or subsequent recovery. Some of the parameters which can be observed in multiple well tests are Storativity (S) and Specific yield (S_y). The storativity of a confined aquifer is defined as the volume of water released from storage per unit surface area of the aquifer or aquitard per unit decline in hydraulic head. Storativity is also known by the terms' coefficient of storage and storage coefficient (Ferris *et al.,* 1962). With the estimate of T obtained from (eq2), S is calculated as follows:

$S = \frac{2.25Tt}{r2}$ ……………………………………………………………………………………4

Where: S= Storativity

T= Transmissivity

t= time to which the set of drawdown data correspond

r= is the distance defined by the intercept of the straight-line fit of the data and zero drawdown axis.

The specific yield is defined as the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Heath, 1983). Bear, (1979) relates specific yield to total porosity as follows:

$n = S_y + S_r$

Where: n = is total porosity (dimensionless),

S_y = is specific yield (dimensionless) and

S_r= is specific retention (dimensionless)

The specific capacity (Q/sw) of a well is the discharge per unit drawdown in the well and is usually expressed in lpm/m. This is a measure of the effectiveness of a well. The specific capacity of a well is not constant but decreases with the increase in pumping rate (Q) and prolonged pumping time (Sterrett, 2007). The equation of the specific capacity is as follows:

Specific capacity = Q/sw ………………………………………………………………..5

Where: Q is the discharge (l/s)

Sw is the drawdown (m)

Well yield is also an aquifer parameter and can be defined as the maximum daily rate at which a borehole can be pumped on a sustainable basis. Well yield can also be defined as the amount of water that can be pumped from a given well per unit of time (Hecox *et al*, 2002). The empirical equation of the well yield is as follows:

$$Q_{sustainable} = Q_{pumping\ test} \times t \times 3.6\ m^3/hr \ldots\ldots\ldots\ldots 6$$

Where: $Q_{sustainable}$ = is the well yield (in m^3/day),

$Q_{pumping\ test}$ = is the constant discharge rate (in L/s), and

t = is the duration time of constant discharge (hours) and 1 L/s = 3.6 m^3/hr.

Moreover, well efficiency (borehole recovery) is also an important parameter that indicates the level to which the aquifer is dewatered, by measuring the residual drawdown after the borehole is allowed to recover. The empirical equation of the borehole recovery is as follows:

$$R=100-\frac{\text{last recovered water level (after 24 hours)}}{\text{last drawdown water level (after 24 hours)}} x100\% \ldots\ldots\ldots\ldots 7$$

The hydraulic parameters and graphs constructed from the observed data help in choosing the appropriate conceptual model. The graphs constructed from the pump testing data include the drawdown versus the time (log-log plots), drawdown versus time (semi-log plots), or the drawdown versus distance to the well. The drawdown from the observed data is then compared to the characteristic type curve of a known conceptual model (theoretical). The theoretical models comprise the confined, unconfined, or leaky aquifers and the inner and outer boundary conditions of the pumped well. Kruseman and De Ridder (1990) showed the relationships of unconsolidated and consolidated aquifers with the classical theoretical diagnostic plots of the time versus drawdown.

Van Tonder *et al.,* (2001) developed the Flow Characteristic Excel-programmed with the derivatives formulas to determine the aquifer characteristics. The program consists of tools that analyse the steps, constant, and recovery drawdown values. At present, model identification makes use of log-log or semi-log derivatives together with the drawdown as a function of time on a logarithmic scale. The derivative is highly sensitive to subtle variations in the shape of the drawdown curve, which solves many problems in curve fitting. After capturing the raw data in the software, the derivative plots are fitted automatically for model identification, and this is becoming a common practice in groundwater investigations. Renard *et al*.,2009 provide drawdown and derivative plots in which the aquifer types can be delineated, based on aquifer response during constant discharge test (Figure 2.8). The aquifer types presented in Figure 2.8 are a) confined aquifer; b) unconfined aquifer; c) infinite linear no-flow boundary; d) infinite linear constant head boundary; e) leaky aquifer; f) well-bore storage and skin effect; g) infinite conductivity vertical fracture.; h) general radial flow—non-integer flow dimension smaller than 2; i) general radial flow model-non-integer flow dimension larger than 2; j) combined effect of well bore storage and infinite linear constant head boundary.

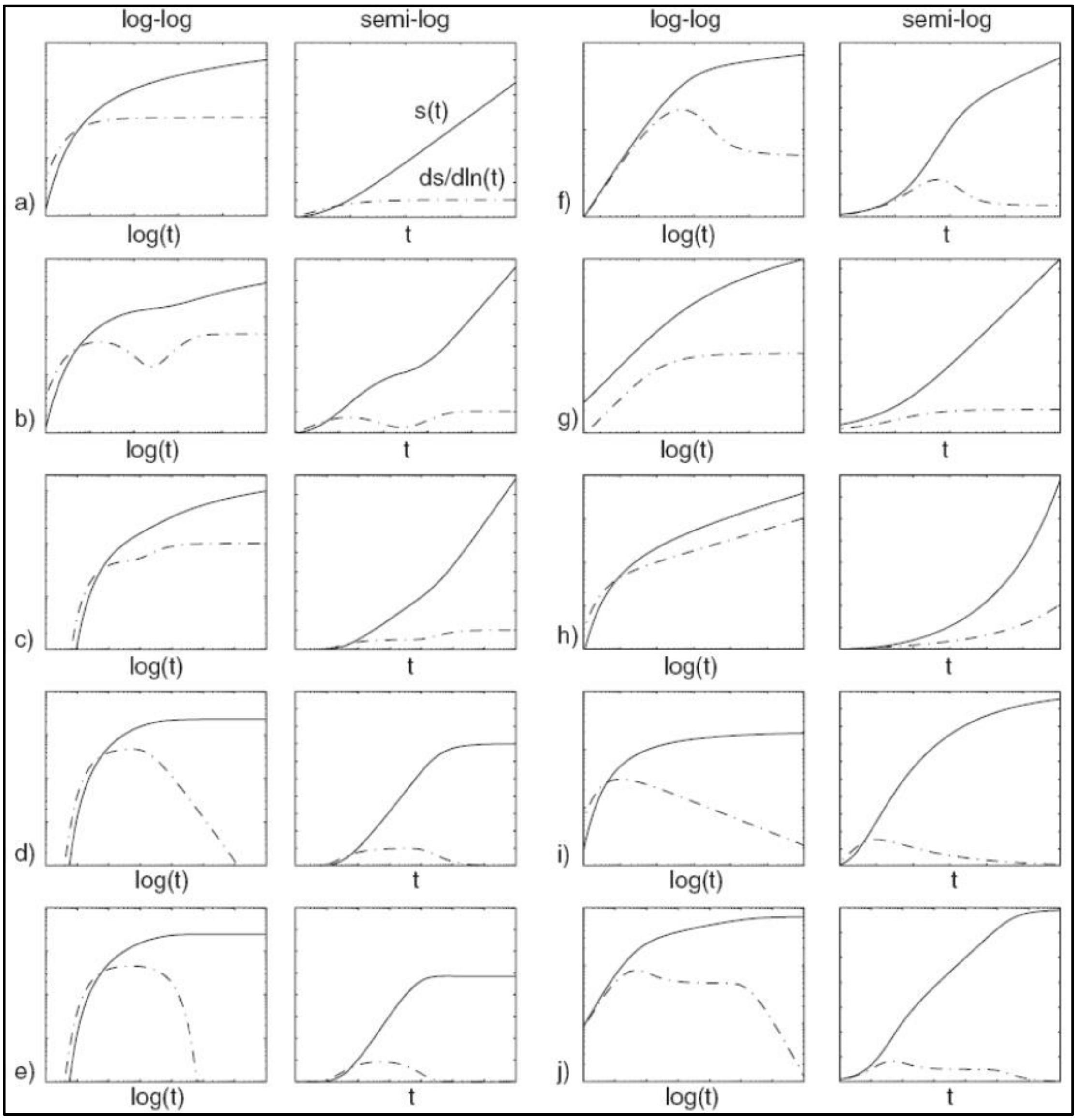


Figure **2.8**: Derivative plots of the aquifer tests encountered during hydrogeological field study (Renard *et al*., 2009).

2.10.3 Aquifer models for crystalline basement aquifer

Dupuit conducted a study in well hydraulics and pump testing in 1863 and developed the first analytical solution to model radial flow to a well in a steady state. Theis also conducted studies in hydraulics and aquifer testing and he published his analytical solution in 1935. Theis made assumptions that the aquifer is isotropic, homogeneous, bidimensional, and confined.

Since the early 1950s, there is improvement in the analytical models and pump testing procedures that are applied to the fractured or weathered lithologies (Jacob, 1955). These analytical solutions are also used in shallow well or large diameter well flow in an anisotropic unconfined aquifer with delayed gravity response (Hantush, 1961). Many authors (Sekhar *et al.,* 1994; Weller, 1985; Gonthier, 2009) indicated that crystalline basement rocks have fractured bedrock (also called semi-confined) with the water table situated on top of it. Gernand and Heidtman (1997) conducted pump testing intending to determine the safe yield of the fractured gneiss aquifer. A single fracture model was used for the aquifer test and the results showed that in crystalline basement rock a single fracture zone may yield most of the water to a well. The schematic representations of the confined and isotropic leaky aquifer are presented below.

The Ideal Confined aquifer

This type of aquifer is assumed to be unlimited in lateral extent, in this type of aquifer there is no recharge or leakage. This is fully confined with non-permeable layers it has a homogeneous storativity and transmissivity (Figure 2.9). In this approach, it is assumed that the weathered and fractured aquifers behave in a similar way. A fractured aquifer will most likely fulfill this assumption when lot of similar fractures intersects the underlying lithology. There is unsteady-state radial convergent flow around the pumping well in a confined isotropic and homogeneous aquifer (Theis, 1935).

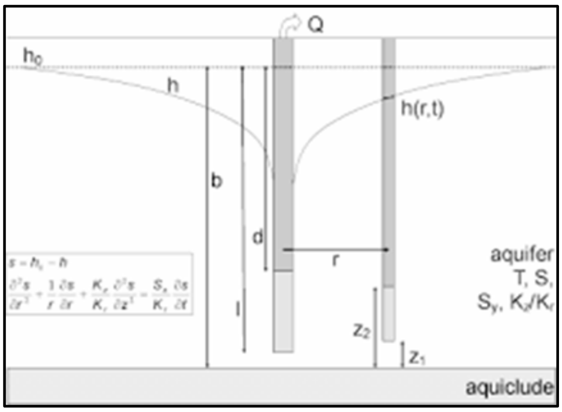


Figure **2.9**: The schematic representation of an idealized confined aquifer (Hantush,1960).

Isotropic leaky confined aquifer

This model considers a leaky confined aquifer overlain by aquitard (Figure 2.10). This type of aquifer receives partial recharge from the overlying aquitard and it is an ideal homogeneous isotropic and infinite two-dimensional aquifer. The flow is assumed to be vertical in the overlying aquitard, there is no storage but there is transmissivity in the aquitard. The analytical solution for this situation was developed by Hantush (1955). Moench (1985) included wellbore storage and wellbore skin, including three configurations for simulating a leaky confined aquifer with aquitard storage.

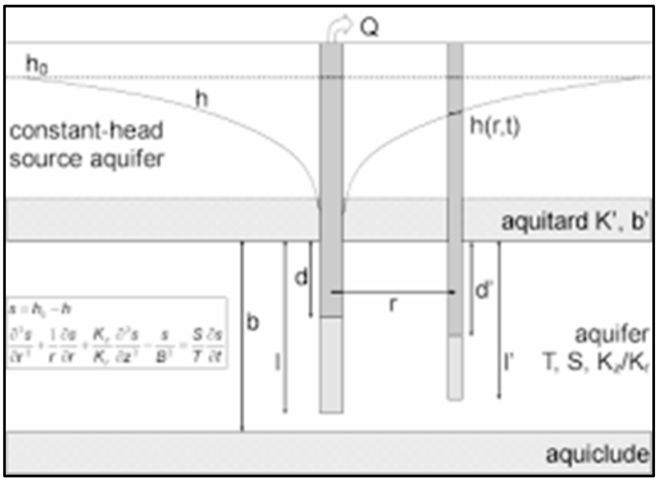


Figure **2.10**: Schematic representation of an isotropic leaky confined aquifer (Hantush,1960).

2.11 Major factors in the availability or potentiality of groundwater resources

Several factors that contribute to the availability of groundwater resources (Figure 2.11)

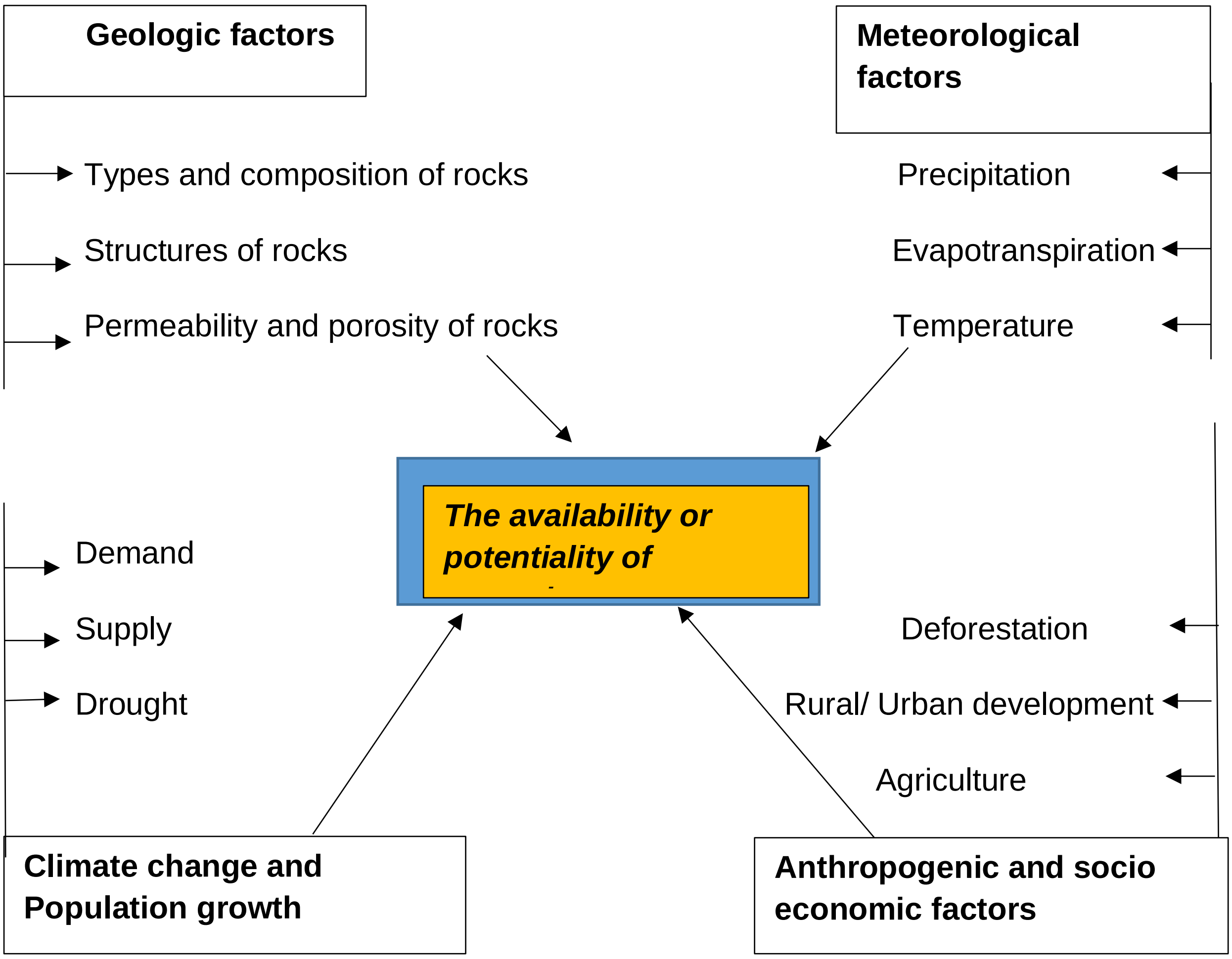


Figure **2.11**: The availability or potentiality of groundwater resources

2.11.1 Geologic factors

Groundwater availability depends on the hydrological parameters of the region, which are rock type, rock structures, porosity, permeability, and topography (Herrick and LeGrand, 1949; Crawford and Kath, 2003; Crawford and Kath, 2001; Kath *et al.* (2001). The water-bearing structures are controlled by the degree of weathering and the storage capacity (Lester *et al*., 2005). Williams *et al*., (2004) indicated the influence of rock type on well yield, they observed that water strikes with high yield are found within the lithological contacts. This confirms earlier observations made by Cressler *et al*. (1983) who reported that high well yields are found only where “localized increased in permeability” occur, usually in association with structural and stratigraphic features such as contact zones between rocks of contrasting character and within multi-layered rocks.

Rock structures influences the groundwater availability in the crystalline basement aquifer. The geologic structure also influences the groundwater flow, yield of the water-bearing zones, distribution by providing the framework along which weathering and possibly stress-relief can occur (Kath, 2003). In this study, the rock structures will refer to small and large-scale features such as fault, joins, and lineaments. Crystalline aquifers are classified as secondary aquifers due to low permeability and porosity. Secondary porosity is porosity that within base rocks after the rock formation, the fracturing, faulting, and dissolution processes create the secondary porosity. The permeability is a measure of the degree to which the pore spaces are interconnected, and the size of the interconnections (Acworth, 1987).

Relela villages are likely to find groundwater stored in structures such as faults, joints, lineaments, or dykes found in the underlying crystalline basement rocks. The sunk wells are likely to produce low to high yields depending on the type and interconnections of those structures.

2.11.2 Anthropogenic and socio-economic factors

Anthropogenic activities are human activities such as deforestation, rural or urban development, unscientific water use, agriculture, and many which affect the distribution, quantity, and quality of surface and groundwater resources (USGS, 2013). Deforestation decreases the evapotranspiration rate, increases storm runoff and soil erosion, and decreases infiltration to groundwater and the base flow of streams. From this point of view groundwater resource quality, groundwater availability (quantity), the increase in storm runoff, soil erosion, and the decrease in evapotranspiration and infiltration is generally viewed as unpleasant (USGS, 1998). The decrease in evapotranspiration and infiltration will result in a decrease in precipitation and the decrease in groundwater recharge (Bouraoui, *et al.,* 1999).

2.11.3 Climate change and Population Growth

Groundwater resources and their long-term replenishment are controlled by long-term climate conditions and population growth. Climate change and population growth will, therefore, have a great impact on groundwater resources (Karen, 2008). According to the Oxford Dictionary, climate change is the changes in the earth's weather, including changes in temperature, wind patterns, and rainfall. Population growth is the increase in the number of individuals in a population. Thus, the increase in population growth and climate change will cause a high demand and supply of groundwater resources.

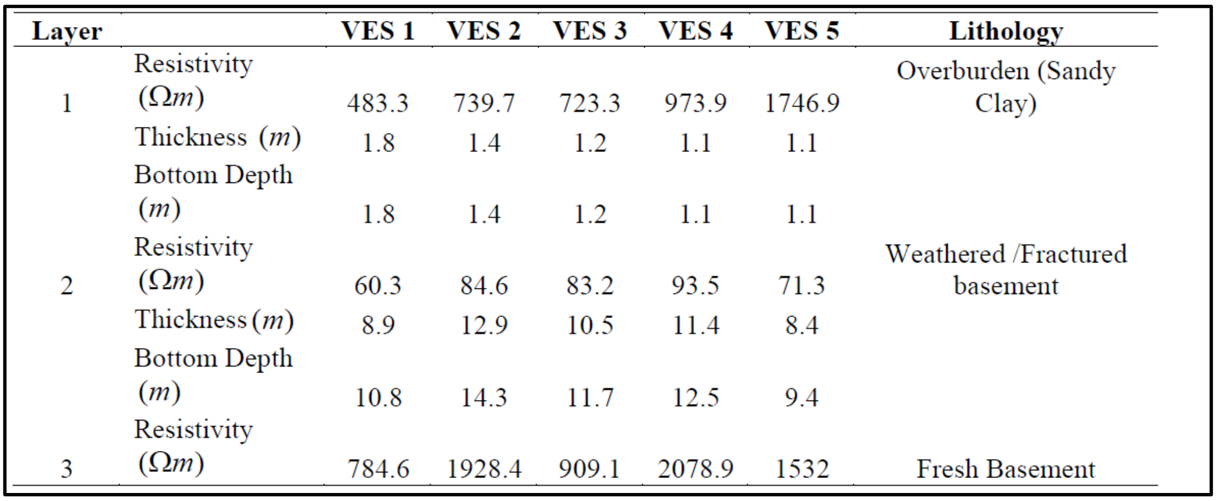
Most rural areas depend on groundwater for survival, and excessive or unwise exploitation of groundwater during drought seasons in combination with the high demand for water usage makes a lethal cocktail (Appleton, 2003). Moreover, climate change and population growth are major factors for groundwater availability or potentiality, therefore the effects of climate change and population growth on groundwater resources cannot be ignored (IPCC, 1998). According to the Department of Statistics South Africa Census data conducted in 2011 shows that Relela villages had a total population of about 6500 individuals with a growth rate of 0.38% and the total households were about 3200. There are about 8% of people who have water in their households and the rest depends on the groundwater or municipality for water supply.

2.12 Case studies

Oyeyemi *et al*., 2018 conducted geoelectrical investigations in the southwestern part of Nigeria in the crystalline basement terrain with the aim of sustainable groundwater resource supply. The underlying geology within the southern part of Nigeria is gneiss-migmatites complex and the metasediments underlie. The gneiss migmatite complexes within this region include minor quartzites and calc-silicate bearing units.

The geophysical technique used for groundwater exploration was the Omega resistivity meter within the Polytechnic of Ibadan campus, Ibadan southwestern Nigeria. Five resistivity soundings were carried out along the five traverse lines with a maximum half-current electrode spread (AB/2) of 75.0 m using the Schlumberger array, which is enough for the anticipated depth of investigation (DOI). Likewise, five 2D electrical resistivity profile lines in the West-East and North-South direction were conducted with each 2D resistivity profile being 110 m in length.

Wenner array with the least electrode spacing of 5.0 m was adopted for the surveys reaching 5 data levels of 5 for each profile. The Wenner configuration was adopted for the 2D ERT survey due to its easy application, strongest signal strength, and greater sensitivity to vertical resistivity variation or structures lying horizontally with respect to the country rocks. The geophysical survey data was interpreted to select the groundwater potential targets for borehole drilling (Figure 2.12)



Layer		VES 1	VES 2	VES 3	VES 4	VES 5	Lithology
1	Resistivity (Ωm)	483.3	739.7	723.3	973.9	1746.9	Overburden (Sandy Clay)
	Thickness (m)	1.8	1.4	1.2	1.1	1.1	
	Bottom Depth (m)	1.8	1.4	1.2	1.1	1.1	
2	Resistivity (Ωm)	60.3	84.6	83.2	93.5	71.3	Weathered /Fractured basement
	Thickness (m)	8.9	12.9	10.5	11.4	8.4	
	Bottom Depth (m)	10.8	14.3	11.7	12.5	9.4	
3	Resistivity (Ωm)	784.6	1928.4	909.1	2078.9	1532	Fresh Basement

Figure **2.12**: Depth-to-base of the geoelectric layers and resistivity results (Oyeyemi *et al.,* 2018).

Ahmad (2017) conducted groundwater exploration at Wadi Allaqi Basin, Egypt in a crystalline basement terrain using geophysical techniques to select the groundwater potential targets for borehole drilling. Wadi Allaqi Basin is underlined by granites, granodiorite, diorite, gabbro. In this study two geophysical techniques were used; Geoelectrical survey and Magnetic surveying, thirteen 1D vertical electrical soundings were conducted to conclude a subsurface resistivity model for assessing the availability of groundwater in the Nubian Sandstone Formation in Wadi Allaqi area. Using a Proton Magnetometer (G-857) with an accuracy of 0.01 nT, five magnetic profiles were conducted in the first area with 110 measured magnetic stations in a detailed survey with station spacing 50–75 m covering an area of about

3.5 km^2. Geophysical survey data was interpreted to identify the groundwater potential targets (figure 2.13-15).

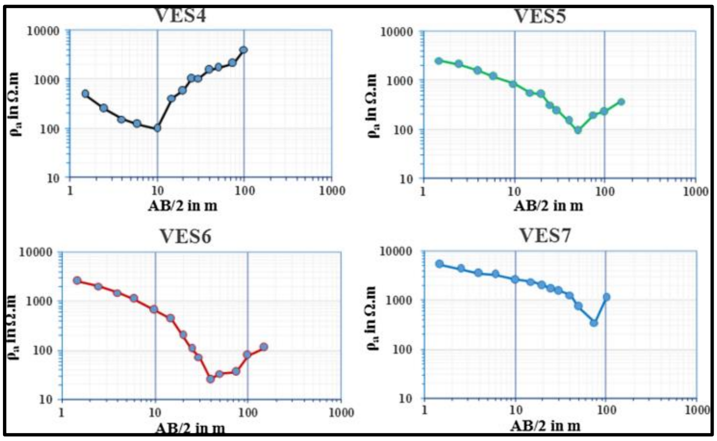


Figure **2.13**: The VES curve for the Geoelectrical profile (Ahmad, 2017).

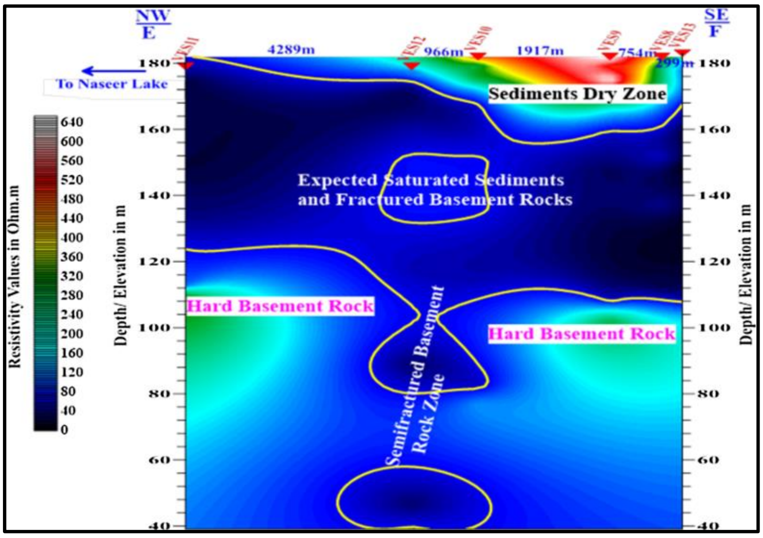


Figure **2.14**: The forward (preliminary) model of the calculated VES curves for the Geoelectrical Profile E-F, along with the expected geological units (Ahmad, 2017)

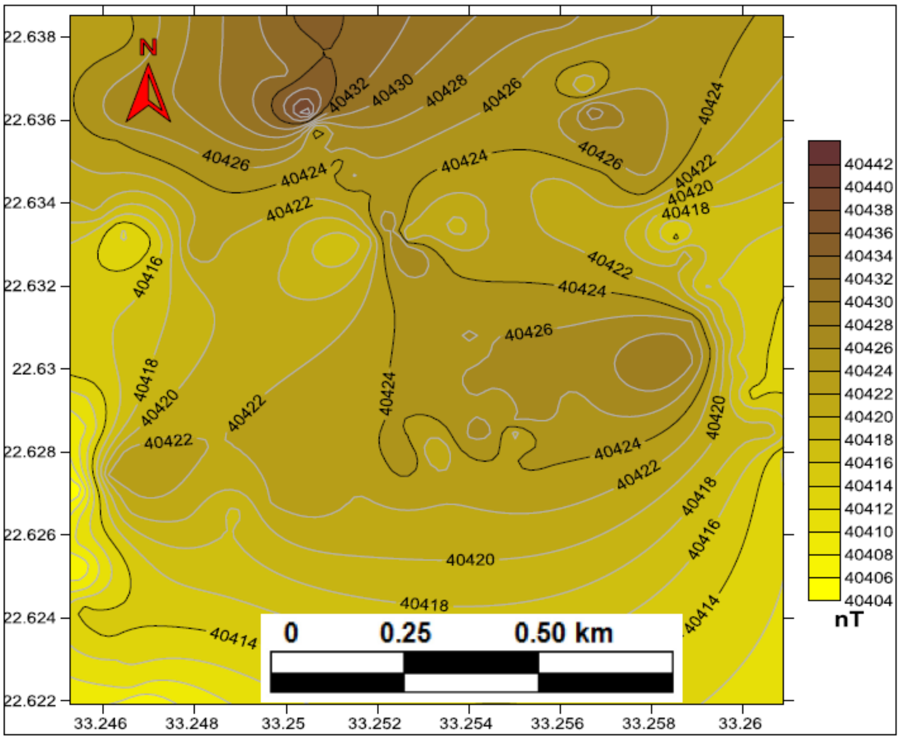


Figure **2.15**: Corrected total magnetic intensity map in the study area (Ahmad, 2017).

CHAPTER 3: RESEARCH METHODOLOGY

This chapter outlines a conceptual framework and provides insight of the research methodology. The research methodology is divided into preliminary studies, fieldwork, laboratory work, and data analysis or results in presentation. A summary of the methodology of this study is presented in the flow chart in Figure 3.1 below.

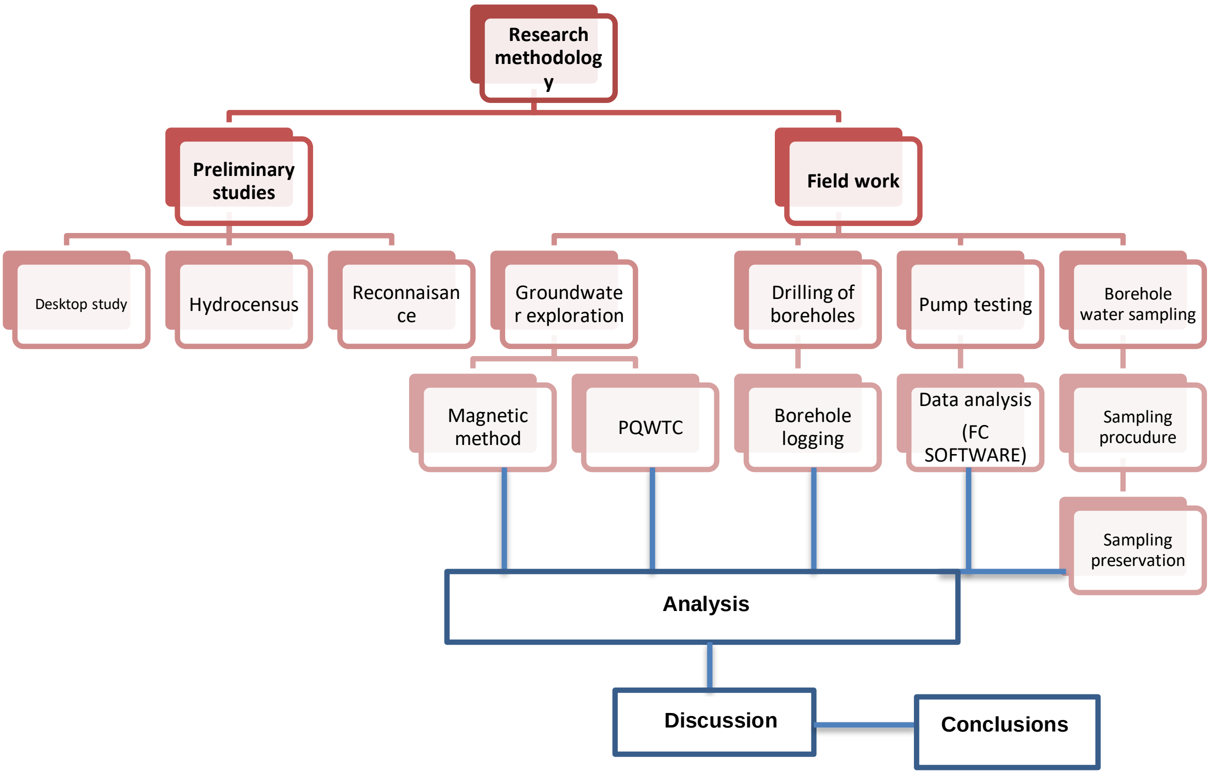


Figure **3.1**: Methodological framework or experimental protocol.

3.1 Preliminary studies

3.1.1 Desktop studies

Desktop studies were conducted before the field work or site visits to acquire first-hand information about the study area. The information about geology, hydrology, and demography of the study area was gathered with the use of arc GIS, published geohydrological maps, satellite images, published geohydrology books, and published journals in hydrogeology.

3.1.2 Hydrocensus

Hydrocensus is the investigation that involves surface or groundwater data gathering such as boreholes status, static water levels, water quality, pollution sources and borehole yield in a particular site (DWAF, 2004). The DWA developed a system called Groundwater Resource Information Project (GRIP) in 2002. This system stores groundwater data gathered by professional geohydrologists in the Limpopo province.

The GRIP helps to improve the development and management of rural groundwater resources in South Africa. GRIP data of the study area were analysed to gather information about the groundwater system of the study area; this includes borehole yields, water levels, and borehole depths of the Relela villages.

3.1.3 Reconnaissance survey

This survey covered information about the climate, topography, vegetation, accessible areas, and the activities around the study area. The survey included demarcation and planning survey layouts in the study area. Topographical maps, geological maps, and satellite images were used to gather information about the study area. All areas were identified to be accessible during this survey.

3.2 Fieldwork

3.2.1 Groundwater exploration

The groundwater exploration (also known as borehole sitting), during this phase of the study, potential areas of groundwater were targeted based on the information acquired from desktop studies (this includes types of rock, rock structures such as fault, joints, or lineaments within the study area). Spitz and Moreno, (1996) stated that groundwater that is associated with fractures or joints, is described as the secondary aquifers. When doing groundwater exploration the boreholes need to be accurately positioned to intersect the subsurface water-bearing structures (Woodford and Chevalier, 2002).

The groundwater survey lines of at least 100-200 meters were drawn perpendicular to the geologic structures, particularly to the area of interest. Two geophysical tools: Magnetometer and PQWTC (Automatic Geophysical Prospecting Water Detector 300 Meters) Figures 3.2 and 3.3, respectively were used for groundwater exploration.

According to Escobar (2005), the objective of the magnetic survey is to detect the lineaments using the magnetic anomalies from the underground rocks' magnetic properties. Blakely (1995) stated that the magnetic data interpretation shows the differences in local abundance of magnetization and this is very useful to locate the geological structures such as faults and geologic contacts. The PQWT-TC300 is a geophysical prospecting tool, which utilizes the natural electric field as a working electromagnetic field source. It measures the natural electric field in the ground to study the abnormal changes which are caused by different geological bodies, based on the resistivity differences of underground rock.

Figure **3.2**: Geoproton (G5) Magnetometer

(a)

Figure **3.3**: PQWTC-300 groundwater detector tool

3.2.1.1 Magnetic method (Geometric proton precession magnetometer)

Groundwater exploration in Relela villages was conducted in four villages, namely: Mabyepelong, Senakwe, Babanana, and Madumane. The traverse lines were set according to the information acquired from the desktop studies, this information includes the groundwater potentiality based on the rock structures (such as faults, joints, or lineaments).

The magnetic intensity of the underlying geological formations was observed at regular intervals of 10 meters. The measured magnetic data was presented as magnetic profiles to show the difference in the geomagnetic field resulting from underlying geologic formations such as dykes, faults, or lineaments. Acworth (1987) stated that crystalline basement aquifers store water in fractures (faults, joints, or lineaments), weathered zones, or contact zones of the subsurface lithologies. The magnetic intensity anomalies in such zones will have a linear trend which could be high if the rocks have a high content of iron e.g dykes and low if they are faults since the shearing oxidises (magnetic) to haematite (non-magnetic).

3.2.1.2 Resistivity method using PQWTC-TC300

The PQWTC equipment (Figure 3.3) was used for groundwater exploration in Senakwe village only, this geophysical tool could not be used in the other villages due to the restrictions caused by artificial objects especially the wire fences on the farms. The survey lines were undertaken perpendicular to the strike direction of the rock units. In preparation for the PQWTC profile surveying, the following equipment were used; electrode cables, copper electrodes, 100m tape measure, GPS, and PQWTC data logger. The tape measure was used to measure the sampling point distances and the GPS measured the station locations.

The electrodes were moved along a survey line at a spacing interval of 5 meters while keeping 10 meters separation between the two electrodes. The recorded data were downloaded from the recorder to a laptop for data analysis and interpretation (Figure 3.3).

3.2.2 Borehole drilling and logging

Boreholes or groundwater wells are holes dug or drilled down from the earth’s surface into aquifers to access groundwater stored therein (Raboucas, 2004). Borehole drilling was conducted by Naledzi Waterworks Pty (Ltd). The drilling was conducted using a rotary drilling rig (Figure 3.4). A drill bit attached at the tip of the drill pipes grinds the rock as it rotates. The compressor exerted the air into the borehole and carry back the broken rock pieces upwards and out of the hole (Figure 3.5). The lithologies penetrated by the drilling rig were recorded into the logbook (referred to as borehole logging) to study the subsurface lithologies.

Sharma, (1997) described borehole logging as the way of detecting the subsurface physical properties of rocks surrounding a borehole. Well logs can include visual observations or be made by instruments lowered into the well during drilling. The borehole logs provide more information about the subsurface lithologies and this information helps the geohydrologist in decision making. For example, the penetration rates, lithological thickness, the depth at which the water strike was found. There are different types of logging systems that are used during borehole drilling (Sharma, 1997). Such systems include the electrical logs providing the resistivity values of the underlying lithologies, calliper logs, radiometric logs, and visual observation of the rock samples. In this study rock samples were observed during drilling and recorded in the datasheet (see Figures 3.4 and 3.5).

Figure **3.4**: Drilling machine

Figure **3.5**: Borehole logging

3.2.3 Pump testing

Pump testing was conducted by Naledzi Waterworks Pty (Ltd) contracted by Greater-Tzaneen municipality to drill reliable groundwater supply for Relela villages. The pump testing program (borehole yield testing) was conducted in the drilled and developed boreholes. According to Duffield, (2017) pumping test is the program conducted to understand the aquifer characteristics, where a pump is used at a controlled rate and discharges the water out of the well while measuring the drawdown. The pumping test aims to find how the aquifer will react when stress is exerted in it. During pump testing the drawdown with respect to the time is measured to determine the aquifer parameters (Driscoll, 1986). The pump testing in this study was conducted in single wells only. The pump testing program consisted of step tests, recovery of step tests, constant discharge tests, and the recovery of constant discharge.

Akpofure and Okiongbo (2012), stated that the use of pumping tests in evaluating aquifer parameters requires several types of equipment to carry them out. In this study various equipment were used for pump testing, these included a pump engine (diesel engine), bucket (50 liter container), discharge pipe, voltmeter, tape measure, discharge pipe, and a stopwatch. Each piece of equipment met the required international procedures to obtain good and reliable results. The pump (diesel engine) pumped water out of the borehole, the voltmeter and tape measure were used to detect the water levels in the borehole. Two cables attached to the voltmeter and tape measure were used to measure the drawdown of the borehole water. The discharge pipe was used to carry water out of the borehole and discharge water into the 50 liter container. A stopwatch was used to measure the elapsed time during pumping wherein the time intervals were set for step tests and constant discharge and the recovery tests for step tests and constant discharge tests. The recorded time was then used to calculate the water discharge rate (Figure 3.6).

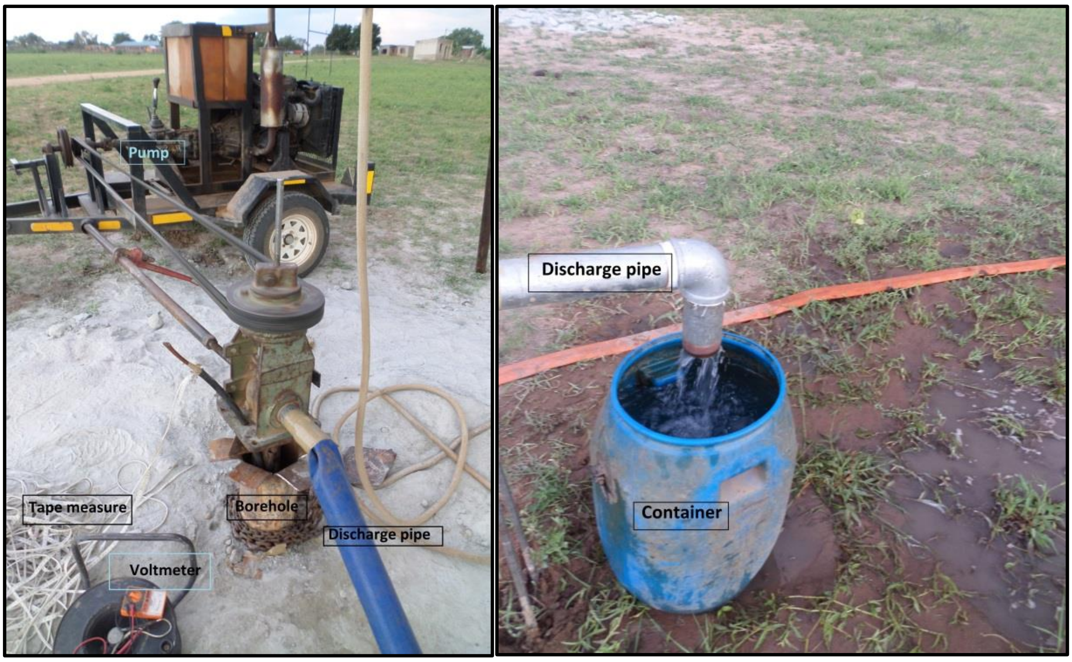


Figure **3.6**: Pump testing equipment

3.2.3.1 Step tests

Jacob (1947) introduced a step drawdown test to understand how the drawdown of a borehole drilled in confined aquifers is affected by the discharge. Step tests were conducted in each newly developed borehole. Several steps were conducted during pump testing of the wells, these included: a) multi-rate step test of 4 x 60-minute steps with sequentially increasing the pumping rates until pump suction is achieved; b) recovery of the step test; c) a CD Test for at least 12 hours; and d) recovery of the Constant Discharge Test until at least 95% of the recovery is achieved. A stopwatch and a discharge water container were used to determine the discharge rate in each step, the discharge rate (l/s) was computed by dividing the amount of water in a bucket by time in minutes or seconds elapsed. The water levels were constantly monitored using a tape measure and voltmeter and noted on the datasheet during each step. This data is usually used to indicate the safe yield that a well can sustain for a constant discharge test.

3.2.3.2 Recovery of steps and constant discharge test

After the completion of the step and constant discharge test, the pump was switched off to collect the recovery data of the boreholes. Water level measurements within the pumped well were taken almost continuously until the borehole was fully recovered. A tape measure was connected to long cables that were linked to a voltmeter. The cable as well as the tape measure was inserted into the borehole to monitor the water level at varying times. Water level measurements were monitored manually, by lowering the cables which were attached to a small weight. When the cables interacted with water the voltmeter deflected to greater than zero units, thus indicated the water level and it was measured immediately. The time intervals which were used during pump testing are shown in Table 3.1. Many studies including; Domenico & Schwart (1990), Discroll (1986), Freeze and Cherry (1979) used the same time intervals for their geohydrological studies.

Table **3.1**: Time intervals used during pump testing and well recovery measurement

Time (min)	**Water level measurements**
0-5	0.5 min
5-10	1 min
10-30	5 min
30-60	10 min
60-120	30 min

3.2.4 Water sampling

3.2.4.1 Sampling procedure

After the completion of pump testing, water samples were collected and sent to the laboratory (Capricorn laboratory) for chemical analysis. All samples were collected using clean sampling procedures specified by DWAF, 1997. A bailer was used to collect samples in each borehole. A bailer is a tool that is used to sample water from the borehole and it is equipped with a check valve at the bottom. This valve allows water to get into the tube when lowered into the borehole. When the bailer was raised the valve stopped water to come out of the tube and a water sample was taken from the borehole into sampling bottles (Figure 3.7).

Figure **3.7**: A bailer collecting water from the well into the sampling bottles

3.2.4.2 Sample preservation

To prevent the loss of target analytes all water samples must be preserved. Preservation stabilizes the element concentrations for a limited period (Rodtke, 2005). All the sample bottles were labeled with the borehole number, location, date, and time for collection. Water samples were stored in the cooler box and sent to the laboratory for further preservation and the analysis of chemical constituents present within the water samples (Figure 3.8).

Figure **3.8**: Sample preservation at Capricorn laboratory

Table **3.2**: Laboratory water sample preservation and holding times used in Capricorn Laboratory are shown in table 4 below

Chemical constituents	**Room temperature**	**Holding period in days**
Br	-	28
Br	-	28
Cl	-	28
Cl	-	28
Cl	Cool to 4°C	immediately
Fl	None required	28
NO_3	Cool to 4°C	2
Combined	conc. H SO24	28 days
(Nitrate/Nitrite)	to a pH <2	-
Nitrite-N	Cool to 4°C	2
0-Phosphate-P	Cool to 4°C	2
SO_4	Cool to 4°C	28 days

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter presents results obtained from groundwater exploration using geophysical techniques, aquifer characteristics results obtained from pump testing (also referred to as aquifer test), and water quality results from all drilled boreholes.

4.1 Introduction

The importance of groundwater as a basic human need cannot be overestimated. Most of the countries around the globe suffer from water supply and therefore they rely on groundwater recourse for their daily needs (Goldman *et al.,* 1993). The problem associated with the sustainable use of groundwater resources can be divided into two independent problems; groundwater exploration and management of available groundwater resources. The solutions to both problems can be achieved through the understanding of the subsurface hydrogeological characteristics of the area of interest. The most direct method of obtaining subsurface data is by drilling observation and pump testing, but this is expensive and, therefore, often inefficient (Goldman *et al*., 1989). The use of relatively inexpensive geophysical methods is the most cost-effective for groundwater exploration thus reducing the cost of drilling dry wells and has been proven to provide a high probability of finding sufficient groundwater.

4.2 Groundwater exploration using geophysical techniques

In this investigation, two geophysical techniques explained in section 3.2.1 were used for groundwater investigation in the study area. The geo proton magnetometer was used in all the four Relela villages (Mabyepelong, Senakwe, Babanana, and Madumane) whereas the PQWTC-300 (resistivity) was applied in one village (Senakwe village) because the other three had inaccessibility restrictions.

4.2.1 Magnetic and resistivity methods survey at Relela villages

When selecting the type of geophysical techniques for any groundwater exploration the geology of the area needs to be considered. Relela villages comprise igneous and metamorphic rocks. These are basement rocks that are known to have porosity permeability and porosity (Gustafson and Krásný, 1994). The groundwater potential zones will be in lineaments, faults, joints, and rock contacts. The igneous rocks consist of ferromagnetic minerals that have magnetic moment responsible rocks magnetic properties therefore their contacts can be established by the change in the magnetic intensities to the adjacent non-magnetic rocks. The faults and other lineaments will also be detected by the anomalous behaviour of the magnetic intensities. The weathering and fracturing of the overlying basement results in groundwater potentiality (Masou, 2009).

Several authors have considered the magnetic method in a similar environment to depict the underground structures which are believed to store water (Al-Garni *et al.,* 2005). The ground magnetic data were collected along with six profiles in four villages (Senakwe, Madumane, Mabyepelong, and Babanana) to delineate geological structures which could be favourable targets for groundwater exploitation within the study area.

4.2.2 Magnetic map of the study area

Before the ground magnetic survey was conducted, airborne magnetic data was studied first to give an overall overview of the magnetic properties in the study area (Figure 4.1). Figure 4.1 shows the total magnetic intensity map (from airborne magnetic data) covering the study area. The airborne magnetic data was acquired from the Council for Geosciences. The data was collected in 1997 by a light aircraft flown at a height of 150m above the surface. From Figure 4.1, it is evident that the study area comprises different lithological structures trending in different directions. Most of the geological structures in the study area are trending in the NE-SW direction (see the prominent linear structures in Figure 4.1). The magnetic anomalies within the study area (Figure 4.1) range from the low, medium into high magnetic intensities resulting from subsurface lithologies. The groundwater potential targets in the study area are in these linear features subsurface structures (faults, lineaments, dykes) (Figure 4.1) and contact zones between two lithologies. It is also expected that these zones will also be weathered or fractured.

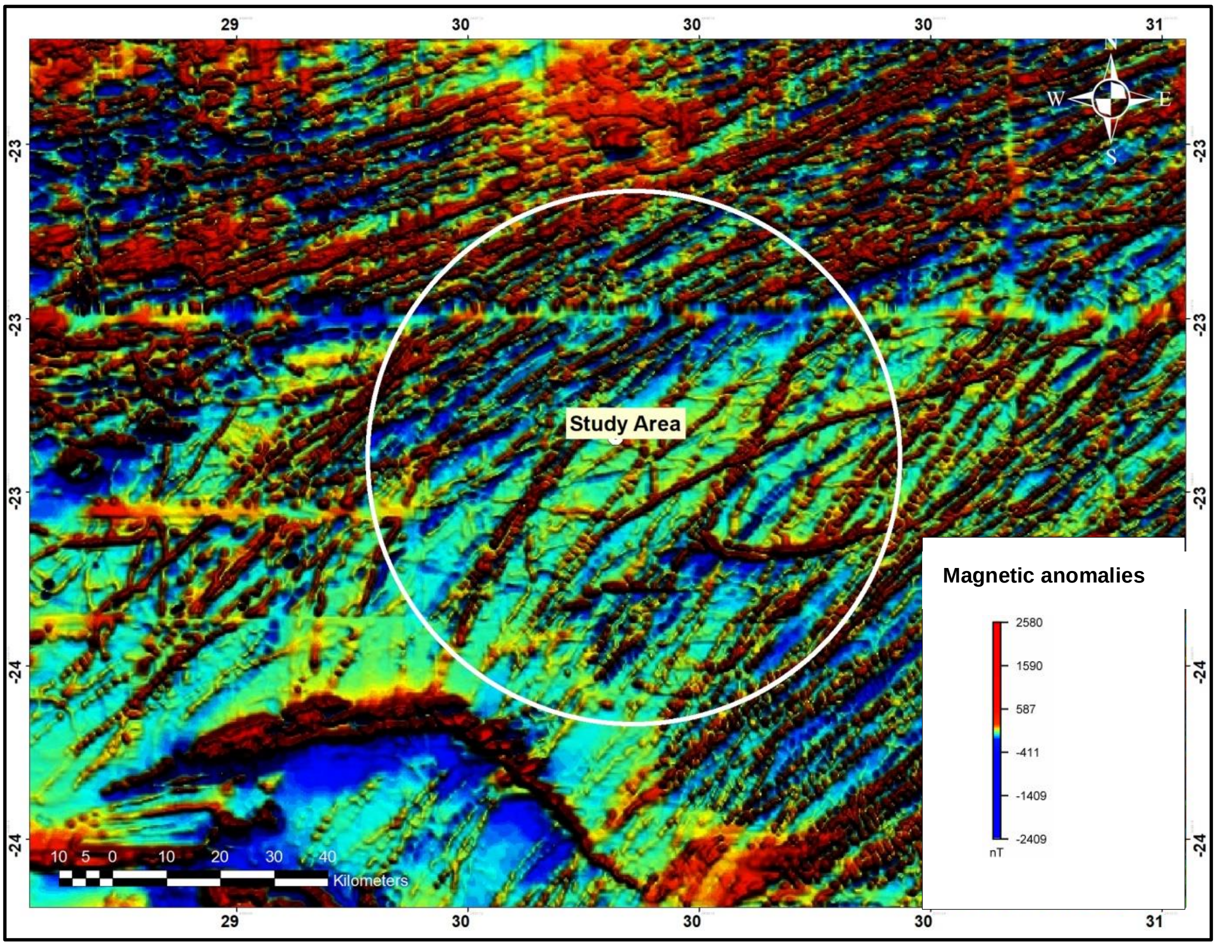


Figure **4.1**: Magnetic intensity map of the study area (adapted from Council of Geosciences).

4.2.3 Data reduction and processing (magnetic survey results)

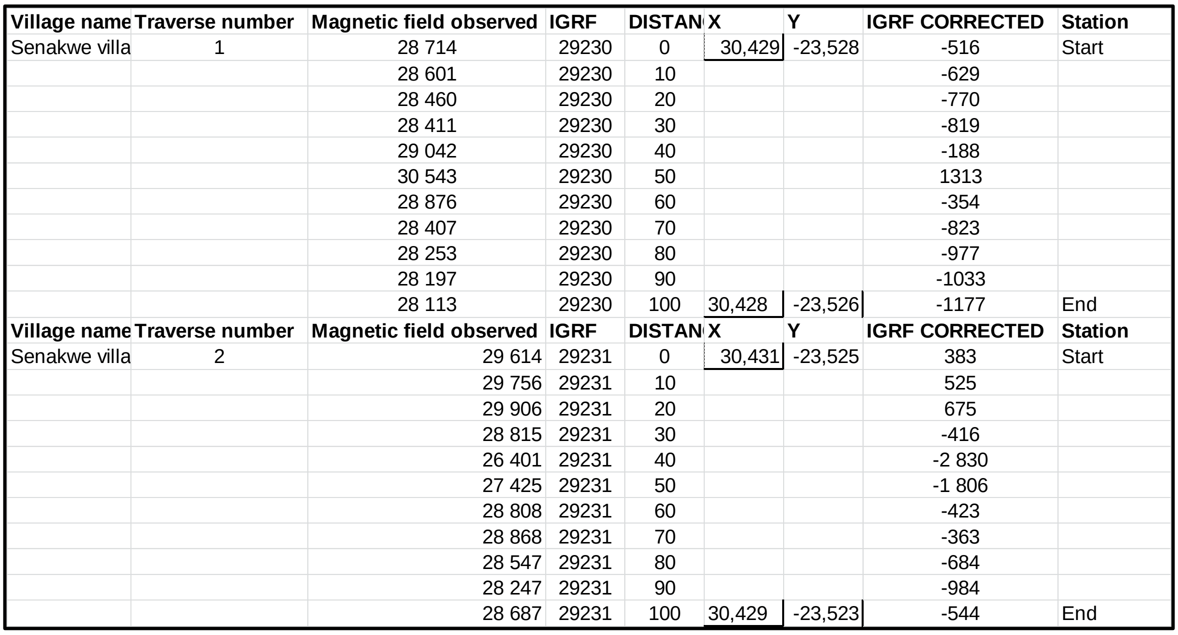
The ground magnetic data was then collected from selected sites across the selected linear features from Figure 4.1 and information gathered from the desktop studies from each of the four villages (discussed below).

However, before magnetic data can be processed for interpretations, it must undergo some correction which is referred to as a reduction in geophysics. Noise reduction is very significant in magnetic surveys (Milligan (1997). The causes of noise in magnetic data are metallic structures, metallic fences, electrical power lines, and any magnetic object. The main magnetic correction that needs to be addressed is the latitude variations of the earth’s magnetic field. The International Geomagnetic Reference Field (IGRF) should be subtracted from the measured data for that surveyed location (latitude and longitude) of the study area to account for these latitude variations. This subtraction removes the earth’s geomagnetic field so that the measured data and the anomalies observed in the measured magnetic data will only be due to the geology and subsurface structures. Formulas for computing IGRF are available online. In this study the IGRF was generated from www.geomag.bgs.ac.uk. The IGRF values which were generated for the four villages are shown in Table 4.1. The IGRF values from the four villages were subtracted from the measured data shown in Tables 4.2-4.5.

Table **4.1**: IGRF values used to subtract the magnetic variation recorded during the survey (source: www. geomag.bgs.ac.uk)

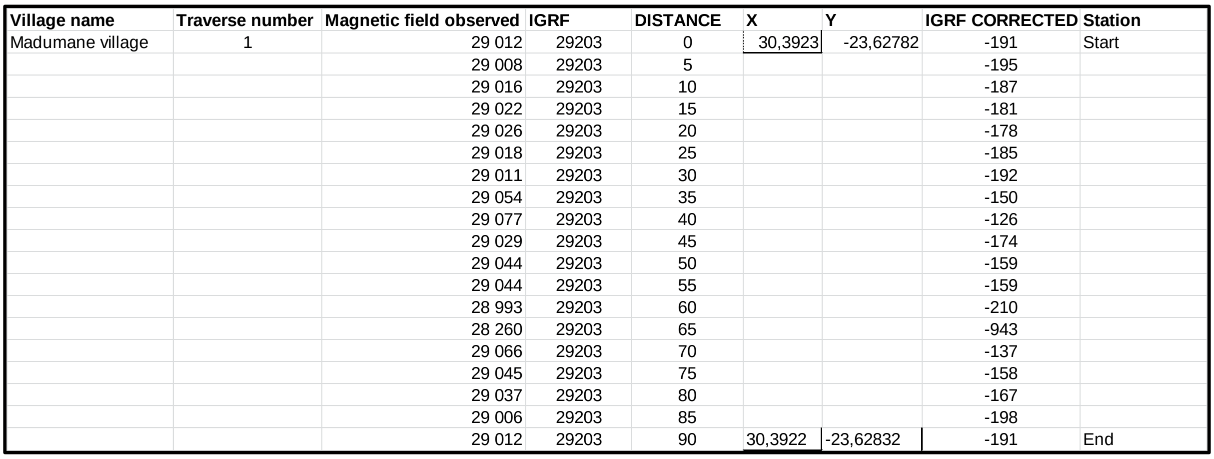
Village name								
Senakwe	Latitude	Longitude	Altitude	Date	Version			
	-23.524	30.43	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-15.997	-60.340	13905	-3986	14465	-25401	29231
	SV	-8.0	6.7	33.9	-44.7	44.9	36.0	-9.1
	Latitude	Longitude	Altitude	Date	Version			
	-23.527	30.429	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-16.001	-60.343	13903	-3987	14464	-25401	29230
	SV	-8.0	6.7	33.9	-44.7	44.9	36.0	-9.1
Madumane	Latitude	Longitude	Altitude	Date	Version			
	-23.628	30.392	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-16.139	-60.417	13849	-4007	14417	-25396	29203
	SV	-8.0	6.7	33.7	-44.8	44.8	35.9	-9.1
Babanana	Latitude	Longitude	Altitude	Date	Version			
	-23.699	30.399	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-16.248	-60.458	13817	-4027	14392	-25395	29190
	SV	-8.1	6.7	33.7	-45.0	44.9	35.7	-8.9
Mabyepelong	Latitude	Longitude	Altitude	Date	Version			
	-23.569	30.458	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-16.075	-60.359	13890	-4003	14455	-25403	29228
	SV	-8.0	6.7	33.9	-44.9	45.0	35.7	-8.8
	Latitude	Longitude	Altitude	Date	Version			
	-23.565	30.444	0.00	2020/02/11	13			
	Comp	D	I	X	Y	H	Z	F
	MF	-16.064	-60.361	13889	-3999	14453	-25402	29226
	SV	-8.0	6.7	33.9	-44.8	44.9	35.8	-8.9
		D = Declination	**I = Inclination**	**X = North Intensity**	**Y = East Intensity**	**H = Horizontal Intensity**	**Z = Vertical Intensity**	**F = Total Intensity**
	MF = Main Field	**degrees east**	**degrees down**	**nT**	**nT**	**nT**	**nT down**	**nT**
	SV = Secular Variation	**arcmin/year**	**arcmin/year**	**nT/year**	**nT/year**	**nT/year**	**nT/year**	**nT/year**

Table **4.2**: Magnetic data recorded during the survey, IGRF values, and corrected magnetic data for Senakwe village



Village name	Traverse number	Magnetic field observed	IGRF	DISTAN	X	Y	IGRF CORRECTED	Station
Senakwe villa	1	28 714	29230	0	30,429	-23,528	-516	Start
		28 601	29230	10			-629	
		28 460	29230	20			-770	
		28 411	29230	30			-819	
		29 042	29230	40			-188	
		30 543	29230	50			1313	
		28 876	29230	60			-354	
		28 407	29230	70			-823	
		28 253	29230	80			-977	
		28 197	29230	90			-1033	
		28 113	29230	100	30,428	-23,526	-1177	End
Village name	**Traverse number**	**Magnetic field observed**	**IGRF**	**DISTAN**	**X**	**Y**	**IGRF CORRECTED**	**Station**
Senakwe villa	2	29 614	29231	0	30,431	-23,525	383	Start
		29 756	29231	10			525	
		29 906	29231	20			675	
		28 815	29231	30			-416	
		26 401	29231	40			-2 830	
		27 425	29231	50			-1 806	
		28 808	29231	60			-423	
		28 868	29231	70			-363	
		28 547	29231	80			-684	
		28 247	29231	90			-984	
		28 687	29231	100	30,429	-23,523	-544	End

Table **4.3**: Magnetic data recorded during the survey, IGRF values, and corrected magnetic data for Madumane village



Village name	Traverse number	Magnetic field observed	IGRF	DISTANCE	X	Y	IGRF CORRECTED	Station
Madumane village	1	29 012	29203	0	30,3923	-23,62782	-191	Start
		29 008	29203	5			-195	
		29 016	29203	10			-187	
		29 022	29203	15			-181	
		29 026	29203	20			-178	
		29 018	29203	25			-185	
		29 011	29203	30			-192	
		29 054	29203	35			-150	
		29 077	29203	40			-126	
		29 029	29203	45			-174	
		29 044	29203	50			-159	
		29 044	29203	55			-159	
		28 993	29203	60			-210	
		28 260	29203	65			-943	
		29 066	29203	70			-137	
		29 045	29203	75			-158	
		29 037	29203	80			-167	
		29 006	29203	85			-198	
		29 012	29203	90	30,3922	-23,62832	-191	End

Table **4.4**: Magnetic data recorded during the survey, IGRF values, and corrected magnetic data for Babanana village

Village name	Traverse number	Magnetic field observed	IGRF	DISTANCE	X	Y	IGRF CORRECTED	Station
Babanana village	1	29 063	29190	0	30,3998	-23,70028	-127	Start
		29 071	29190	5			-119	
		29 073	29190	10			-117	
		29 074	29190	15			-116	
		29 079	29190	20			-111	
		29 075	29190	25			-116	
		29 080	29190	30			-111	
		29 074	29190	35			-116	
		29 076	29190	40			-114	
		29 083	29190	45			-107	
		29 054	29190	50			-136	
		29 059	29190	55			-132	
		28 983	29190	60			-207	
		29 000	29190	65			-190	
		29 025	29190	70			-165	
		29 102	29190	75	30,3989	-23,6992	-88	End

Table **4.5**: Magnetic data recorded during the survey, IGRF values and corrected magnetic data for Mabyepelong village

Village name	Traverse number	Magnetic field observed	IGRF	DISTANCE	X	Y	IGRF CORRECTED	Station
Mabyepelong village	2	29 864	29226	0	29,8152	-23,492157	638	Start
		29 139	29226	10			-87	
		29 401	29226	20			175	
		29 402	29226	30			176	
		29 433	29226	40			207	
		29 517	29226	50			291	
		29 213	29226	60			-13	
		29 725	29226	70			499	
		29 957	29226	80			731	
		30 145	29226	90			919	
		30 657	29226	100			1 431	
		29 243	29226	110			17	
		29 999	29226	120			773	
		29 744	29226	130			518	
		29 735	29226	140			509	
		30 011	29226	150			785	
		29 224	29226	160			-2	
		28 996	29226	170			-230	
		28 879	29226	180			-347	
		28 834	29226	190			-393	
		28 874	29226	200			-352	
		28 813	29226	210			-413	
		28 799	29226	220			-428	
		28 741	29226	230			-485	
		28 724	29226	240			-502	
		28 720	29226	250	29,8154	-23,494408	-506	End

4.2.4 Discussion of the findings (magnetic survey)

4.2.4.1 Senakwe village

Two traverse lines were set perpendicular to the geological structures (Figure 4.2) with the station spacing intervals range of 10 m. The observed total magnetic intensity at each station along the two traverse lines is shown in (Table 4.2, Figures 4.3 and 4.4).

Traverse line 1 trending in the southwestern part of the study area (Figure 4.3) covered a distance of 100 m in a NW-SE trending direction. From Figure 4.3, station 5 at 50 m produced a positive magnetic anomaly with no artificial source associated with it, and this may indicate possible water-bearing structures such as dyke or fault. At 30 m a negative anomaly was also picked, indicating non-magnetic subsurface lithologies. The drilling target was selected at station 50 m. Traverse line 2 trending from the central to the northwestern part of the study area (Figure 4.2) covered a distance of 100 m in NW-SE trending direction. At station 20 m a positive anomaly was picked which may be indicating high magnetic subsurface lithologies. At station 40 m a negative anomaly was picked which indicates nonmagnetic subsurface structures such as fault or highly weathered zone (weathering is known to destroy magnetic properties of rocks). The drilling target was selected at station 40 m, targeting fault/ highly weathered zone.

Figure **4.2**: Traverse lines and drilling targets at Senakwe village

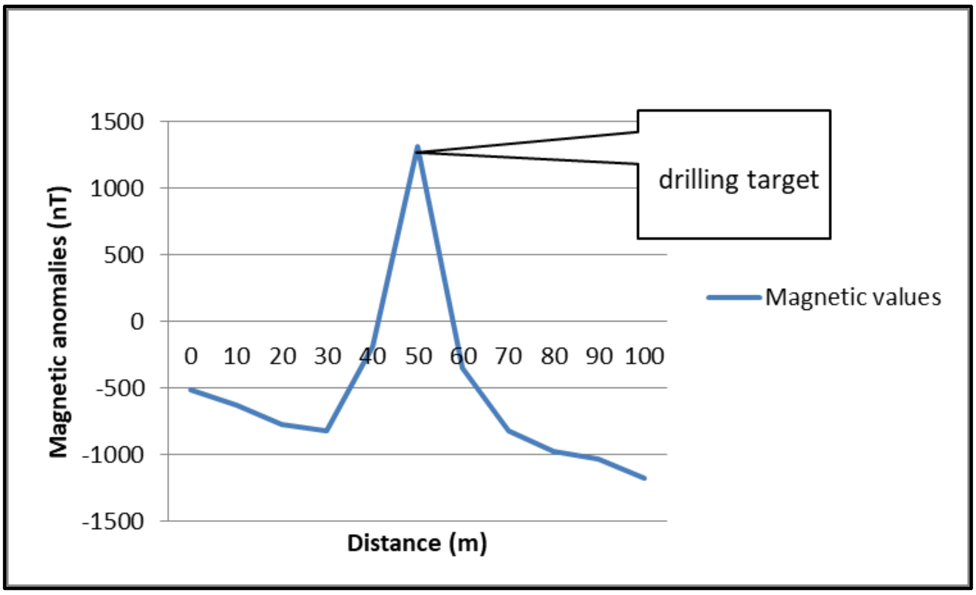


Figure **4.3**: Magnetic intensity profile for traverse line 1 at Senakwe village

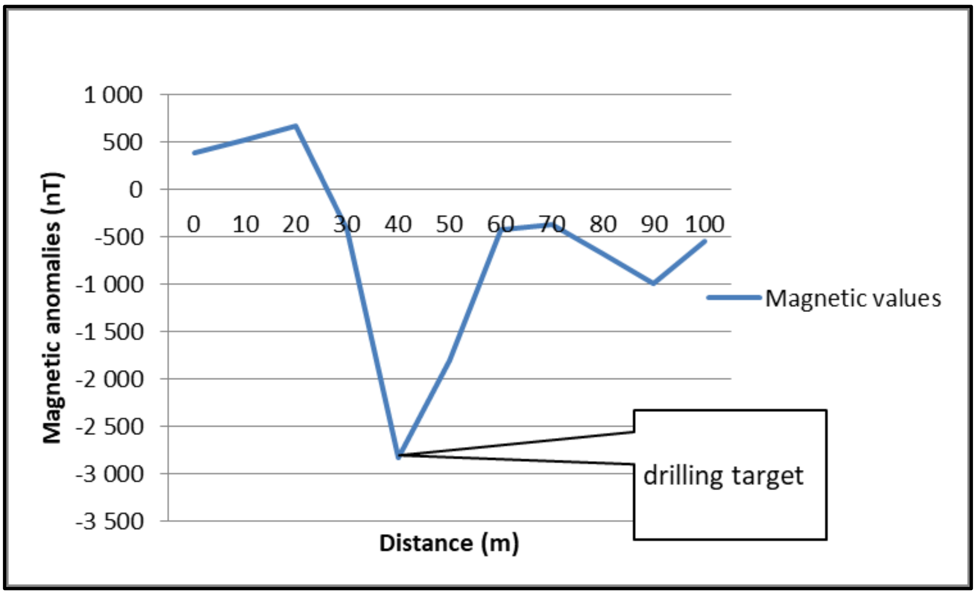


Figure **4.4**: Magnetic intensity profile for traverse line 2 at Senakwe village

4.2.4.2 Madumane village

One traverse line was set perpendicular to the local geology and geological structures with station interval spacing of 5 m (Figure 4.7). The total magnetic intensity observed along the traverse line is shown in Figure 4.8. This area was not accessible for the resistivity method.

The traverse line covered a distance of 100 m trending in the NW-SE trending direction. From Figure 4.8, station at 60 m produced a negative magnetic intensity anomaly with no artificial source associated with it, and this may indicate a highly weathered subsurface structure such as dyke or fault. The station at 60 m was selected as the drilling target. The magnetic trough on the profile is indicative of a subsurface geological structure such as a dolerite dyke which is likely to store groundwater.

Figure **4.5**: Traverse line and drilling target at Madumane village

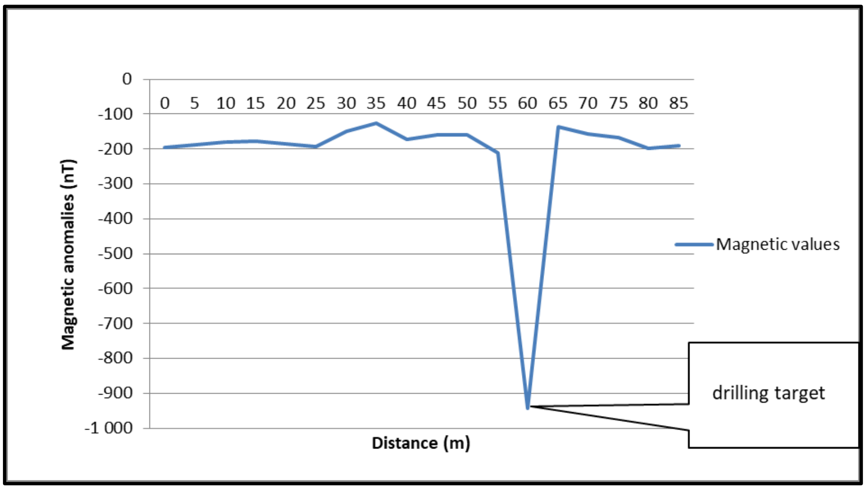


Figure **4.6**: Magnetic intensity profile for traverse line 1 at Madumane village.

4.2.4.3 Babanana village

One traverse line was set perpendicular to the local geology and geological structures with spacing intervals of 5 m (Figure 4.9). The total magnetic intensity observed at each station along the traverse lines is shown in Figure 4.1.

The traverse line covered a distance of 100 m trending in the NW-SE trending direction. From Figure 4.10, the station 55 m produced a negative magnetic anomaly with no artificial source associated with it, and this may indicate a highly weathered subsurface structure such as dyke or fault. The magnetic trough on the profile is indicative of subsurface geological structures such as dolerite dyke which is likely to store groundwater. Station 55 m was selected as the drilling target.

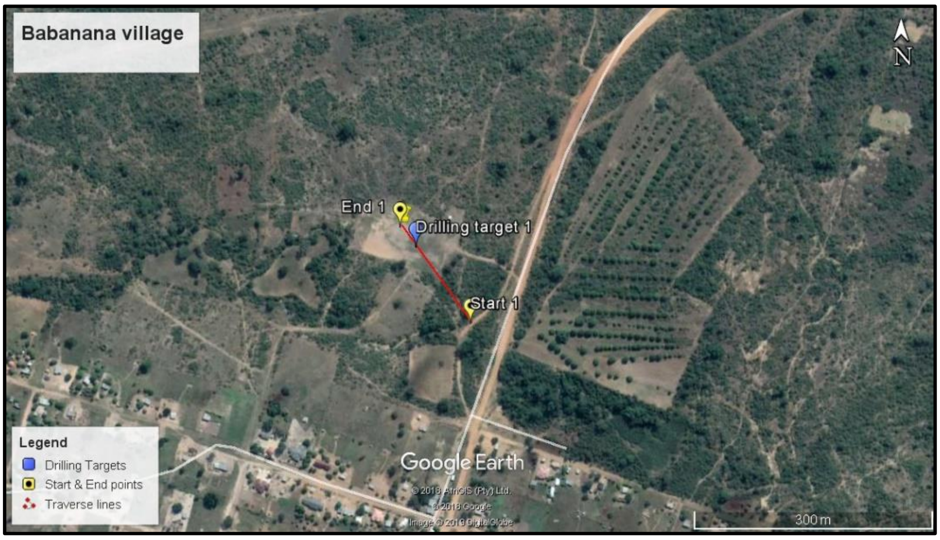


Figure **4.7**: Traverse line and drilling target at Babanana village

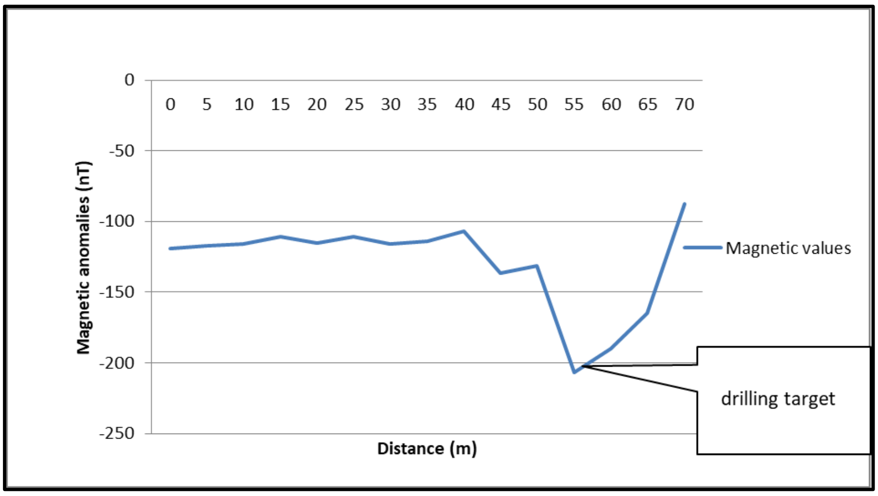


Figure **4.8**: Magnetic intensity profile for traverse line 1 at Babanana village.

4.2.4.4 Mabyepelong village

Two traverse lines were set perpendicular to the local geology and geological structures with station spacing intervals of 10 m (Figure 4.11). The observed total magnetic intensity at each station along the two traverse lines are shown in Figures 4.12 and 4.13.

Traverse line 1 in the southeastern part of the study area covered a distance of 240 m, trending in the NW-SE. Stations at 60 m and 160 m produced negative magnetic anomalies with no artificial source associated with them, and this may indicate highly weathered subsurface structures such as dyke or fault (Figure 4.12). The drilling target was selected at station 40 m and due to logistical problems station 160 m was left out (but was a good potential zone). Traverse line 2 in the western part of the study area (Figure 4.11) covered a distance of 240 m trending in the NW-SE direction. Stations at 110 m and 140 m produced positive magnetic anomalies which may be indicating high magnetic subsurface lithologies(Figure 4.13). Drilling target was selected at station 50 m, targeting either fault or dyke, stations 110 m and 140 m were left out due to logistical problems.

Figure **4.9**: Traverse lines and drilling targets at Mabyepelong village

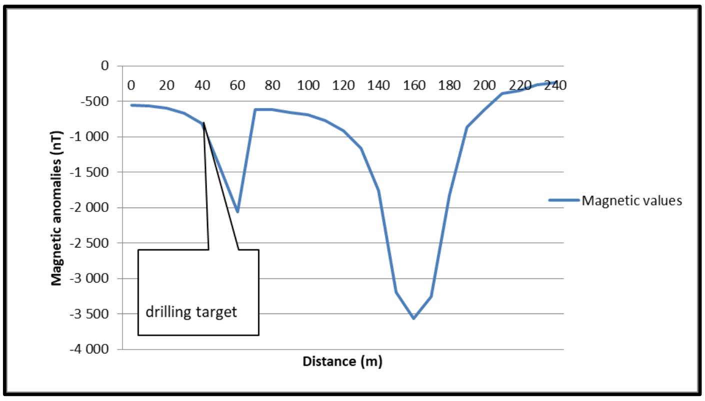


Figure **4.10**: Magnetic intensity profile for traverse line 1 at Mabyepelong village.

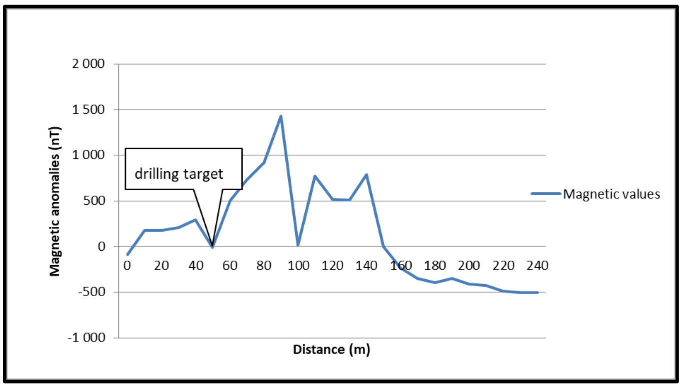


Figure **4.11**: Magnetic intensity profile for traverse line 2 at Mabyepelong village.

4.2.5 Data reduction and processing (resistivity survey)

The PQWTC instrument uses the natural electromagnetic field of the earth as the working field source to study the electrical structure inside the earth. The earth's electromagnetic response sequence studies the difference in electrical variation of geological bodies at different depths in the subsurface and determines the occurrences of underground geological bodies (Daniels and Alberty 1966). The electromagnetic waves are sent to the ground and the propagation of the electromagnetic waves in the earth and soil follows the Maxwell equation (Huhan geologic exploration institute, 2017). It is assumed that most of the subterranean geotechnical soil is non-magnetic and is uniformly conductive macroscopically, there is no change in accumulation, then the Maxwell equation can be simplified to:

$\nabla^2 H + K^2 H = 0$…………………………………………………………………………..…1

Where k is called the wave number (or propagation coefficient)

H is the magnetic field component

$K= (\omega^2 \mu\varepsilon\text{-}i\omega\sigma\mu)^{1/2}$…………………………………………………………………..…….2

Considering that the propagation coefficient k is a complex number, let k = b = ia, where a is called the phase coefficient and b is called absorption coefficient. The electromagnetic frequency measured by the PQWTC ranges from 0.1 Hz to 5 kHz, the displacement current can usually be ignored and k is further simplified as:

$K= -i\omega\sigma\mu$……………………………………………………………………………..……3

A magnetic field with a change in the Helmholtz equation induces a changing electric field, and we have a magnetoelectric relationship:

$\frac{E}{H} = -\frac{i\omega\rho}{K}$…………………………………………………………………………….….4

The surface impedance Z is defined as the ratio of the surface electric field and the horizontal component of the magnetic field. In the case of uniform earth, this impedance is independent of the polarization of the incident field and is related to the earth resistivity and the frequency of the electromagnetic field:

$Z=\frac{E}{H} = \sqrt{\omega\mu\rho\varepsilon^{\frac{i\pi}{4}}}$……………………………………………………………………….……..5

Formula (5) can be used to determine the resistivity of the earth:

$\mathbf{p} = \frac{1}{5f}(\frac{E}{H})^2$…………………………………………………………………………….....6

in non-magnetic media the skin depth is:

$\delta \approx 503\sqrt{\frac{p}{f}}$……………………………………………………………………………...7

Where $\boldsymbol{\delta}$ is the penetration depth, p is the AC resistivity and f is the frequency

It can be seen from the above equation that the penetration of depth of electromagnetic waves is related to frequency and resistivity. The frequency is certain, the higher the resistivity, the greater the penetration depth. The pqwtc machine stores data automatically after recording and also create subsurface resistivity profiles after automated data processing.

4.2.5.1 Discussion of the findings (resistivity results at Senakwe village)

The resistivity method was used on the same traverse lines as for the magnetic method above (Figure 4.2). The resistivity data in traverse line 1 with station spacing of 10m shows that at station 5 (50 m), there are low resistive subsurface lithology from 0 – 45 m depth and, from 55 to 240 m depth (Figure 4.5) and this coincides with magnetic data anomaly at station 50 m (Figure 4.3). The resistivity data for traverse line 2 shows that at station 4 (at 40 m), there are low resistive materials from 0 – 210 m deep (Figure 4.6). This coincides with the magnetic data which indicated a negative anomaly at station 40 m (Figures 4.4). Water is a good conductor therefore rock units coating groundwater will show low resistivity values.

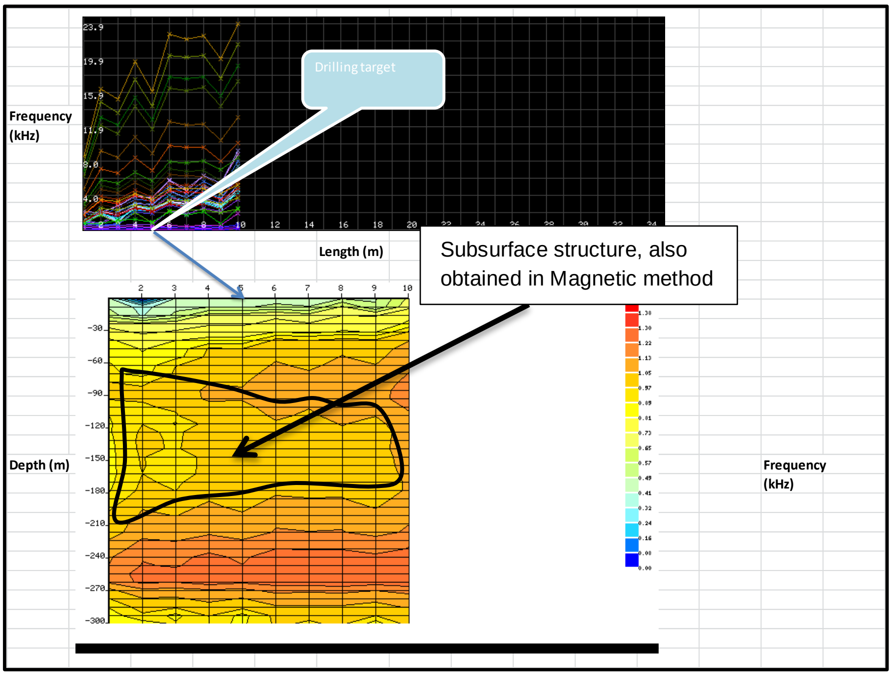


Figure **4.12**: Pseudo-section 2D view of resistivity profile for traverse line 1 at Senakwe village

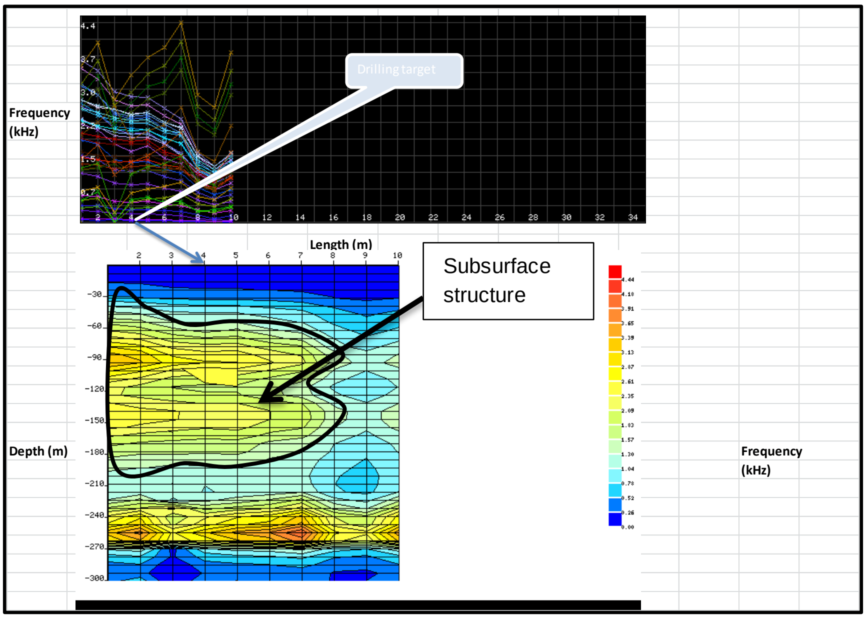


Figure **4.13:** Pseudo-section 2D view of resistivity profile for traverse line 2 at Senakwe village

The drilling target number one at Senakwe village was selected in station 50 m on traverse line 1 due to low resistive materials from 0 – 55 m deep, from 60 – 120 m deep there are high resistive subsurface lithologies (Figure 12). There is a pick in the magnetic intensity profile (Figure 4.3) this may indicate subsurface geological structures such as a fault or dolerite dyke which is likely to store groundwater. The drilling target number 2 on traverse line 2 was selected at station 40 m on the profile indicated by low magnetic and resistivity anomalies in Figures 4.4 and 4.13 respectively, which may indicate a high degree of weathering in the subsurface structure (dolerite dyke/ fault).

A summary of the drilling targets from the surveyed areas will be shown in Table 4.6. The table indicates the traverse line number, coordinates of the drilling targets, geological structures, and the main geology within the study area.

Table **4.6**: Drilling positions at Senakwe village, Madumane village, Babanana village, and Mabyepelong village

Village name	**Traverse line**	**Drilling target coordinates**	**Geological structures**	**Main geology**
Senakwe	1	-23.52961 S, 30.42848 E	Fault/dyke	Archean Granite & Gneiss
	2	-23.52407 S, 30.43020 E	Fault/dyke	Archean Granite & Gneiss
Madumane	1	-23.627627 S, 30.392087 E	Fault/dyke	Archean Granite & Gneiss
Babanana	1	-23.70029 S, 30.39980 E	Fault/dyke	Archean Granite & Gneiss
Mabyepelong	1	-23.56823 S, 30.45712 E	Geological contact	Archean Granite & Gneiss
	2	-23.56502 S, 30.44335 E	Geological contact	Archean Granite & Gneiss

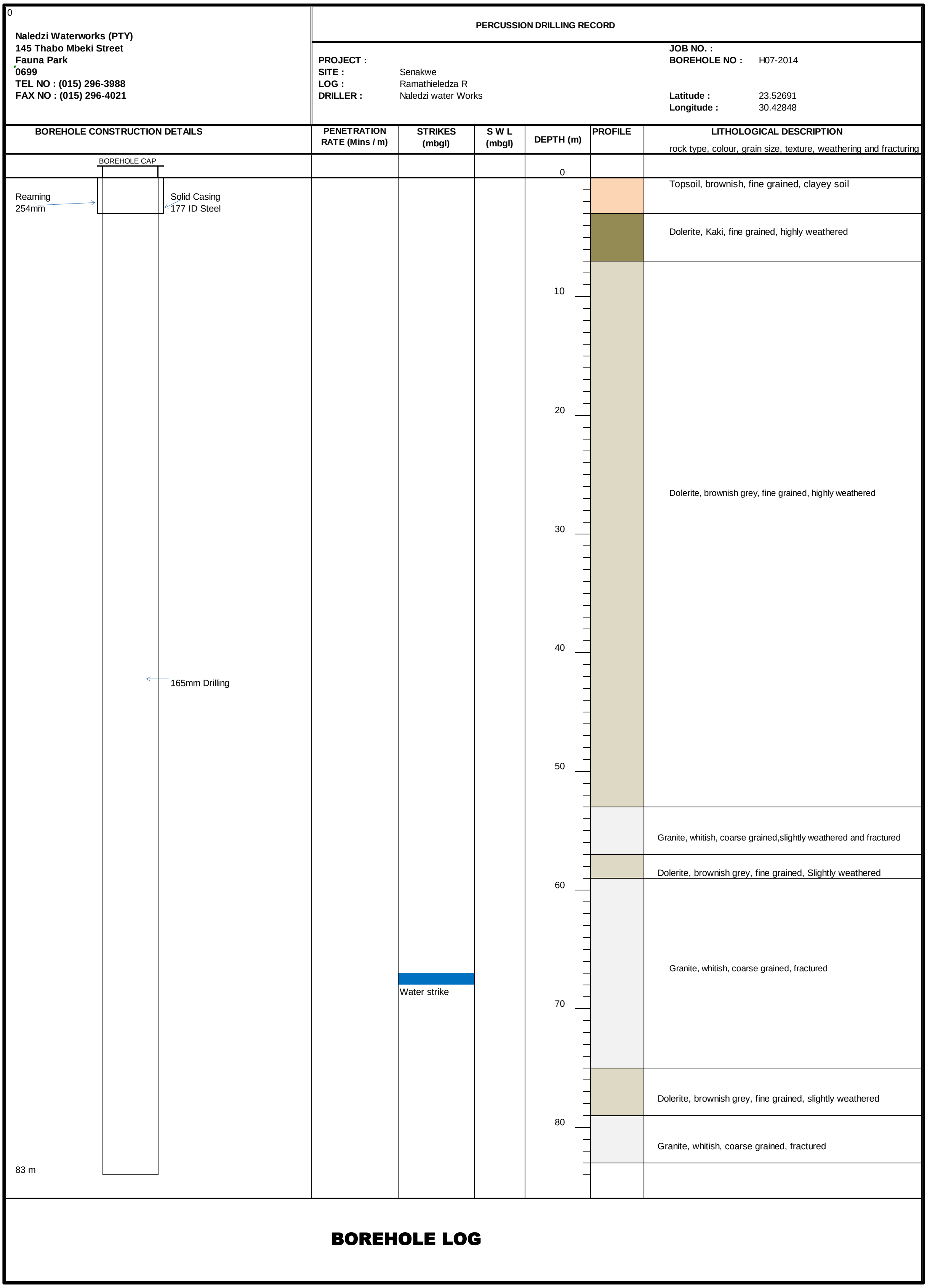
4.3 Drilling of boreholes in Relela villages

Naledzi waterworks PTY LTD conducted the drilling in the Relela villages, namely; Senakwe, Babanana, and Madumane. The drilling was conducted as per the contractual agreement with the Mopani municipality for groundwater supply to communities at Relela villages. During the drilling of boreholes, core logs were logged. The different lithologies encountered during the drilling were recorded on a log sheet. The borehole logging considered different properties which included visual observations of the rock/soil types, colour, grain sizes, weathering, or fracturing of the subsurface lithologies. The borehole locality maps are shown in appendix c.

4.3.1 Senakwe village

Senakwe village had two potential drilling targets, that were drilled and their subsurface lithologies were studied for a better understanding of the subsurface conditions. The different rock types which were encountered during drilling were recorded on a borehole log profile (Figure 4.15 and 4.16). Borehole H07-2014 (Figure 4.14) was drilled up to the depth of 83 m below the ground level. Topsoil was encountered between 0 – 3 m deep, highly weathered dolerite dyke was encountered from 4 – 53 m deep, and fractured granites were encountered from 54 – 83 m deep. The groundwater strike was encountered at 68 m below the ground level. The type of aquifer can be classified as a deep fractured aquifer. Titus et al, (2009) described deep aquifers as the aquifers that are associated with highly fractured rocks at a depth greater than 50 m deep. The blow yield of the borehole was measured to be about 0.1 l/sec, this was considered a low yield.

Figure **4.14**: Satellite image showing the drilled boreholes (H07 2015 and H07 2014) at Senakwe village.



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Naledzi Waterworks (PTY)
145 Thabo Mbeki Street
Fauna Park
0699
TEL NO : (015) 296-3988
FAX NO : (015) 296-4021

PERCUSSION DRILLING RECORD

PROJECT :
SITE : Senakwe
LOG : Ramathieledza R
DRILLER : Naledzi water Works

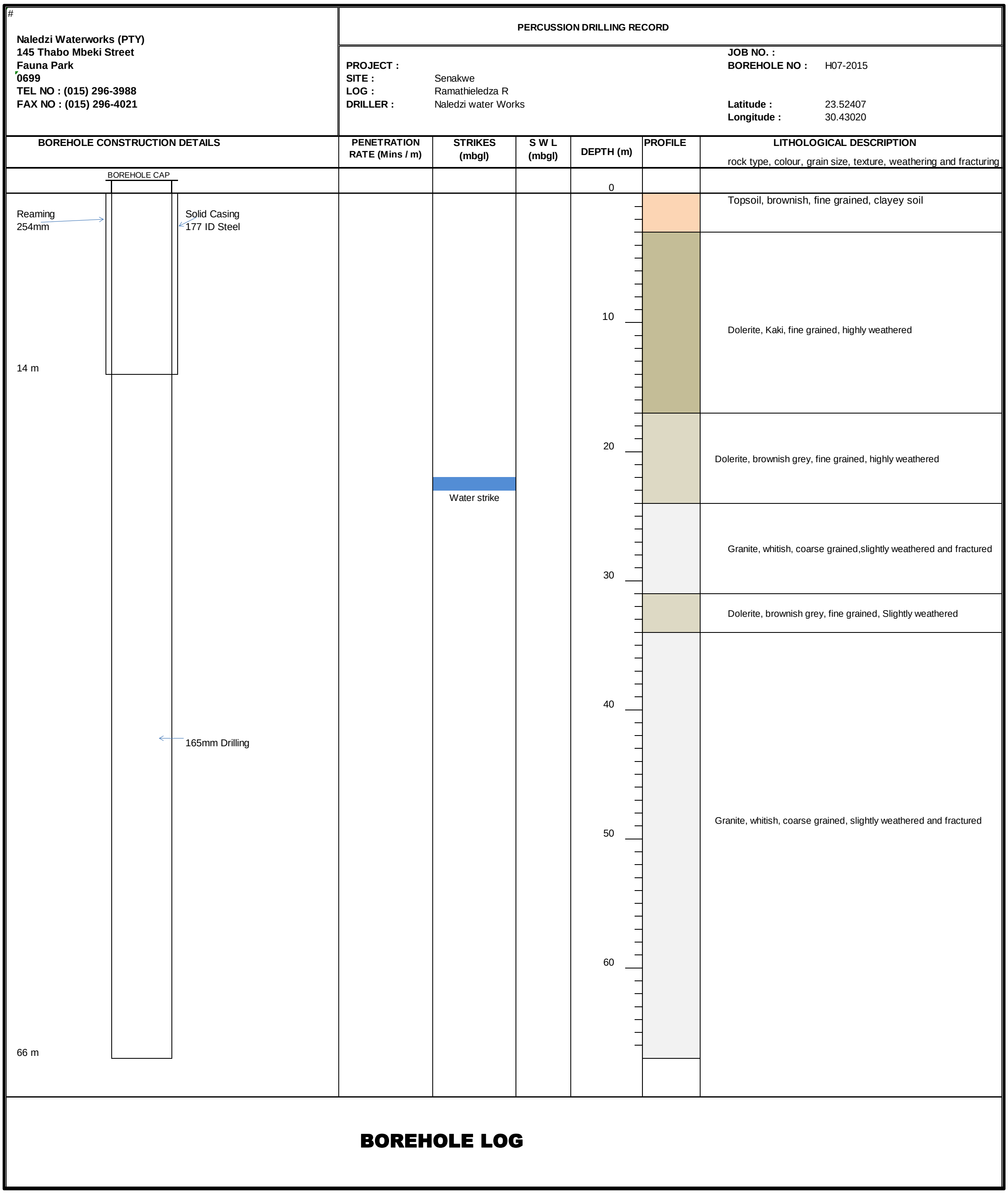
JOB NO. :
BOREHOLE NO : H07-2014
Latitude : 23.52691
Longitude : 30.42848

BOREHOLE CONSTRUCTION DETAILS	PENETRATION RATE (Mins / m)	STRIKES (mbgl)	S W L (mbgl)	DEPTH (m)	PROFILE	LITHOLOGICAL DESCRIPTION rock type, colour, grain size, texture, weathering and fracturing
BOREHOLE CAP				0		
Reaming 254mm Solid Casing 177 ID Steel						Topsoil, brownish, fine grained, clayey soil
						Dolerite, Kaki, fine grained, highly weathered
165mm Drilling				10 20 30 40 50		Dolerite, brownish grey, fine grained, highly weathered
						Granite, whitish, coarse grained,slightly weathered and fractured
						Dolerite, brownish grey, fine grained, Slightly weathered
		Water strike		60 70		Granite, whitish, coarse grained, fractured
						Dolerite, brownish grey, fine grained, slightly weathered
83 m				80		Granite, whitish, coarse grained, fractured

BOREHOLE LOG

Figure **4.15**: Senakwe village borehole log for borehole number H07-2014

Borehole number H07-2015 (Figure 4.14) was drilled up to the depth of 66 m below the ground level (Figure 4.19 and Table 4.8). Topsoil was encountered found from 0 – 3 m deep, highly weathered dolerite dyke was encountered from 4 – 17 m deep and fractured granites were encountered from 18 – 66 m deep. The water strike was encountered at 23 m below the ground level. The type of aquifer at which the water strike was encountered can be classified as a shallow fractured aquifer. Titus *et al*, (2009b) also described shallow aquifers as the aquifers that are associated with highly weathered rocks at an approximate depth of about 50 mbgl. The blow yield of the borehole was measured at about 2 l/sec, this was considered a moderate yield.



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Fauna Park
0699
TEL NO : (015) 296-3988
FAX NO : (015) 296-4021

PERCUSSION DRILLING RECORD

PROJECT :
SITE : Senakwe
LOG : Ramathieledza R
DRILLER : Naledzi water Works

JOB NO. :
BOREHOLE NO : H07-2015
Latitude : 23.52407
Longitude : 30.43020

BOREHOLE CONSTRUCTION DETAILS

BOREHOLE CAP
Reaming 254mm
Solid Casing 177 ID Steel
14 m
165mm Drilling
66 m

PENETRATION RATE (Mins / m)	STRIKES (mbgl)	S W L (mbgl)	DEPTH (m)	PROFILE	LITHOLOGICAL DESCRIPTION rock type, colour, grain size, texture, weathering and fracturing
			0		Topsoil, brownish, fine grained, clayey soil
			10		Dolerite, Kaki, fine grained, highly weathered
	Water strike		20		Dolerite, brownish grey, fine grained, highly weathered
			30		Granite, whitish, coarse grained,slightly weathered and fractured
					Dolerite, brownish grey, fine grained, Slightly weathered
			40 50 60		Granite, whitish, coarse grained, slightly weathered and fractured

BOREHOLE LOG

Figure **4.16**: Senakwe village borehole number H07-2015

4.3.2 Madumane village

Madumane village had one groundwater potential drilling target that was drilled and the subsurface lithologies studied. The different rock types which were encountered during drilling are shown on a borehole log profile (Figure 4.18). Borehole H07-1685 was drilled up to the depth of 60 m below the ground level (Figure 4.17 and 4.18). Topsoil was found from 0 – 2 m deep, highly weathered granite was encountered from 3 – 17 m deep and fractured granites were encountered from 18 – 60 m deep. The water strike was encountered at 22 m below the ground level. The type of aquifer at which the water strike was encountered can be classified as a shallow fractured aquifer. The blow yield of the borehole was measured at about 0.1 l/sec, this was considered a low yield.

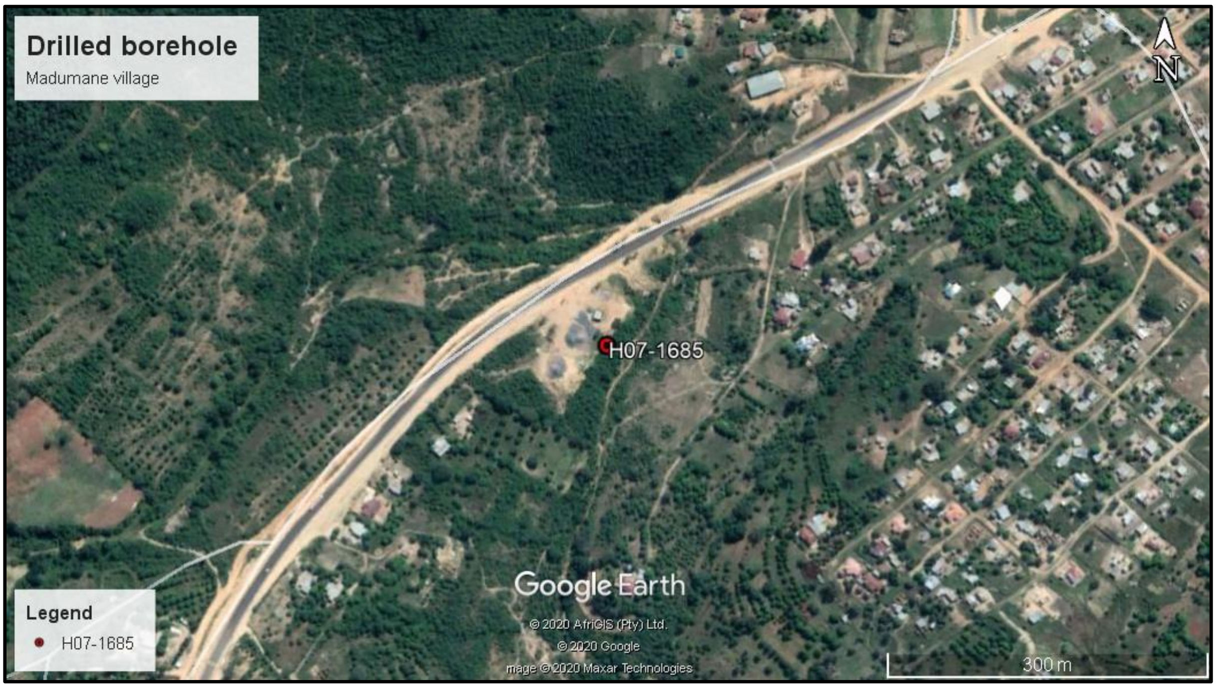
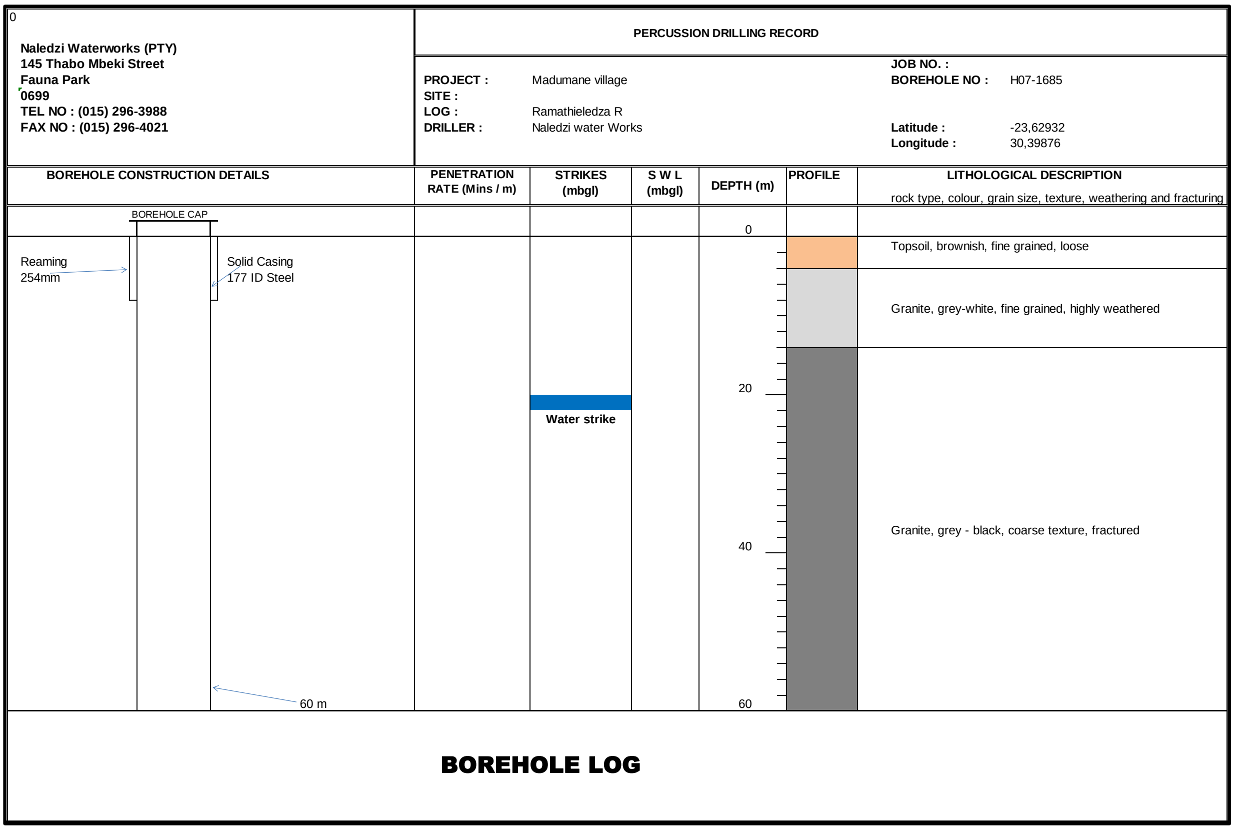


Figure **4.17**: Satellite image showing drilled targets at Madumane village.



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FAX NO : (015) 296-4021

PERCUSSION DRILLING RECORD

PROJECT : Madumane village
SITE :
LOG : Ramathieledza R
DRILLER : Naledzi water Works

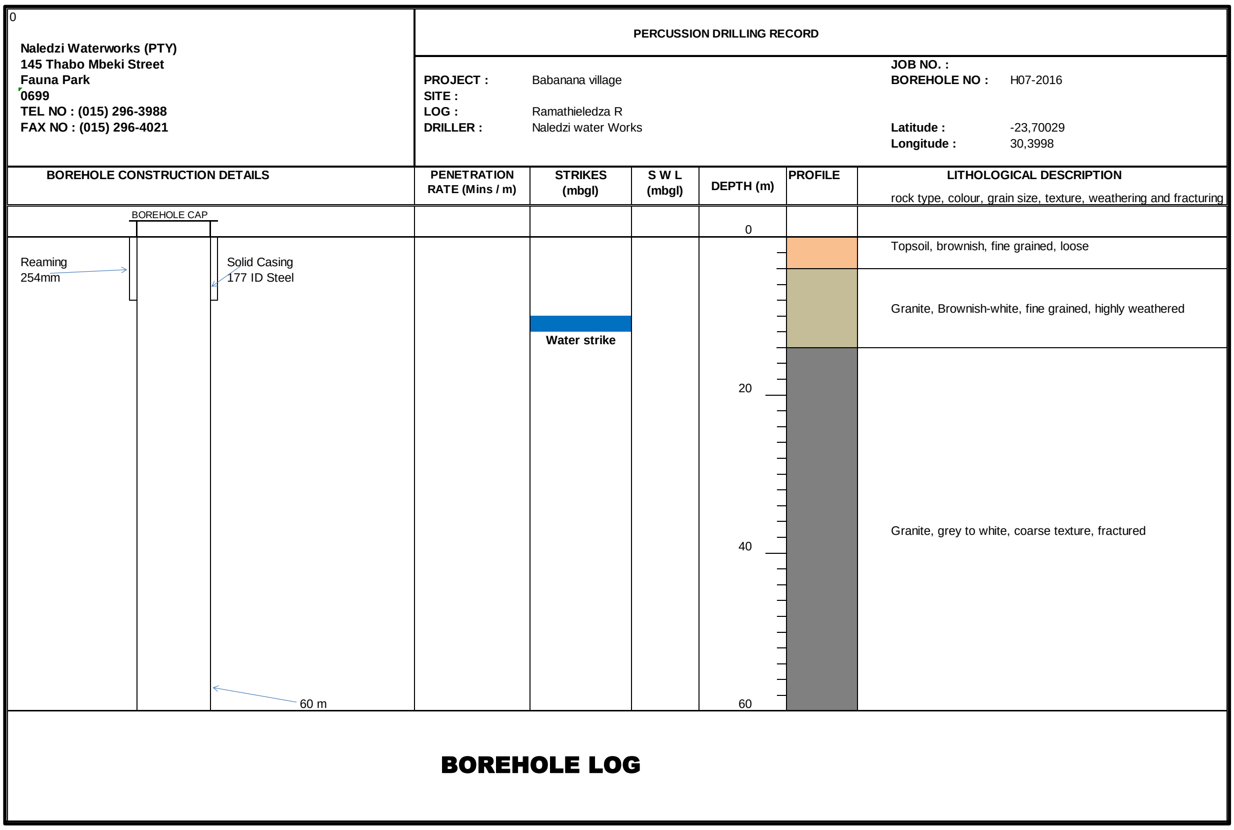
JOB NO. :
BOREHOLE NO : H07-1685
Latitude : -23,62932
Longitude : 30,39876

Figure **4.18**: Madumane village borehole number H07-1685

4.3.4 Babanana village

Babanana village had one groundwater potential drilling target which was drilled and the subsurface lithologies were studied. The different rock types which were encountered during drilling are shown on a borehole log profile (Figure 4.20). Borehole H07-2016 (Figure 4.19 and 4.20) was drilled up to the depth of 60 m below the ground level. Topsoil was encountered from 0 – 2 m deep, highly weathered granite was encountered from 3 – 16 m deep and fractured granites were encountered from 17 – 60 m deep. The water strike was encountered at 14 m below the ground level (Figure 4.20). The type of aquifer at which the water strike was encountered can be classified as a shallow fractured aquifer. The blow yield of the borehole was measured at about 0.2 l/sec, this was considered a low yield.

Figure **4.19**: Satellite image showing drilled target at Babanana village



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0699
TEL NO : (015) 296-3988
FAX NO : (015) 296-4021

PERCUSSION DRILLING RECORD

PROJECT : Babanana village
SITE :
LOG : Ramathieledza R
DRILLER : Naledzi water Works

JOB NO. :
BOREHOLE NO : H07-2016
Latitude : -23,70029
Longitude : 30,3998

BOREHOLE CONSTRUCTION DETAILS	PENETRATION RATE (Mins / m)	STRIKES (mbgl)	S W L (mbgl)	DEPTH (m)	PROFILE	LITHOLOGICAL DESCRIPTION rock type, colour, grain size, texture, weathering and fracturing
						Topsoil, brownish, fine grained, loose
						Granite, Brownish-white, fine grained, highly weathered
						Granite, grey to white, coarse texture, fractured

BOREHOLE LOG

Figure **4.20**: Babanana village borehole number H07-2016

4.3.5 Mabyepelong village

Mabyepelong village had two potential drilling targets, that were drilled and the subsurface lithologies were studied. The different rock types which were encountered during drilling are shown on borehole log profiles (Figure 4.22 and 4.23). Borehole H07-2022 and H07-2023 were drilled up to the depth of 60 m below the ground level (Figure 4.21). In borehole H07-2023 topsoil was found from 0 – 2 m deep, highly weathered granite was encountered from 3 – 5 m deep, and fractured dolerite dyke was encountered from 6 – 60 m deep. The water strike was encountered at 16 m below the ground level (Figure 4.22). The type of aquifer at which the strike was encountered can be classified as a shallow weathered aquifer. Aquifers that are found in less or equal to 50 m deep are considered shallow aquifers (Titus et al, 2009b). The blow yield of the borehole was measured at about 1.4 l/sec, this was considered a low yield.

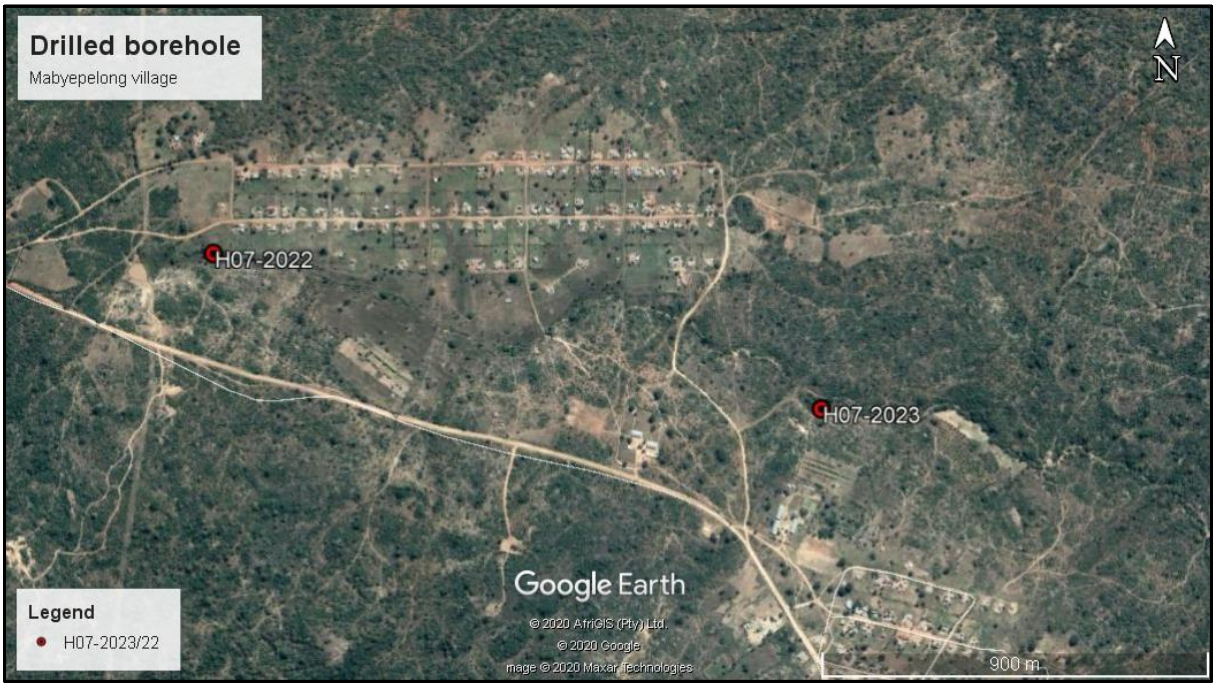
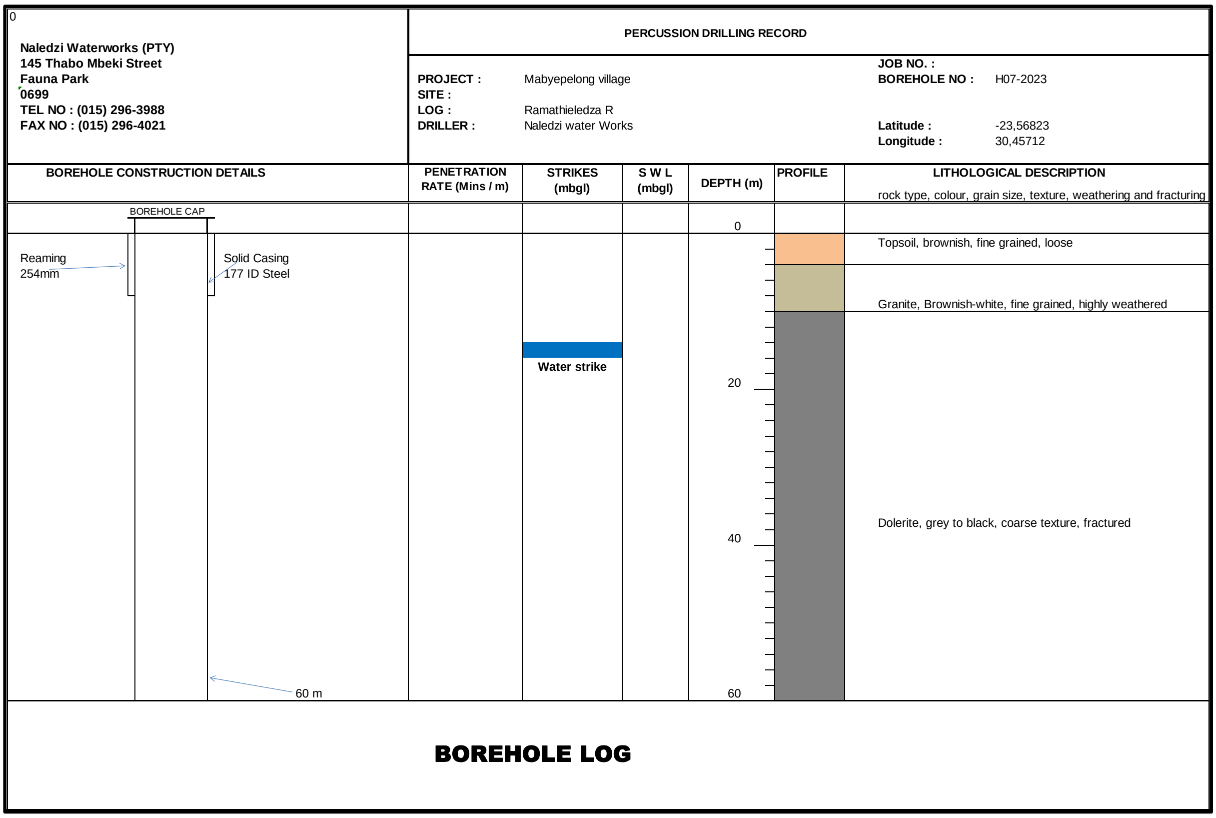


Figure **4.21**: Satellite image showing drilled targets at Mabyepelong village



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Fauna Park
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TEL NO : (015) 296-3988
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PERCUSSION DRILLING RECORD

PROJECT : Mabyepelong village
SITE :
LOG : Ramathieledza R
DRILLER : Naledzi water Works

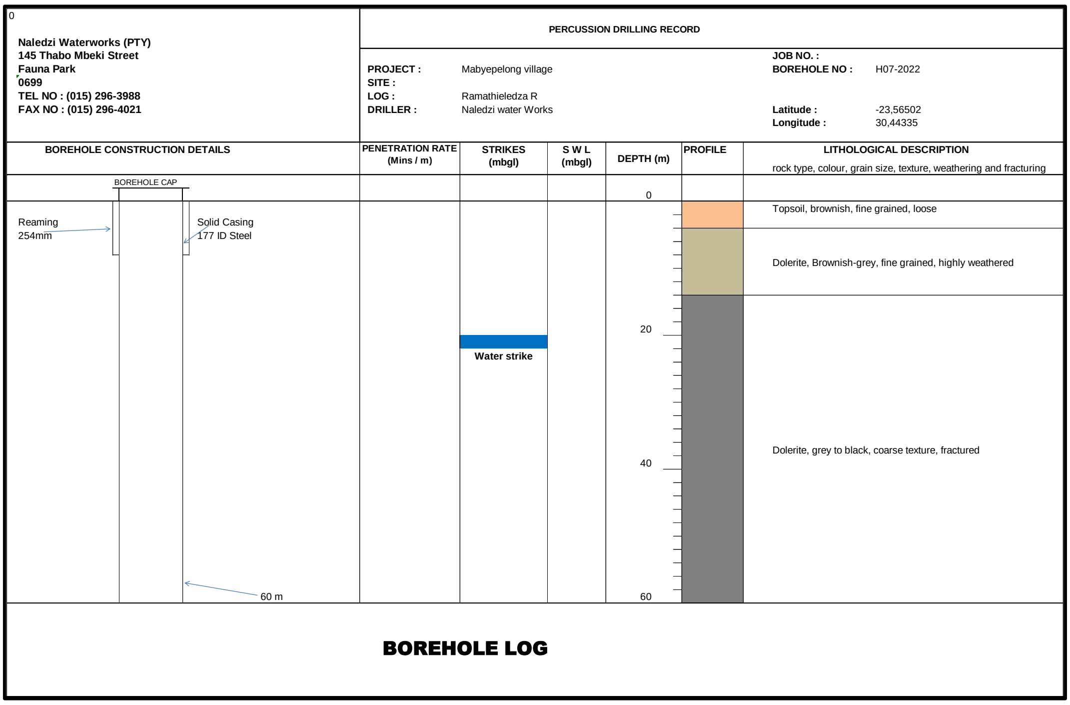
JOB NO. :
BOREHOLE NO : H07-2023

Latitude : -23,56823
Longitude : 30,45712

BOREHOLE LOG

Figure **4.22**: Mabyepelong village borehole number H07-2023

Borehole H07-2022 was drilled up to the depth of 60 m below the ground level (Figure 4.23). Topsoil was found from 0 – 4 m deep, highly weathered granite was encountered from 5 – 12 m deep, and fractured dolerite dyke was encountered from 13 – 60 m deep. The water strike was encountered at 22 m below the ground level (Figure 4.23). The type of aquifer at which the strike was encountered can be classified as a shallow fractured aquifer, the water strike was found in a fractured dolerite dyke. The blow yield of the borehole was measured at about 0.5 l/sec, this was considered a low yield.



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145 Thabo Mbeki Street
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0699
TEL NO : (015) 296-3988
FAX NO : (015) 296-4021

PERCUSSION DRILLING RECORD

PROJECT : Mabyepelong village
SITE :
LOG : Ramathieledza R
DRILLER : Naledzi water Works

JOB NO. :
BOREHOLE NO : H07-2022
Latitude : -23,56502
Longitude : 30,44335

BOREHOLE CONSTRUCTION DETAILS	**PENETRATION RATE (Mins / m)**	**STRIKES (mbgl)**	**S W L (mbgl)**	**DEPTH (m)**	**PROFILE**	**LITHOLOGICAL DESCRIPTION** rock type, colour, grain size, texture, weathering and fracturing
						Topsoil, brownish, fine grained, loose
						Dolerite, Brownish-grey, fine grained, highly weathered
		Water strike				Dolerite, grey to black, coarse texture, fractured

BOREHOLE LOG

Figure **4.23**: Mabyepelong village borehole number H07-2022

4.4 Discussion of borehole drilling

A total number of six (6) boreholes were drilled in the study area. The drilling results show that there are subsurface lithological variations in and within the vicinity of the study area. The dominating geology within the study area are granites and gneiss, however, there are some intrusions within granites and gneiss. The most dominant intrusions found within the study area are the dolerite dykes with some of them being almost vertical while others are inclined. These intrusions can be correlated to the magnetic anomalies encountered during groundwater exploration with the use of the geo-proton precision magnetometer.

Water strikes were found at different depths in the six boreholes drilled. The water strikes ranged between 15 m to 70 m below the groundwater level. Two main types of aquifers were namely, shallow and deep weathered/fractured aquifers. The blow yields range from 0.1 l/sec to 2 l/sec.

Boreholes with a high degree of weathering had better yields compared to boreholes that had a lower degree of weathering. The degree of weathering was the primary source of the transmissivity and storativity of groundwater in the study area. These are in agreement which confirms the observations made by Herrick and Legrand (1949); Crawford and Kath (2003), and Kath *et al*., (2001); that the groundwater availability depends on the hydrological parameters of the region which are rock types, rock structures, porosity, permeability and the topography of the study area.

All the boreholes could not be drilled further than 90 m deep to encounter deeper aquifers, due to the financial budgets which were allocated for this project. It is possible that if the boreholes could have been drilled to over 200 m below the ground level, the results could have been different, as deeper aquifers could have been encountered. After the completion of the drilling, a pumping test (aquifer testing) was conducted on the six boreholes to determine the aquifer characteristics (borehole yield, maximum abstraction per day, recommended pumping rate for a certain period, pump setting, etc.).

4.5 Pumping test (Aquifer testing)

A pumping test was conducted on all the six drilled boreholes to determine the quantity (sustainable yields) that the boreholes can supply to the Relela community. Numerous researchers have used the pumping test to evaluate aquifer parameters (i.e Anomohanran, 2013b; 2014b; Gogoi, 2013; Murry *et al*., 2012; Botha, 2017; Halford *et al.,* 2006; Rajasekhar *et al*.,2014; Straface *et al*., 2007; Tizro *et al*., 2014).

The aquifer parameters which were estimated include transmissivity (T), specific capacity (Sc), and safe yield ($Q_{\text{stainable}}$). A borehole's safe yield is the discharge rate that will not result in overexploitation of the underlying aquifer (Van Tonder *et al*., 2002). Transmissivity is the ability of an aquifer to transmit water from one media to another and it is important in understanding the groundwater flow and occurrence (Holland, 2012). The storativity of the aquifer could not be estimated since there were no observation wells as the pumping test was conducted in single wells only. The detailed pumping test data is shown in Appendix B.

4.4.1 Senakwe village

4.4.1.1 Borehole H07-2014

A multi-rate step test of 4 x 60 minutes was conducted at varying discharge rates of 0.80 l/sec, 1.77 l/s, 3.36 l/sec, and 5.80 l/sec discharge rate that lasted for only 15 minutes to reach a final drawdown of 55.14 m in 3 hours 15 minutes. A constant discharge test was conducted at a rate of 1.82 l/sec for 24 hours to reach a final drawdown of 54.06 m (Appendix B).

The cooper and Jacob method was used to plot semi-log, recovery of steps, and constant discharge vs the residual drawdown graphs. The flow characteristics software developed by Van Tonder et al., (2001) (which has the built-in formulas of Cooper and Jacob methods) was used to estimate the hydraulic parameters.

The step test drawdown vs time graph (Figures 4.24a and b) shows that the drawdown increases with the increase in discharge rate. The higher the discharge rate the higher the drawdown. According to Dawson and Istok (1991), the discharge rate should be sufficient to ensure that the aquifer is stressed and that drawdown can be measured accurately. Using low discharge rates in step 1 (0.8 l/sec) and 2 (1.77 l/sec) the drawdown seemed to be running slow but when the discharge was increased in step 3 (3.36 l/sec) and 4 (5.80 l/sec), the borehole reached the pump suction (Figure 4.24a). After the completion of step tests, the pump engine was switched off, the recovery of step tests was measured (Figure 4.24b).

Allen, (1999) stated that the borehole recovery phase shall continue until the water level in the well has recovered to at least 90% of the pre-test non-pumping water level. Step test recovery was good and it was estimated at 94 % after the pumping test had stopped. After the recovery of step tests, a constant discharge test was conducted. The graphs in (Figures 4.25a, b, and c) show the constant discharge test conducted at a rate of 1.82 l/sec for 24 hours with the recovery estimated at about 91% (Figure 4.25d). The transmissivity from this borehole was estimated at 2.9 m^2/d. This is a relatively low transmissivity aquifer, indicating that the underlying aquifer cannot transmit enough water from one point to another.

The specific capacity was calculated after 12 hours and 24 hours of the constant discharge test to evaluate the well performance. At 12 hours the specific capacity was estimated at 0.15 l/s per m and after 24 hours it was 0.03 l/s per m.

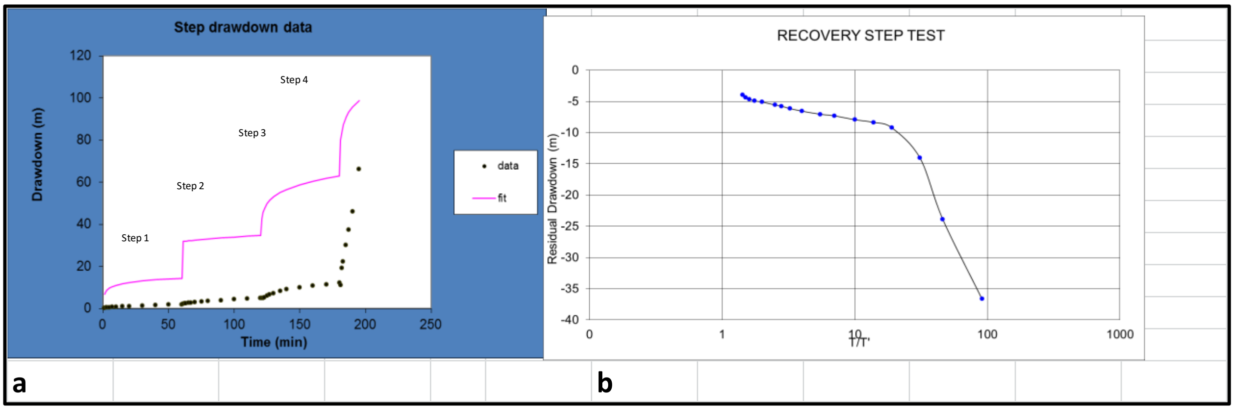


Figure **4.24**: a) Step test for borehole H07-2014; b) Recovery of step test for Borehole H07-2014

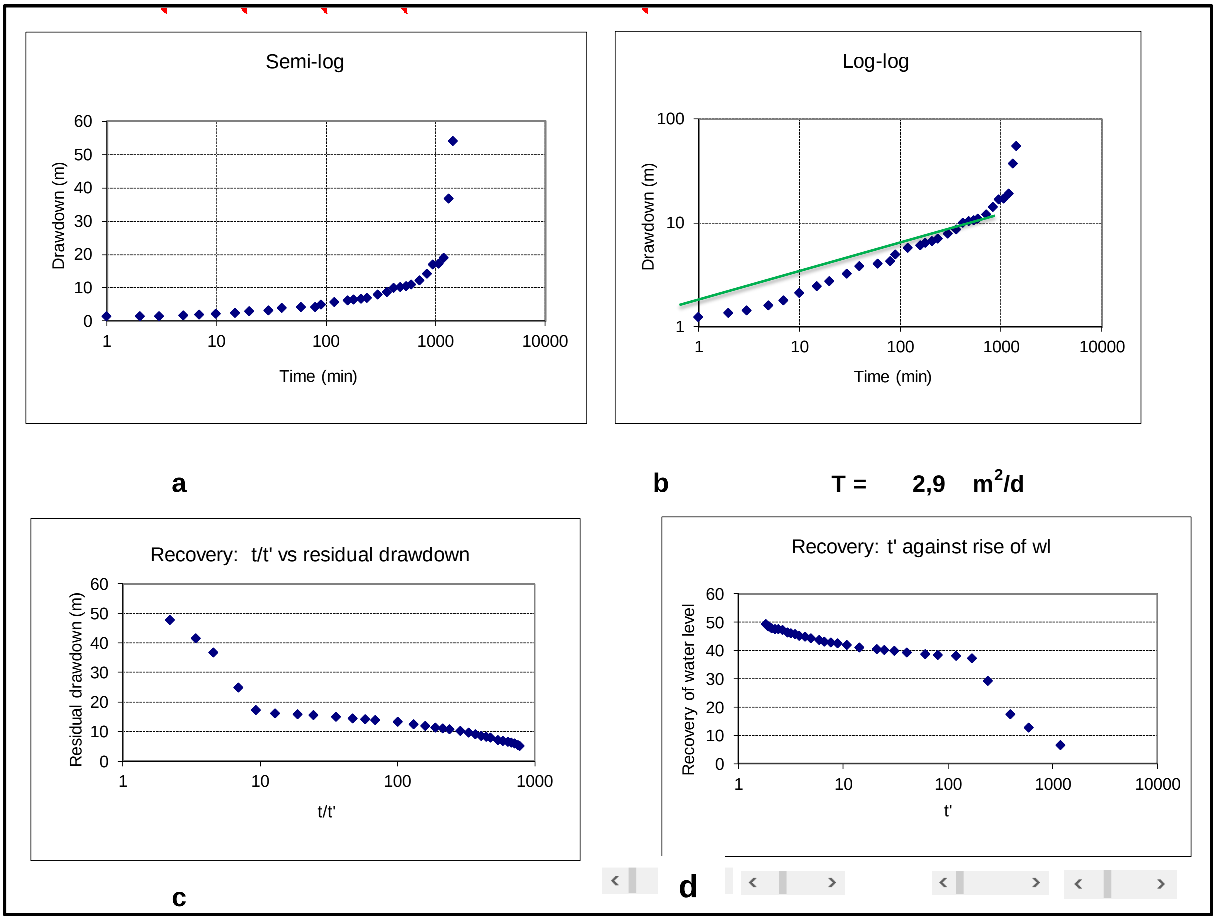


Figure **4.25**: Constant discharge test and recovery for borehole H07-2014

4.4.1.2 Borehole H07-2015

A multi-rate step tests of 2 x 60 minutes were conducted at varying discharge rates of 0.70 l/sec, 1.10 l/s, and a step of 2.20 l/sec which lasted for only 10 minutes, to reach a final drawdown of 55.14 m in 2 hours 10 minutes (Figures 4.26 a and b) This was followed by a recovery of step test and a constant discharge test (Figures 4.26b and 4.27d).

The step test drawdown vs time graph (Figure 4.26 a) shows that the drawdown increases with the increase in discharge rate. The higher the discharge rate the higher the drawdown. The recovery test followed after switching off the pump engine (Figure 4.26b). The recovery of constant discharge tests was good reaching a recovery of about 99% after the pumping period. A constant discharge test was conducted at 0.80 l/sec for 24 hours to reach a final drawdown of 38.02 m (Figures 4.27a, b and c). The transmissivity value for this borehole was estimated at 5 m^2/d, this shows that the underlying aquifer cannot transmit enough water from one point to another. The specific capacity was also calculated after 12 hours and 24 hours of the constant discharge test to evaluate the well performance. The specific capacity was estimated at 0.04 l/s per m and 0.02 l/s per m for 12 and 24 hours respectively.

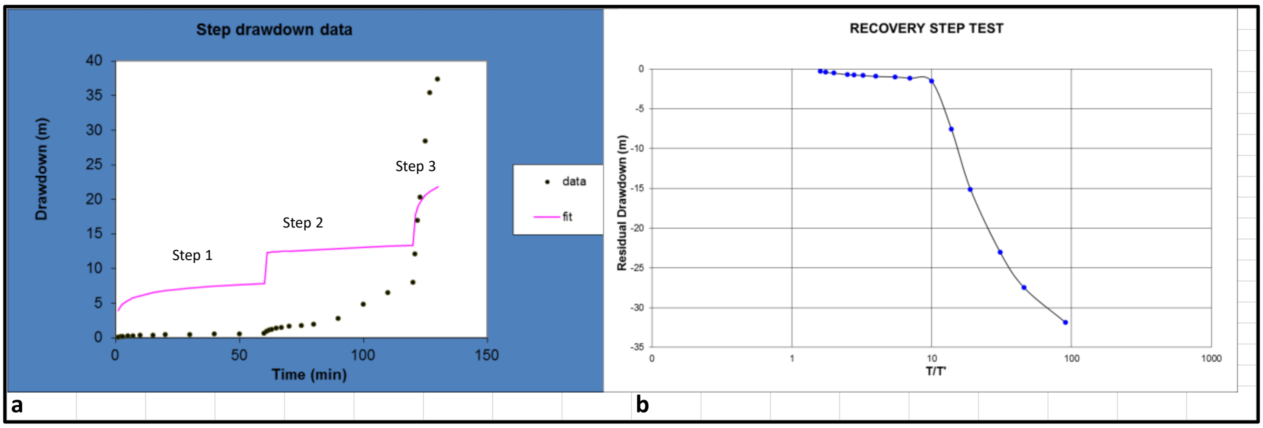


Figure **4.26**: a) Step tests for borehole H07-2015; b) Recovery of step tests for borehole H07-2015

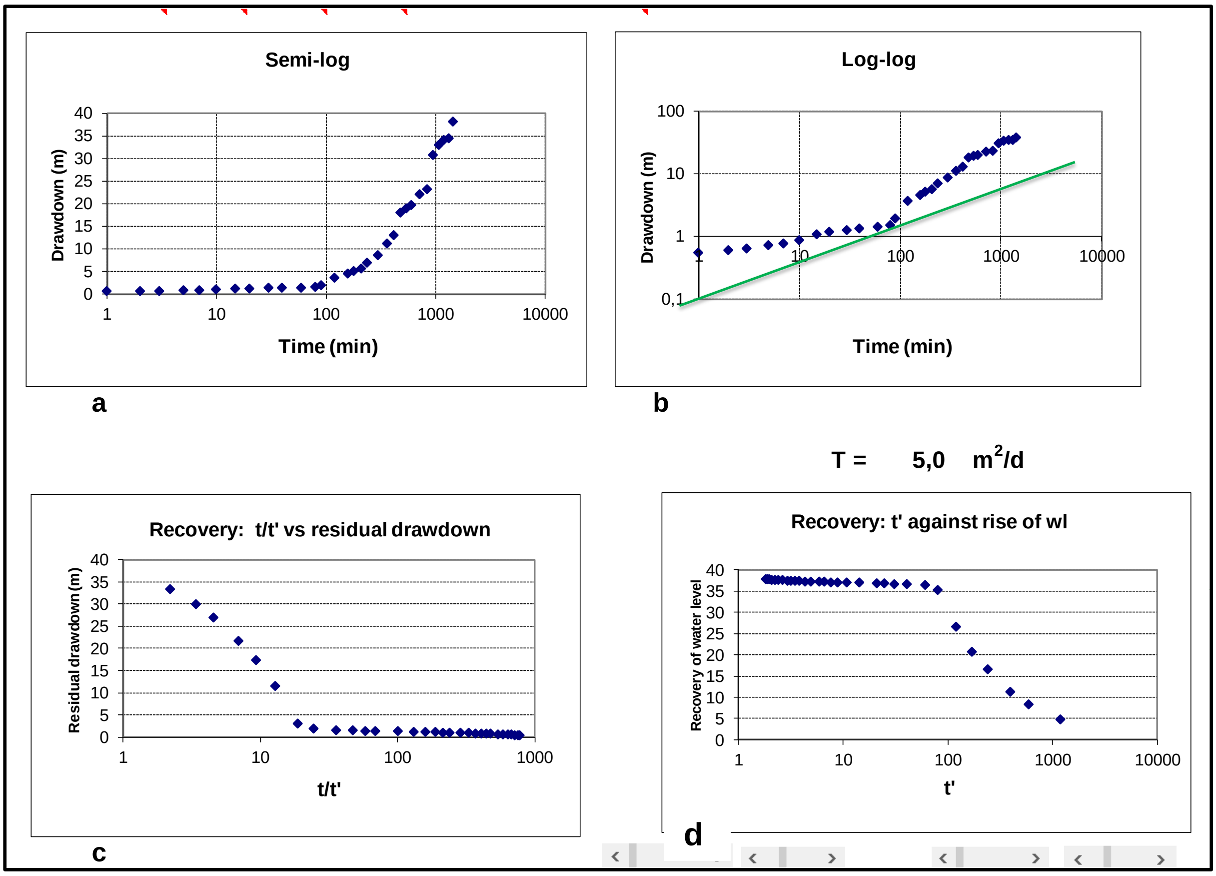


Figure **4.27**: Constant discharge test and recovery for borehole H07-2015.

4.4.2 Madumane village

A one-step test was conducted at a rate of 0.37 l/sec to reach a final drawdown of 35.24 m in 30 minutes (Figures 4.28a and b). A constant discharge test was not conducted because the borehole had little water. After the completion of step tests, the recovery was measured (Figure 4.29). The step test was not fully recovered, it only recovered 18% and this was regarded as poor borehole recovery. The transmissivity of borehole H07-1685 was estimated at 1.1 m^2/day. This shows that the underlying aquifer cannot transmit enough water from one point to another.

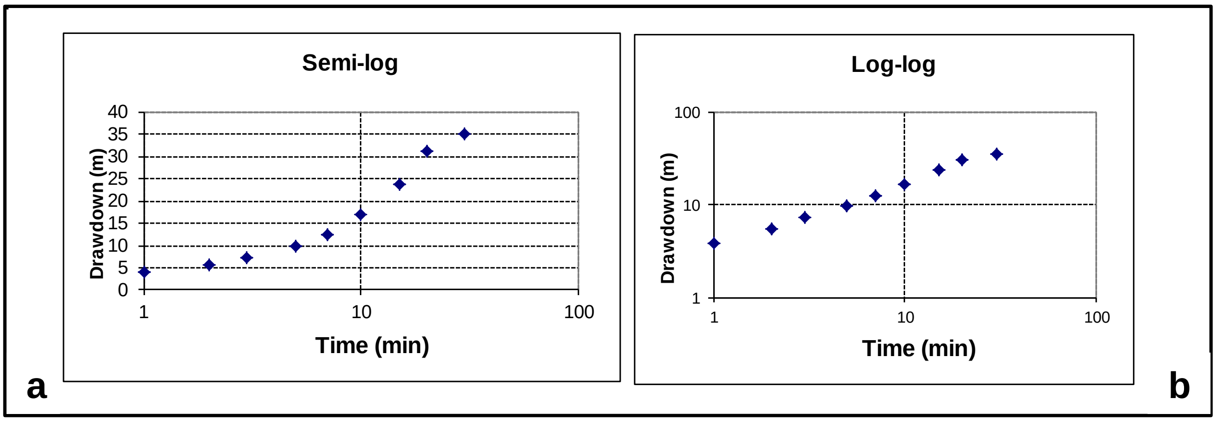


Figure **4.28**: a) Semi-log and b) Log-log graph of a step test for borehole H07-1685.

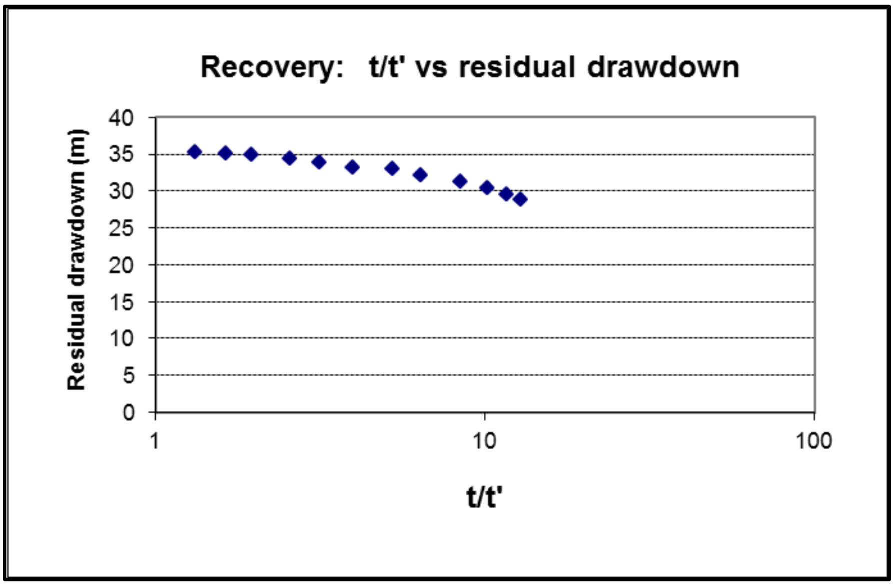


Figure **4.29**: Recovery of step test for borehole H07-1685.

4.4.3 Babananana village

A one-step test was conducted at a rate of 0.38 l/sec to reach a final drawdown of 37.99 m in 20 minutes (Figures 4.30a and b). A constant discharge test was not conducted because the borehole had little water. After the completion of the step, the recovery of step tests was measured (Figure 4.31). The step test was not fully recovered, it only recovered 68% and this was regarded as poor recovery. The transmissivity of borehole H07-2016 was estimated at 1.2 m^2/day, this shows that the underlying aquifer cannot transmit enough water from one point to another.

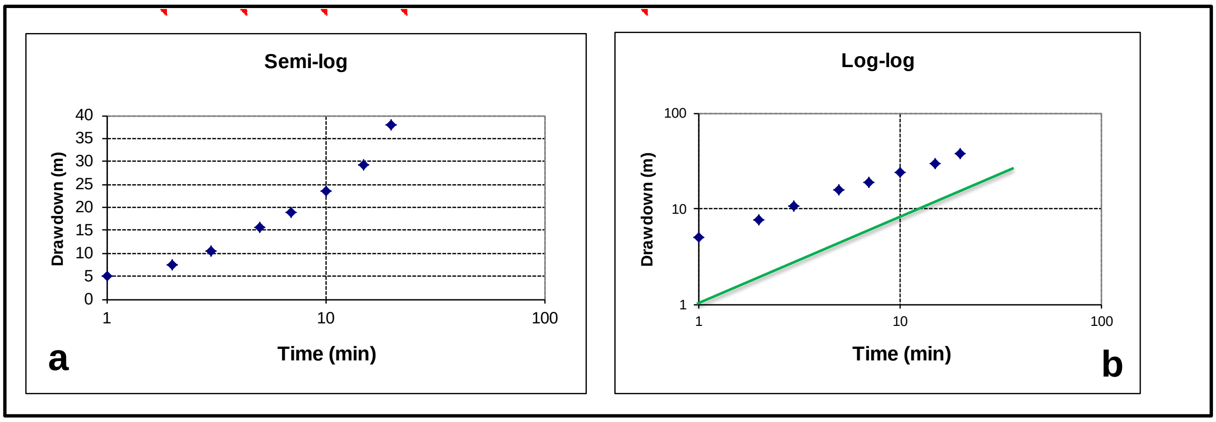


Figure **4.30**: a) Semi-log and b) Log-log graph of a step test for borehole H07-2016

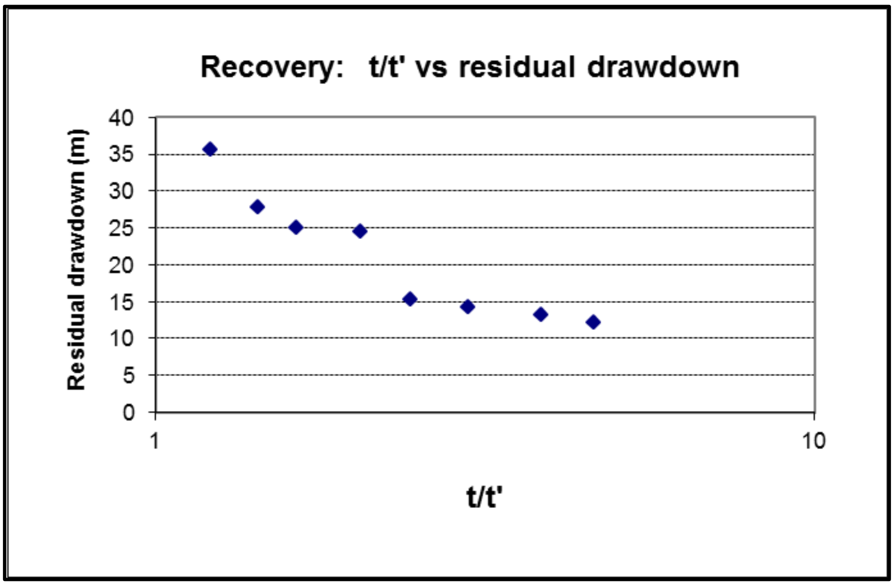


Figure **4.31**: Recovery of step test for borehole H07-2016.

4.4.4 Mabyepelong village

4.4.4.1 Borehole H07-2023

A multi-rate step test of 2 x 60 minutes was conducted at varying discharge rates of 0.37 l/sec, 0.60 l/s, and a step of 1.20 l/sec which lasted for only 15 minutes to reach a final drawdown of 38.12 m in 2 hours 15 minutes (Figures 4.32a, and b). This was followed by a recovery of step test which was estimated at 79% (Figure 4.32b) Constant discharge test was conducted at 0.44 l/sec for 12 hours reaching a final drawdown of 37.66 m (Figure 4.33a,b, and c). The recovery of the constant discharge test was estimated at 85% after the pumping period (Figure 4.33d).

The step test drawdown vs time graph (Figure 4.32a) shows that the drawdown increases with the increase in discharge rate. The higher the discharge rate the higher/ the drawdown. Borehole H07-2023 reached the pump suction after step test three which was conducted for fifteen minutes. The transmissivity value was estimated at 1.2 m^2/d, this shows that the underlying aquifer cannot transmit enough water from one point to another. The specific capacity was calculated after 6 hours and 12 hours of the constant discharge test to evaluate the well performance, the specific capacity was estimated at 0.05 l/s per m and 0.01 l/s per m after 6 and 12 hours, respectively.

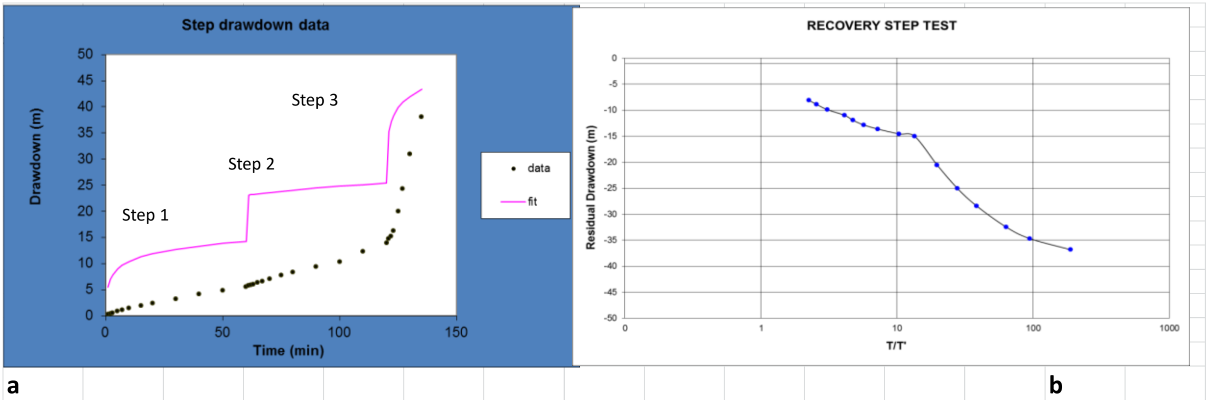


Figure **4.32**: a)Step test for borehole H07-2023; b) Recovery test for Borehole H07-2023.

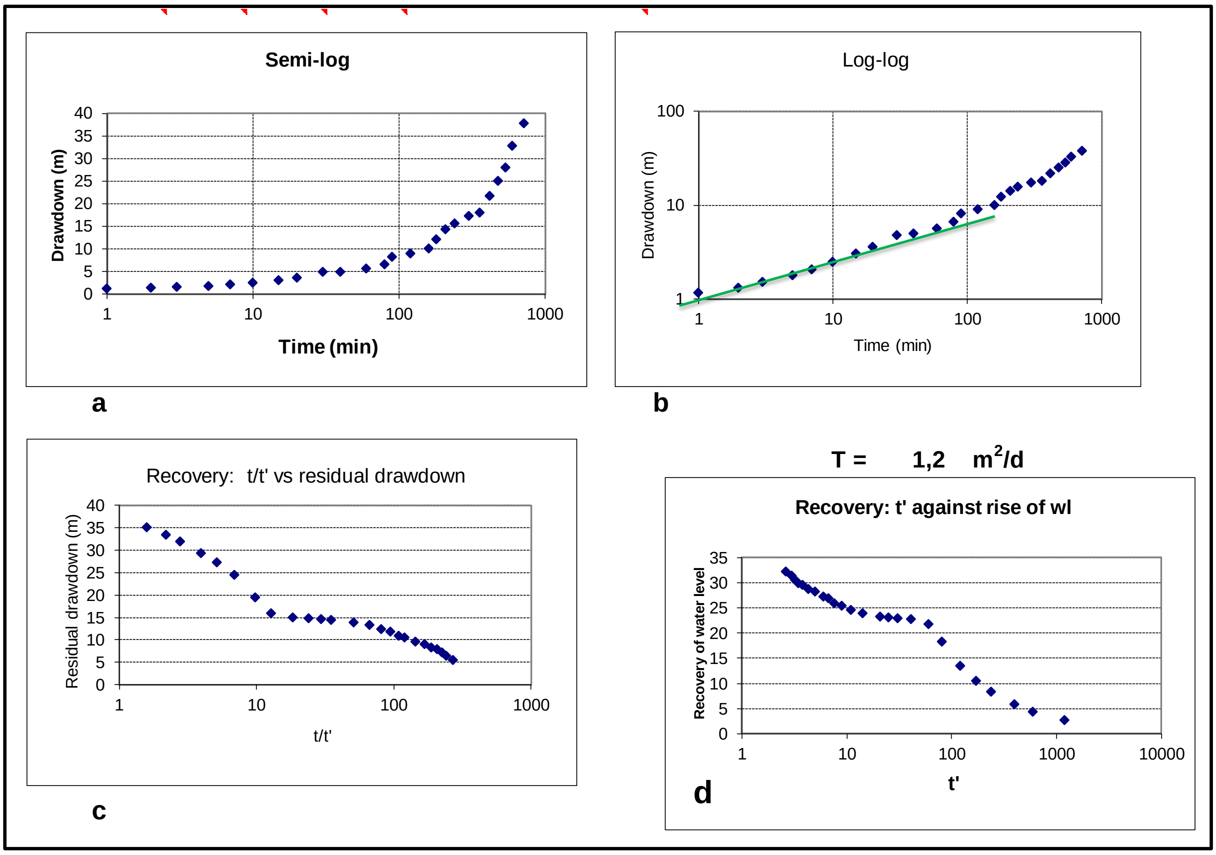


Figure **4.33**: Constant discharge test and recovery for borehole H07-2023.

4.4.4.2 Borehole H07-2022

One-step tests of 1 x 60 minutes were conducted at a discharge rate of 0.31 l/sec and a step of 0.57 l/sec which lasted for only 15 minutes to reach a final drawdown of 47.03 m in 1 hour 15 minutes. The step test drawdown vs time graph (Figure 4.34a) shows that the drawdown increases with the increase in discharge rate. The higher the discharge rate the higher the drawdown. Borehole H07-2022 reached the pump suction after step test two which was conducted for fifteen minutes. This indicates that the borehole had a low yield. After the completion of step tests, the recovery of step tests was measured (Figure 4.34b). The step test recovery was estimated at 73%. The constant discharge test was not conducted because the borehole had a low yield. From the data obtained the transmissivity of borehole H07-2022 was estimated at 1.0 m^2/day, this shows that the underlying aquifer cannot transmit enough water from one point to another.

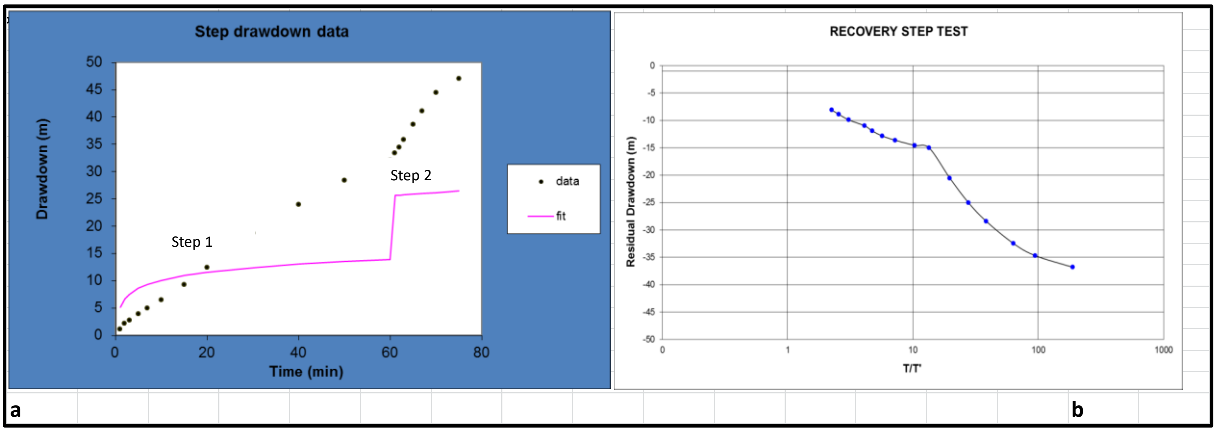


Figure **4.34**: a) Step test for borehole H07-2022; b) Recovery test for Borehole H07-2022.

The summary of aquifer parameters (transmissivity, specific capacity, safe yield, recovery rate) are shown in Table 4.7. Anomohanran, (2014b) established that the higher productive aquifer is associated with high transmissivity and the low productive aquifer is associated with low transmissivity. The transmissivity values in all six tested boreholes ranged from about 1 – 5 m^2/day. The specific capacity which shows the well efficiency ranged from 0.01 l/s per m to 0.15 l/s per m. A high specific capacity indicates a good yielding well whereas a low specific capacity indicates a poor yielding well (Hecox et al, 2002). The constant discharge tests ranged from 0 44 l/s to 1.8 l/s. This is not a maximum recommended abstraction rate at Relela villages. The safe yield was estimated from the constant discharge tests (Table 4.7).

Table **4.7**: Summary of aquifer parameters in Relela villages.

Borehole num	Transmissivity (m2/day)	Specific capacity (l/s per m)	Constant discharge test	Safe yield (CD) l/s	Comments
H07-2014	2.9	0.15 (12 hrs) & 0.03 (24 hrs)	1.82	0.5	moderate productive well
H07-2015	5	0.04 (12 hrs) & 0.02 (24 hrs)	0.80	0.30	moderate productive well
H07-2016	1.1		No CD conducted	0.4	low productive well
H07-1685	1.2		No CD conducted	0.01	low productive well
H07-2022	1.2		No CD conducted	0.01	low productive well
H07-2023	1.0	0.05 (12 hrs) & 0.01 (24 hrs)	0.44	0.01	moderate productive well

The boreholes with no constant discharge (CD) conducted indicated low yielding ranging from 0.01 l/sec to 0.05 l/sec in less or equal to four hours.

4.5 Water quality analysis

Several factors such as mineral content contained in a bedrock, topography, soils type, climate, and anthropogenic activities affect the groundwater quality. Todd (1980); Sarkram *et al.,* (2013); Aghazadeh and Mogaddam, (2010) stated that geochemical reactions such as weathering, dissolution, precipitation, ion exchange, and various biological processes affect the groundwater quality. The collected water samples are chemically analysed for the major cations Na+, K+, Ca^{2+}, $Mg^{2+,}$ Pb, Cd and Ar and major anions (Cl, SO_4^{2-}, NO^{3-} and HCO^{3-}) to understand the geochemical processes in the underlying lithologies (Ghoraba and Khan, 2013).

After the completion of the pumping test program, all boreholes were sampled for chemical analysis. Six water samples were sent to the Capricorn laboratory for chemical analysis. The main aim for chemical analysis was to ensure that the water samples from the Relela community is of good quality and meets the SANS 241: 2011 water quality standards (shown in Appendix A Table A-1). From the laboratory analysis, the water samples from the different boreholes were then classified as poor, marginal, or good water quality for domestic uses purposes. The Durov diagrams were also used to understand the geochemical processes occurring in the study area. Durov Diagram is software developed to analyse chemical constituents where the cations are plotted against the anions of interest (Lloyd and Heathcoat, 1985).

4.5.1 Groundwater quality

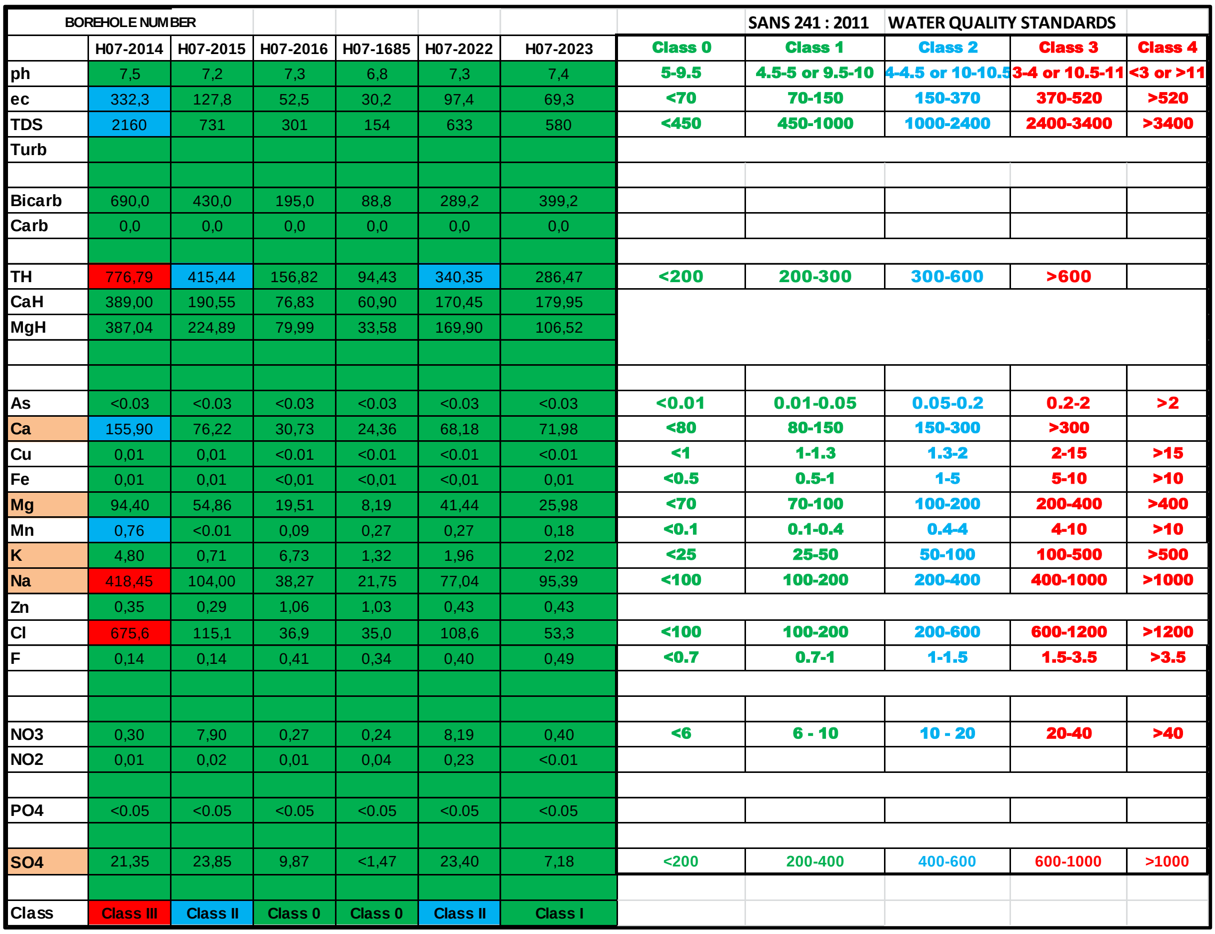
The pH values varied from 6.8 to 7.5 in all six water samples, showing a slightly acidic to alkaline nature which is preferable for domestic uses. The electric conductivity was in a range of 30.2 to 332.3 µS/cm; total dissolved solid was in a range of 154 to 2160 mg/L; total alkalinity 88.8 to 690.4 mg/L and the total hardness was in a range of 94.48 to 776.79 mg/L. Among these physical and aggregate properties of groundwater, the total hardness in borehole H07-2014 exceeded the SANS 2011, water quality standards, and the rest were within the standards limits.

For the metals As, Ca, Mg, Mn, K, Na, and Zn, their concentrations were in a range of 0 mg/l -0.03 mg/l, 24.36 mg/l -155.90 mg/l, 8.19 mg/l – 94.40 mg/l, 0.01 mg/l –

0.76 mg/l, 0.71 mg/l – 4.80 mg/l, 21.75 mg/l – 418.45 mg/l, and 0.29 mg/l – 1.06 mg/l respectively. All these metal constituents were within the standard limits for domestic purposes except borehole H07-2014 which exceeded the standards limits for sodium concentration of 418.45 mg/l, according to SANS 241: 2011 this concentration falls in class 3 (Table 4.8).

For inorganic and non-metallic constituents: Cl, F, NO_3-N, NO_2-N, PO_4-P,and SO_4, their concentrations were in the ranges of 35 mg/l – 675.6 mg/l, 0.14 mg/l – 0.49 mg/l, 0.24 mg/l – 8.19 mg/l, 0.01 mg/l – 0.23 mg/l, 0 mg/l -0.05 mg/l, and 1.47 mg/l – 23.85 mg/l respectively. Borehole H07-2014 exceeded the standards limits for Cl concentration (675.6 mg/l), this concentration falls in class 3 according to SANS 241: 2011 water quality standards (Tables 4.8 and A-1 appendix A).

Table **4.8**: Water chemistry results for borehole H07-2014, H07-2015, H07-2016, H07-1685, H07-2022, and H07-2023



BOREHOLE NUMBER								SANS 241 : 2011	WATER QUALITY STANDARDS		
	H07-2014	H07-2015	H07-2016	H07-1685	H07-2022	H07-2023	Class 0	Class 1	Class 2	Class 3	Class 4
ph	7,5	7,2	7,3	6,8	7,3	7,4	5-9.5	4.5-5 or 9.5-10	4-4.5 or 10-10.5	3-4 or 10.5-11	<3 or >11
ec	332,3	127,8	52,5	30,2	97,4	69,3	<70	70-150	150-370	370-520	>520
TDS	2160	731	301	154	633	580	<450	450-1000	1000-2400	2400-3400	>3400
Turb											
Bicarb	690,0	430,0	195,0	88,8	289,2	399,2					
Carb	0,0	0,0	0,0	0,0	0,0	0,0					
TH	776,79	415,44	156,82	94,43	340,35	286,47	<200	200-300	300-600	>600	
CaH	389,00	190,55	76,83	60,90	170,45	179,95					
MgH	387,04	224,89	79,99	33,58	169,90	106,52					
As	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.01	0.01-0.05	0.05-0.2	0.2-2	>2
Ca	155,90	76,22	30,73	24,36	68,18	71,98	<80	80-150	150-300	>300	
Cu	0,01	0,01	<0.01	<0.01	<0.01	<0.01	<1	1-1.3	1.3-2	2-15	>15
Fe	0,01	0,01	<0,01	<0,01	<0,01	0,01	<0.5	0.5-1	1-5	5-10	>10
Mg	94,40	54,86	19,51	8,19	41,44	25,98	<70	70-100	100-200	200-400	>400
Mn	0,76	<0.01	0,09	0,27	0,27	0,18	<0.1	0.1-0.4	0.4-4	4-10	>10
K	4,80	0,71	6,73	1,32	1,96	2,02	<25	25-50	50-100	100-500	>500
Na	418,45	104,00	38,27	21,75	77,04	95,39	<100	100-200	200-400	400-1000	>1000
Zn	0,35	0,29	1,06	1,03	0,43	0,43					
Cl	675,6	115,1	36,9	35,0	108,6	53,3	<100	100-200	200-600	600-1200	>1200
F	0,14	0,14	0,41	0,34	0,40	0,49	<0.7	0.7-1	1-1.5	1.5-3.5	>3.5
NO3	0,30	7,90	0,27	0,24	8,19	0,40	<6	6 - 10	10 - 20	20-40	>40
NO2	0,01	0,02	0,01	0,04	0,23	<0.01					
PO4	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05					
SO4	21,35	23,85	9,87	<1,47	23,40	7,18	<200	200-400	400-600	600-1000	>1000
Class	Class III	Class II	Class 0	Class 0	Class II	Class I					

🟩 Class 0	Ideal water quality-suitable for lifetime use.
🟩 Class 1	Good water quality-suitable for use, rare instances of negative effects.
🟦 Class 2	Marginal water quality-conditionally acceptable. Negative effects may occur in some sensitive groups.
🟥 Class 3	Poor water quality-unsuitable for use without treatment. Chronic effects may occur.
🟥 Class 4	Dangerous water quality-totally unsuitable for use. Acute effects may occur.

Class 0	Drinking health :	No effects, suitable for many generation
	Drinking Aesthetic :	Water is pleasing
	Food preparation, Bathing, laundry	No effects
Class 1	Drinking health :	Suitable for life time use. Rare instances of sub-clinical effects
	Drinking Aesthetic :	Some awsthetic effects may be apparent
	Food preparation, Bathing, laundry	Suitable for life time use, minor effects on bathing, minor effects on laundry
Class 2	Drinking health :	May be used without health effects by majority by majority of individuals of all ages but may cause effects in some individuals. Some effects possible after lifetime use
	Drinking Aesthetic :	Poor taste and appearance are noticable
	Food preparation, Bathing, laundry	May be used without health effects, slight effects on bathing, slight effects on laundry
Class 3	Drinking health :	Poses a risk of chronic health effects, especially in babies, children and elderly
	Drinking Aesthetic :	Bad taste and appearance may lead to rejection of the water
	Food preparation, Bathing, laundry	Poses a risk of chronic health effects, especially in babies, children and elderly Significant effects on bathing, significant effects on laundry
Class 4	Drinking health :	Severe acute health effects, even with short term use
	Drinking Aesthetic :	Taste and appearance will lead to rejection of the water
	Food preparation, Bathing, laundry	Severe acute health effects, even with short term use, serious effects on bathing serious effects on laundary

The water samples were classified according to SANS 241: 2011 water quality standards into class 0 – class 4 as shown in Table 4.7. Boreholes H07-2016, H07-1685, and H07-2023 have good water quality and this type of water can be used for various domestic purposes such as drinking, cooking, bathing, and washing. Borehole H07-2015 and H07-2022 were found with marginal water quality, this type of water may be used for various domestic purposes with slightly negative effects to some sensitive groups. Borehole H07-2014 was found with poor water quality, severe negative effects may occur if this type of water is used without treatment. If used for human consumption, acute health effects may occur with short-term use.

The comparison of TDS, NO_3, F, and total hardness were analyzed and interpreted to understand the trend of their concentrations in the study area. Total dissolved solids against nitrates have no clear relation between their concentrations, and this means that the presence of high or low TDS concentration does not influence the presence of nitrate concentration. The total hardness against nitrates also seems to have no clear relation to their concentration. There is a slight correlation between TDS and fluoride. As the TDS increases in concentration, the fluoride values also increased in the borehole number (H07-2014, H07-2015, H07-2016, and H07-1685). However, all this concentration ranged within the SANS 241: 2011 water quality standards. The nitrates against fluoride have no clear relation in their concentration, thus simply means that the high or low concentration of nitrates does not influence fluoride concentration.

4.5.2 Hydrogeochemical analysis

To understand the geochemical processes of the study area, the major ions were analysed and they include Na^+, Ca^{2+}, K^+, Mg^{2+}, $SO^{4\ 2-}$, Cl^-, HCO^{3-} and CO_3^{2-}. The geochemical evolution of groundwater can be understood by constructing either Piper (1944) trilinear diagram or Durov (1948) plot. In this study, the Durov plot (1948) was used to understand the hydrochemical processes involved with the underlying aquifers of the study area. The hydrogeochemical analysis was analysed using an excel spreadsheet to plot two tertiary diagrams with the percentages of the cation of interest plotted against that of the anion of interest. The Durov diagram interpretations also assisted in identifying the water quality type of aquifer in terms of; dynamic, static, and stagnant water.

Dynamic water means that the ion exchange is occurring at a shallow depth and the groundwater recharge (short & long term rainfall) plays a significant role in this reaction, static water simply means that there is a simple dissolution or mixing of various cations and anions at an intermediate depth; percolation and leaching play a significant role in this reaction. The stagnant water simply means that there is ion exchange or reverse ion exchange occurring very deep in the underlying aquifers; percolation and leaching play a significant role in this reaction.

Dynamic water type is prevalent in the study area as supported by data plotted on Durov diagrams in Figures 4.35 to 4.40 for boreholes H07-2015, H07-2016, H07-1685, H07-2022, H07-2023 respectively. The data was plotted in field 2 of the Durov plot. Only one out of six samples plotted in field 9 and this was described as stagnant water.

The water type was also described based on Lloyd and Heathcoat, (1985) classifications (Table 4.9). Boreholes H07-2015, H07-2016, H07-1685, H07-2022, H072023 show Mg-HCO3-as dominant cation/anion, and this indicates that the recharge water is associated with dolerite dykes (Table 4.9). Borehole H07-2014 shows Na-K-Cl as a dominant cation/anion, and this is the ion exchange or reverse ion exchange associated with the gneiss chemical weathering process (Table 4.9).

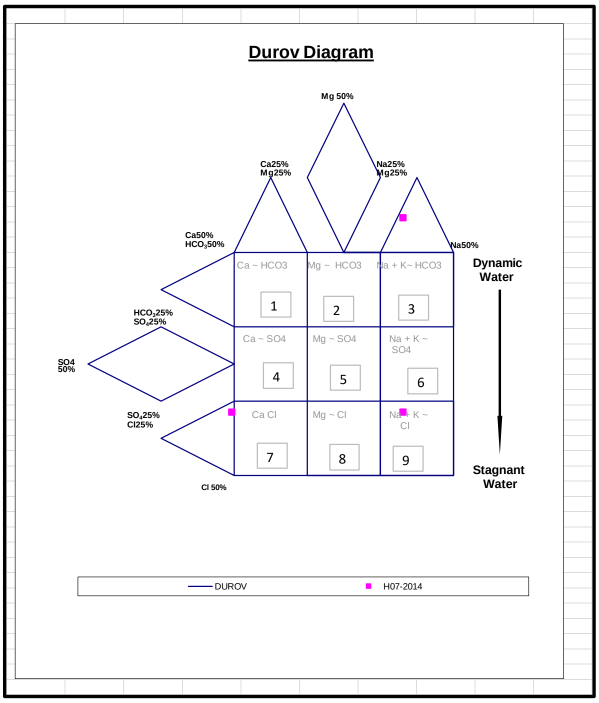


Figure **4.35**: Durov diagram depicting hydrochemical processes in H07-2014

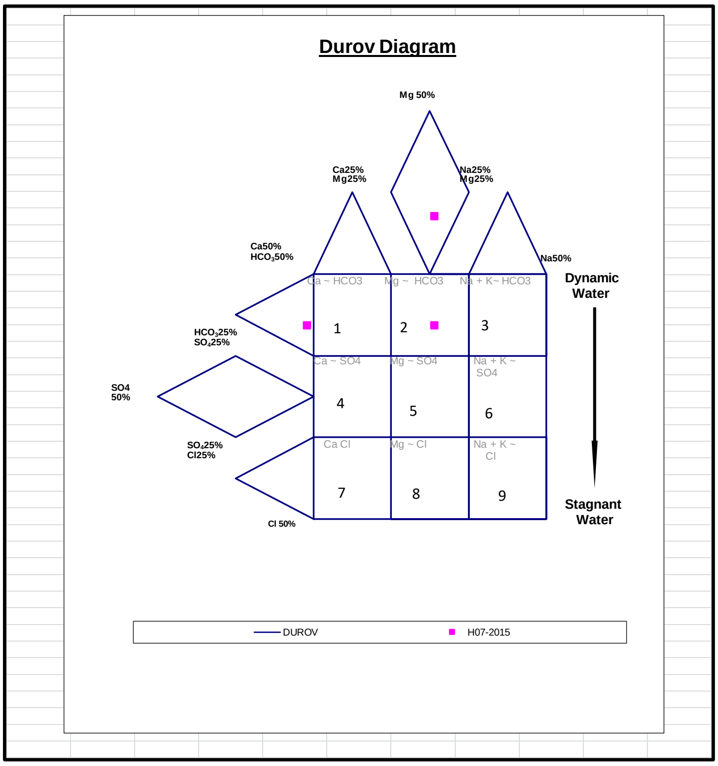


Figure **4.36**: Durov diagram depicting hydrochemical processes in H07-2015

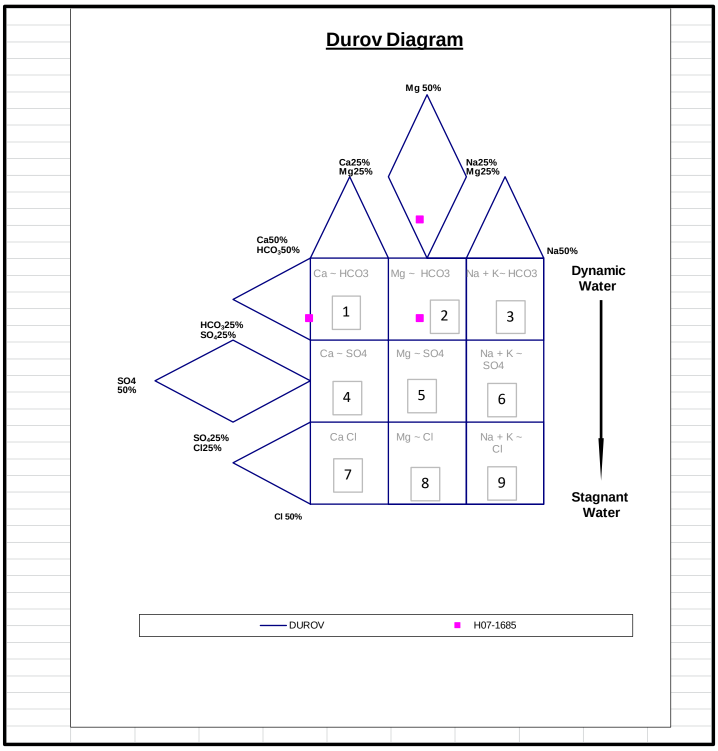


Figure **4.37**: Durov diagram depicting hydrochemical processes in H07-1685

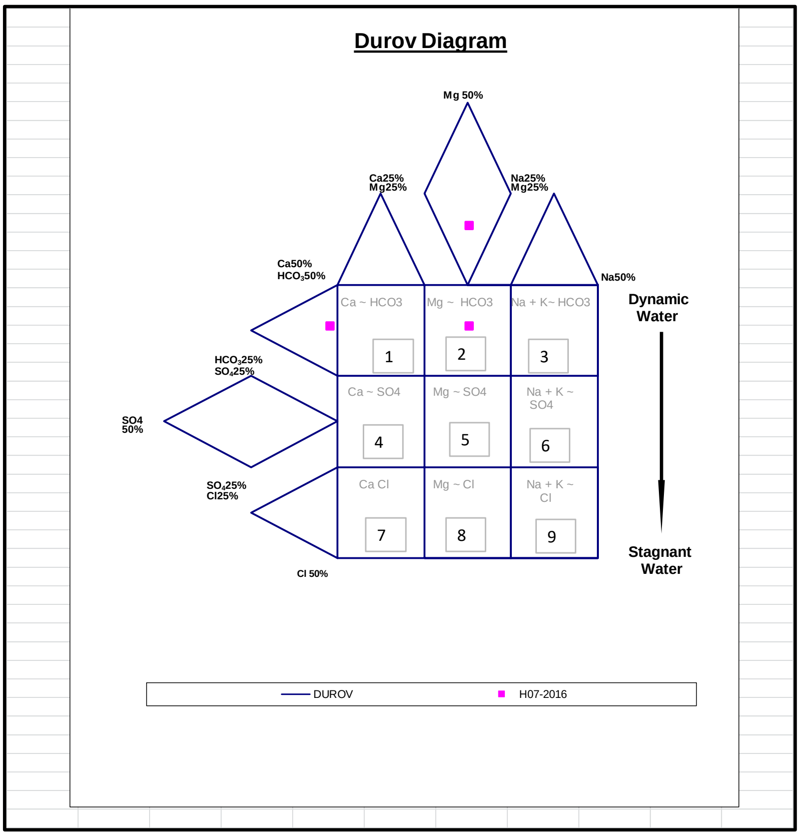


Figure **4.38**: Durov diagram depicting hydrochemical processes in H07-2016

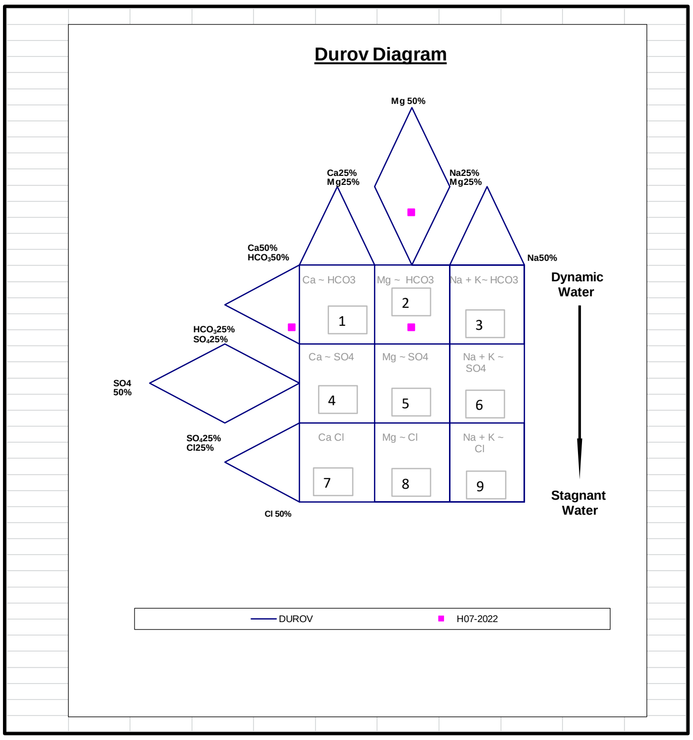


Figure **4.39**: Durov diagram depicting hydrochemical processes in H07-2022

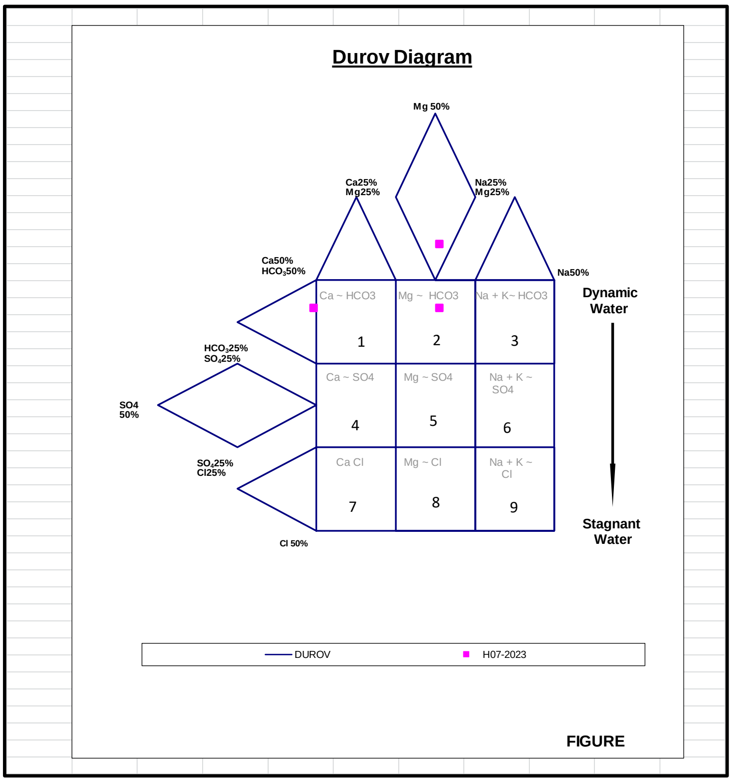


Figure **4.40**: Durov diagram depicting hydrochemical processes in H07-2023

Table **4.9**: Groundwater classification of based on durov diagram (Lloyd and Heathcoat, 1985).

Sl. No	**Water Types**	**No. of samples (GW=19; SW=5)**	**%**
1	HCO_3 and Ca dominant, frequently indicates recharging waters in limestone, sandstone, and many other aquifers	----	---
2	This water type is dominated by Ca and HCO_3 ions. Association with dolomite is presumed if Mg is significant. However, those samples in which Na is significant, an important ion exchange is presumed	----	---
3	HCO_3 and Na are dominant, normally indicates ion exchanged water, although the generation of CO_2 at depth can produce HCO_3 where Na is dominant under certain circumstances	----	---
4	SO_4 dominates, or anion discriminant and Ca dominant, Ca and SO_4 dominant, frequently indicates recharge water in lava and gypsiferous deposits, otherwise mixed water or water exhibiting simple dissolution may be indicated.	01 (1 GW; 0 SW)	4.16
5	No dominant anion or cation, indicates water exhibiting simple dissolution or mixing.	20 (15 GW; 5 SW)	83.34
6	SO_4 dominant or anion discriminate and Na dominant; is a water type that is not frequently encountered and indicates probable mixing or uncommon dissolution influences.	01 (1 GW; 0 SW)	4.16
7	Cl and Na dominant is frequently encountered unless cement pollution is present. Otherwise the water may result from reverse ion exchange of Na-Cl waters.	----	---
8	Cl dominant anion and Na dominant cation, indicate that the ground waters be related to reverse ion exchange of Na-Cl waters.	02 (2 GW; 0 SW)	8.34
9	Cl and Na dominant frequently indicate end-point down gradient waters through dissolution	----	---

CHAPTER 5: DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

This chapter outlines the discussions, conclusions, and recommendations made for future studies and referrals.

5.1 Discussion

Groundwater exploration, groundwater exploitation (drilling), aquifer testing, and groundwater quality analysis were conducted to answer the questions governed by the objectives of this study.

Traverse lines for groundwater exploration were delineated based on the information acquired from desktop studies such as the geology of SA, satellite images, previous studies conducted, and airborne magnetic data. Geophysical techniques were used to identify the potential field targets for drilling. The drilling targets were selected based on the measured magnetic and resistivity data obtained during the field survey. The study area displayed variations in magnetic intensities from low to high magnetic anomalies, resulting from subsurface lithologies and structures. The magnetic anomalies ranged from (- 2080 – 1431 nT). The resistivity anomalies also varied across the study area showing both low to high resistivity values.

The measured magnetic and resistivity anomalies depicted various subsurface structures such as dykes and faults. These structures are known to store groundwater (Crawford and Kath, 2001). From these magnetic and resistivity anomalies, six drilling targets were selected for drilling boreholes. A rotary drilling machine was used to drill the groundwater. Several lithologies were encountered during the drilling and these included: topsoils; weathered/fractured diabase dykes; and weathered/fractured gneiss. These are in agreement with the geology of the study area which comprises a wide spectrum of granitoids gneisses (Brandl, 1986, 1987; Dutoit et al., 1983; Anhaeusser, 1992; Brandl and Kroner, 1993).

The borehole logs showed highly weathered dolerite dykes at a depth of about 9 m – 35 m deep. These weathered and fractured dolerite dykes are the main aquifers of the study area. Five factors contribute to the weathering of basement rocks (Acworth, 1987). a) rock fractures; b) geomorphology of the area; c) groundwater occurrence and temperature; d) base rock's mineral composition, and e) the climate change. Groundwater is mostly found in deeper fractures within the basement rocks. It is assumed that these deep fractured aquifers can yield about 1 - 5 l/s (MacDonald, et al., 2005). The groundwater resources found within deeper fracture zones depend on the thickness of the water-bearing zone and the relative depth of the water table. In this study, the water strikes were found in a range of about 14 m – 80 m below the earth's surface. About 83% of water strikes were found at a shallow depth indicating that the study area is dominated by shallow aquifers. About 17% of the water strikes were from deep aquifers.

The hydraulic parameters such as sustainable yield and transmissivity were estimated using Cooper Jacobs's method. The constant discharge tests indicated borehole yields ranging from 0.4 l/sec – to 1.82 l/sec in less or equal to twenty-four hours. From the results, the recommended safe yield should range between 0.01 l/sec – 0.5 l/sec in less or equal to 24 hours. The available GRIP data also shows very low safe yields for existing boreholes in and around the study area with the recommended values ranging between 0.2 l/sec – 1.4 l/sec in less or equal to twenty-four hours. The total recommended maximum abstraction rate in all six boreholes at the Relala community is 81.10 m^3/day (Table 5.1). The estimated transmissivity using the cooper and Jacob method ranged from 1 m^2/day – to 5 m^2/day. This transmissivity indicates that the underlying aquifers within the study area cannot transmit enough water from one point to another hence the borehole yields are also small. A series of basement aquifers within Limpopo Province were investigated by Holland and Witthuser (2011) and identified transmissivity values in the range of 5 m^2/d to 40 m^2/day.

5.2 Groundwater chemistry evaluation

Six samples from the six boreholes were analysed for chemical properties at Capricorn laboratory, in Polokwane. Water samples were tested for physical and chemical properties. Borehole H07-2014 had elevated chemical constituents of TH of 776.79, Ca of 155.90 mg/l, Mn of 0.76 mg/l, Na of 418.45 mg/l, Cl of 675.6 mg/l, Ec of 332.3 mS/m, and Total hardness of 776.79 mg/l. This borehole had poor water quality (class 3) according to SANS 241: 2011 water quality standards. The cause of elevated constituents might be due to the anthropogenic activities since the borehole is located close to the settlements at Senakwe village and also due to the hydrochemical processes between the water and host rock (aquifer media). Drever (1982) stated that groundwater chemistry is determined by the period the water is in contact with the bedrock.

Borehole H07-2015 and H07-2022 were found to have class 2 types with a total hardness of 415.44 and 340.35 respectively. This is marginal water quality which is conditionally accepted to use for various purposes such as drinking, food preparation, laundry, and bathing.

Borehole H07-2016 and H07-1685 were found to have class 0 type, this is good water quality which is suitable to use without any treatment according to SANS 241: 2011 water quality standards. And lastly, borehole H07-2023 was found to have class 1 type, this is also good water quality which is suitable to use for human consumption and other domestic purposes.

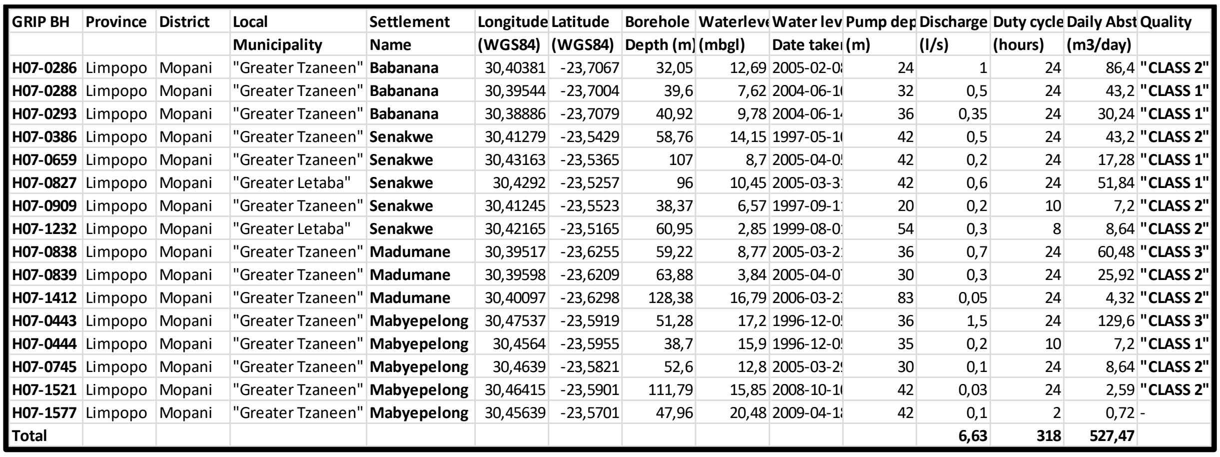
5.3 Water Demand at Relela villages

Based on the study conducted by the Department of Statistics South Africa in 2011, Relela villages had about 6500 people. About 8% of people in Relela villages rely on piped water from the Greater-Tzaneen municipality, while the rest rely on groundwater supply. Those who cannot afford to drill their boreholes in their household end up buying water for survival. To estimate the water demand for the current population at Relela villages, the total recommended abstraction rates from all six boreholes and the total recommended rates from the existing borehole information on GRIP data were used. The total recommended abstraction rate in the six drilled boreholes were estimated at 81.10 m^3/day and the total abstraction rates from GRIP data is 527.47 m^3/day from the existing boreholes (Tables 5.1 and 5.2), the borehole locality maps for GRIP data is also attached in appendix C.

Table **5.1**: Total recommended abstraction rate in all six drilled boreholes

Borehole number	**Discharge rate (l/sec)**	**Recommended abstraction rate in m^3/day**	**Duty cycle in hours/day**
H07-2014	0.5	43.2	24 hours
H07-2015	0.30	25.92	24 hours
H07-2016	0.4	11.52	8 hours
H07-1685	0.01	0.144	4 hours
H07-2022	0.01	0.144	4 hours
H07-2023	0.01	0.144	4 hours
Total	1.23	81.01	68 hours

Table **5.2**: Total recommended abstraction rate from GRIP data in Senakwe, Madumane, Babanana, and Mabyepelong village.



GRIP BH	Province	District	Local Municipality	Settlement Name	Longitude (WGS84)	Latitude (WGS84)	Borehole Depth (m)	Waterleve (mbgl)	Water lev Date take	Pump dep (m)	Discharge (l/s)	Duty cycle (hours)	Daily Abst (m3/day)	Quality
H07-0286	Limpopo	Mopani	"Greater Tzaneen"	**Babanana**	30,40381	-23,7067	32,05	12,69	2005-02-0	24	1	24	86,4	**"CLASS 2"**
H07-0288	Limpopo	Mopani	"Greater Tzaneen"	**Babanana**	30,39544	-23,7004	39,6	7,62	2004-06-1	32	0,5	24	43,2	**"CLASS 1"**
H07-0293	Limpopo	Mopani	"Greater Tzaneen"	**Babanana**	30,38886	-23,7079	40,92	9,78	2004-06-1	36	0,35	24	30,24	**"CLASS 1"**
H07-0386	Limpopo	Mopani	"Greater Tzaneen"	**Senakwe**	30,41279	-23,5429	58,76	14,15	1997-05-1	42	0,5	24	43,2	**"CLASS 2"**
H07-0659	Limpopo	Mopani	"Greater Tzaneen"	**Senakwe**	30,43163	-23,5365	107	8,7	2005-04-0	42	0,2	24	17,28	**"CLASS 1"**
H07-0827	Limpopo	Mopani	"Greater Letaba"	**Senakwe**	30,4292	-23,5257	96	10,45	2005-03-3	42	0,6	24	51,84	**"CLASS 1"**
H07-0909	Limpopo	Mopani	"Greater Tzaneen"	**Senakwe**	30,41245	-23,5523	38,37	6,57	1997-09-1	20	0,2	10	7,2	**"CLASS 2"**
H07-1232	Limpopo	Mopani	"Greater Letaba"	**Senakwe**	30,42165	-23,5165	60,95	2,85	1999-08-0	54	0,3	8	8,64	**"CLASS 2"**
H07-0838	Limpopo	Mopani	"Greater Tzaneen"	**Madumane**	30,39517	-23,6255	59,22	8,77	2005-03-2	36	0,7	24	60,48	**"CLASS 3"**
H07-0839	Limpopo	Mopani	"Greater Tzaneen"	**Madumane**	30,39598	-23,6209	63,88	3,84	2005-04-0	30	0,3	24	25,92	**"CLASS 2"**
H07-1412	Limpopo	Mopani	"Greater Tzaneen"	**Madumane**	30,40097	-23,6298	128,38	16,79	2006-03-2	83	0,05	24	4,32	**"CLASS 2"**
H07-0443	Limpopo	Mopani	"Greater Tzaneen"	**Mabyepelong**	30,47537	-23,5919	51,28	17,2	1996-12-0	36	1,5	24	129,6	**"CLASS 3"**
H07-0444	Limpopo	Mopani	"Greater Tzaneen"	**Mabyepelong**	30,4564	-23,5955	38,7	15,9	1996-12-0	35	0,2	10	7,2	**"CLASS 1"**
H07-0745	Limpopo	Mopani	"Greater Tzaneen"	**Mabyepelong**	30,4639	-23,5821	52,6	12,8	2005-03-2	30	0,1	24	8,64	**"CLASS 2"**
H07-1521	Limpopo	Mopani	"Greater Tzaneen"	**Mabyepelong**	30,46415	-23,5901	111,79	15,85	2008-10-1	42	0,03	24	2,59	**"CLASS 2"**
H07-1577	Limpopo	Mopani	"Greater Tzaneen"	**Mabyepelong**	30,45639	-23,5701	47,96	20,48	2009-04-1	42	0,1	2	0,72	-
Total											**6,63**	**318**	**527,47**	

The combined abstraction rates of newly drilled boreholes and GRIP data abstraction rates at Relela villages is about 608.57 m^3/day (by summing the two rates), this is about 608570 l/day. According to the WHO and UNICEF, (2000), twenty liters per day per person can meet the requirements for domestic uses. SPHERE 1998 project sets out 15 liters of water used per capita per day as being a key indicator in meeting minimum standards for disaster relief. Carter *et al*.,(1997) and Gleick (1996) suggested that the international community adopt a figure of 50 liters per capita per day as a basic water requirement for domestic water supply. It should be noted that the use of water per capita may vary due to the needs of specific individuals. In this study, a figure of 50 liters per capita per day will be used to evaluate water demand in Relela villages (Table 5.3).

Table **5.3**: Water demand calculations for Relela community

Relela community 2011 census population size	**Recommended Abstraction rate per day in l/day**	**(Carter et al., 1997 and Geleick, 1996)minimum water needed per day (50 liters)**
6 500	608 570	6 500 x 50 litres
		= **325 000 liters per day**

Water demand calculations show that the available water from newly developed boreholes and existing boreholes can meet the water demand for the present population in Relela villages. The available recommended abstraction rate is 608 570 l/d and the minimum water usage was estimated to be about 325 000 liters per day. This means that the withdrawal from the boreholes (newly developed and existing boreholes) can satisfy the water need of the current population. In the future as the population growth increases, water demand will also increase. The Department of Statistics South Africa 2011, estimated the population growth of 0.38% per annum in the Relela community. Taking into consideration 10 years projected water demand plan. The population growth can be estimated using the following formula:

$$\mathbf{P_i = P_o\,(1+r)^n}.$$

Where **Pi** is the projection population, **Po** is the present population, **r** is the growth rate, and **n** is the period in years.

$P_i = 6\,500 \times (1+0.0038)^{10} = 6\,751$

The ten years projected demand for water supply for the Relela community will still not exceed the present recommended abstraction rate if the boreholes are used as per the recommendation provided in Tables 5.1 and 5.2.

The average annual rainfall across this semi-arid part of South Africa ranges between 500 – 725 mm/a. This demonstrates that in arid areas, the groundwater recharge is unpredictable. The groundwater recharge and the annual rainfall have no direct relationship, the recharge values of about 10 - 50 mm can occur where the average annual rainfall is less than 500 mm (Edmunds *et al.,* 2002). Climate change alters the rain fall patterns and the groundwater recharge across Africa. Groundwater supply in rural communities does not require higher recharge values, and a simple mass balance indicates that a recharge of 10 mm per annum would support community boreholes (5 m^3/d or 0.17 l/s) with hand pumps at a spacing of 500 m across. With this in mind, the available groundwater at Ralela villages if used as per the recommendations can be sustainably used. If we assume that a borehole is supplying a minimum of 5 m^3/d to be successful and that recharge is not a restraint, then the minimum aquifer properties can be estimated that would give a successful source. MacDonald et al., (2005) stated that the transmissivity >1 m^2/d will give a successful borehole, the computed transmissivity of this study is in this range.

The study area falls under quaternary catchment B81E of about 665 km^2 which has an annual recharge value of 28.4302 mm/a according to GRA II (2003). The total abstraction rate in which newly developed boreholes and existing boreholes can supply is 608.57 m^3/day (608 570 l/day). To supply the total demand of 608.57 m^3/day to Relela villages thus will require a recharge catchment of about 7.81 km^2 (608.57 m^3/day x 365 days/ 0.0284302 m). The recharge for the catchment area of 7.81 km^2 will be evaluated as follows:

Recharge= 781 0000 m^2 x 0.0284302 m/a

= 22 204 m^3/a or 60.83 m^3/day

In drought seasons, the recharge could be reduced and any abstraction would need to draw water from storage (Haupt, 2015). It is there for significant to estimate groundwater storage. It is very much difficult to determine the aquifer storativity. The study area is underlined by the intergranular and fractured aquifer, the storage will be estimated from the GRA II, (2003) as about 0.0019 and the aquifer thickness is estimated to be about 16m. The groundwater storage will be estimated to be :

Area x Thickness x Storativity

= 781 0000 m^2 x 16 m x 0.0019

= 23 742.4 m^3

An abstraction rate of 608,57 m^3/day will need about 39 days (23 742.4 m^3/608.57 m^3/day) of storage during drought seasons. Based on groundwater resource evaluations the recommended borehole abstractions can sustainable if it is used efficiently and strictly as per recommendations.

5.4 Recommendations

Based on the results and discussion, the following recommendations emanate from the present study:

- A groundwater monitoring framework must be established within the study area to ensure that all boreholes are abstracted as per the recommendations provided.
- A continuous water quality monitoring program should be implemented to ensure that water quality does not elevate to class 4.
- All boreholes should be caged to prevent the water pump's vandalisation.
- In terms of electric shortage, diesel engines, windmills, and solar panels can be used to pump and supply water to the community.

REFERENCES

Acworth, R.I. (1987). *The development of crystalline basement aquifers in a tropical environment*. Q. J. Eng. Geol., 20: 265-272.

Alley, W.M. and Leake, S.A. (2004). *The journey from safe yield to sustainability*. Ground Water **42** (1) 12-16.

Appleton, B. (2003). *Climate Changes the Water Rules. Dialogue on Water and Climate.* Printfine Ltd., Liverpool, UK.

Banks, D. and Robbins, N. (2002). *An introduction to Groundwater in Crystalline Bedrock*. Norway.

Brandl, G. (1987). *The geology of the Tzaneen area*: explanation of Sheet 2330 (1:250000), Geological Survey of South Mrica, Pretoria, 55p.

Braune, E and Mutheiwana, S. (2009). *Towards sustainable utilization of basement aquifers in Southern Africa.* Department of Earth Science, University of Western Cape.

Chilton, P.J. and Foster, S.D. (1995). *Hydrogeological characteristics and water-supply potential of basement aquifers in tropical Africa*. Hydrogeology Journal, 3, 1, 36-49.

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

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

Crawford, T.J. and Kath, R.L. (2001). *Ground-water exploration and development in igneous and metamorphic rocks*: Part I — Influencing factors and considerations, in Adams, D.B., Burke, Katrina, Hemingway, Bruce, Keay, Jeff, and Yurewicz, Michael, comps., U.S. Geological Survey Appalachian Region Integrated Science Workshop Proceedings, Gatlinburg, Tennessee, October 22 – 26, 2001: U.S. Geological Survey Open-File Report 01-406, p. 106.

Butterworth, J.A. *et al.* (1999). Hydrological processes and water resources management in a dryland environment III: groundwater recharge and recession in a shallow weathered aquifer. Hydrology and Earth System Sciences, 3, 345-352.

Crawford, T.J. and Kath, R.L. (2003). *Ground-Water exploration and development in igneous and metamorphic rocks in the southern Piedmont/Blue Ridge*, in Williams, L.J., comp., Methods used to assess the occurrence and availability of ground water in fractured-crystalline bedrock: An excursion into areas of Lithonia Gneiss in eastern Metropolitan Atlanta, Georgia: Georgia Geologic Survey Guidebook 23, 58 p.

Crawford, T.J. *et al.* (1999). *Revision of stratigraphic nomenclature in the Atlanta, Athens, and Cartersville 30x60 quadrangles, Georgia*: Georgia Geologic Survey Bulletin 130, 45 p.

Cressler *et al.* (1983). *Ground water in the greater Atlanta region, Georgia*: Georgia Geologic Survey, Information Circular 63, 144 p.

Cressler, C.W., Thurmond, C.J., and Hester, W.G. (1983). *Ground water in the greater Atlanta region, Georgia*: Georgia Geologic Survey, Information Circular 63, 144 p.

CSIR (Council for Scientific and Industrial Research) and CIDB (Construction Industry Development Board). 2010. *Towards a framework for the maintenance of municipal infrastructure*: In support of government growth objectives. A CSIR/CIDB Discussion document.

Danielopol *et al.* (2003). Present state and future prospects for groundwater resource ecosystem. *Environmental conservation*, **30**(2), 104-130.

Devlin, J.F. and Sophocleous, M. (2005). *The persistence of the water budget myth and its relationship to sustainability*. Hydrogeol J., 13: 549-554.

DeWiest, R.J.M. (1965). *Hydrology*. John Willey and sons.

DWAF (DEPARTMENT OF WATER AFFAIRS AND FORESTRY) (2004b) Groundwater Resource Assessment II – Task 1D Groundwater identification. Department of Water Affairs and Forestry, Pretoria.

Edmunds, W. M. & Gaye, C. B. (1994). Estimating the spatial variability of groundwater recharge in the Sahel using chloride. Journal of Hydrology, 156, 47-59.

Edmunds, W. M., Fellman, E. Goni, I. & Prudhomme, C. (2002). Spatial and temporal distribution of groundwater recharge in northern Nigeria. Hydrogeology Journal, 10, 205215.

Escobar, D. (2005). *Estudio magnético terrestre en la zona geotérmica de San Vicente*. LaGeo, S.A. de C.V., internal report.

Ferris *et al*. (1962). *Theory of Aquifer Tests. U.S. Geological Survey*, Water-Supply Paper 1536E.

Fetter, C.W. (1988)*. Applied Hydrogeology*. Merrill Pub. Co., Columbus.

Gleick, P. (1998). How Water is Used, *Population Reports*. Vol. 26, No.1, pp. 53-73.

Grady, M.O. (1997). *Analysis Aquifer Test*. Denver Colarado.

Haupt, C.J. (2015). Report on a hydrogeological evaluation for the Bolobedu solar park, Nganyeni, Greater Letaba Municipality, Limpopo province.

Groundwater Resource Information Project, 2010. South Africa, Limpopo.

Hearst *et al*. (2000). *Well Logging for Physical Properties*. 2nd Edition, John Wiley & Sons, Chicester.

Hecox *et al*. (2002). *Calculation of yield for high plains wells*: Relationship between saturated thickness and well yield: Kansas Geological survey Open-File report 2002-25C.

Herrick, S.M. and LeGrand H.E. (1949). *Geology and ground-water resources of the Atlanta area*: Georgia State Division of Conservation Department of Mines, Mining and Geology, Bulletin Number 55, 124 p.

Holland, M. and Witthüser, K. (2011). Evaluation of geologic and geomorphologic influences on borehole productivity in crystalline bedrock aquifers of Limpopo Province, South Africa. Hydrogeology Journal 19, 1 065-1 083

Huisman, L. and Olsthoorn, T. (1983). *Artificial Groundwater Recharge*. Pitman Publishing Inc., Marshfield, 320 p.

Hulme, M. *et al*. (2001). African climate change: 19002100. Climate Research, 17, 145-168.

IPCC. 1998. *The Regional Impacts of Climate Change*: An Assessment of Vulnerability, London, Cambridge Univ. Press. 122 p.

Jackson P.E, 2000. *Ion Chromatography in Environmental Analysis.* John Wiley & Sons Ltd, Chichester.

Jones, M.J. (1985). T*he weathering zone aquifers of the basement complex areas of Africa*. Quarterly Journal of Engineering Geology, 18: 35-46.

Jorgensen, D.G. and Petricola, M. (1995). *Research Borehole-Geophysical Logging in Determining Geohydrologic Properties*. Ground Water **33**(4): 589 – 596.

Karen, G. (2008). *Groundwater and Climate Change*: Challenges and Possibilities. Geological Survey of Denmark and Greenland. Denmark.

Kath *et al*. (2001). *Ground-water exploration and development in igneous and metamorphic rocks*: Part II — Case histories from the southeastern Piedmont/Blue Ridge Province, in Adams, D.B., Burke, Katrina, Hemingway, Bruce, Keay, Jeff, and Yurewicz, Michael, comps., U.S. Geological Survey Appalachian Region Integrated Science Workshop Proceedings, Gatlinburg, Tennessee, October 22–26, 2001: U.S. Geological Survey Open-File Report 01-406, p. 120.

Kathrin, K. (2011). *The challenges facing sustainable and adaptive groundwater management in South Africa.* Osnabrück, Germany.

Khan, H.A. (1997). *Technology, Energy and Development*: The South Korean Transition, Edward Elgar.

Lee, R.D. (1997). *A handbook of population growth and family economic.* Vol 1B, Amsterdam: North Holland. pp. 1063-115.

Lester *et al*. (2005). *Influence of Geologic Setting on Ground-Water Availability in the Lawrenceville Area*, Gwinnett County, Georgia.

Macdonald *et al*. (1995). *Sustainability of yield from wells and boreholes in crystalline basement aquifers*. British Geological Survey Technical Report WC/95/50. Wallingford, UK: BGS.

MacDonald, A et al. (2005). Developing groundwater: a guide for rural water supply. ITDG Publishing, Rugby, UK, 358 pp.

Macfarlane *et al*. (1992). *Geomorphological controls on borehole yields: a statistical study in an area of basement rocks in central Malawi*. In: Wright, E.P. and Burgess, W.G. (eds.) Hydrogeology of Crystalline Basement Aquifers in Africa. Geological Society Special Publication No 66. Geological Society, London.

Martin, H. (2011). *Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province.* South Africa.

Matshidiso *et al*. (2014). *Water Shortage Management at Letaba Water Catchment Area in Limpopo Province*, of South Africa. University of Limpopo.

Monyatsi *et al*. (2012). *Groundwater quality in South Africa Rural community*: A possible threat to public health. Department of Environment, water and Earth Sciences, Tswane University of Technology, Acardia Campus.

Mukheibir, P. and Sparks, D. (2005). *Climate variability, climate change and water resource strategies for small municipalities*. WRC Report No. K5/1500. Water Research Commission, Pretoria.

Pidwirmy, M. (2006). *The hydrologic cycle*. Fundamental Physical Geography, 2nd edition. Physical geography.net

Rae, S.N. (1988). Water and Soil Resource of the Wairau, Vol 1, *Groundwater Resources*. Marlborough Catchment and Regional Water Board.

Rahman *et al*. (1997). *Domestic water contamination in rapidly growing megacities of Asia*: Case of Karachi, Pakistan. Environ. Monit. Asses. **44** (1-3), 339-360.

Rosen, S. & Vincent, J. R. (1999). *Household Water Resources and Rural Productivity in Sub- Saharan Africa*: A Review of the Evidence. Development Discussion Paper No. 673, Harvard Institute for International Development, Harvard University.

Sarbeswar, H. and Prasenjit, S. (2015). *Identifying the Causes of Water Scarcity in Purulia, West Bengal, India - A Geographical perspective*. Memari College, Burdwan.

Schulze, R.E. (2005). Looking into the future: Why research impacts of possible climate change on hydrological responses in Southern Africa? In: Schulze R.E (ed.) *Climate Change and Water Resources in Southern Africa*: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. WRC Report No. 1430/1/05. Water Research Commission, Pretoria.

Seward *et al.* (2006). Sustainable groundwater use, the capture principle, and adaptive management. *Water SA* **32** (4) 473-282.

Shafic *et al*. (2004). *Groundwater Recharge Assessment of the basement aquifers of central Namaqualand*. Groundwater group, University of Western Cape.

Sophocleous, M. (2009). *Groundwater recharge*. In:Groundwater, Vol. 1, Encyclopedia of Life Support Systems, L. Silveira and E. Usunoff, (Eds.). United Nations Educational, Scientific, and Cultural Organization (UNESCO).

Taylor *et al.* (1990). *Evaluation of Selected Borehole Geophysical Methods for Hazardous Waste Site Investigations and Monitoring*. Final Report, United States Environmental Protection Agency, EPA/600/490/029, Las Vegas, Nevada.

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

Theys, P.P. (1991). *Log Data Acquisition and Quality Control*. – Éditions Technip, Paris.

Thiem, G. (1906). *Hydrologische Methoden*; Gebhardt, Leipzig.

Todd, D.K. (1959). *Groundwater Hydrology*. US Geological survey. Piedmont, California. 200 p.

UNEP/WHO, (1996). *Water Quality Monitoring* - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes. United Nations Environment Programme and the World Health Organization.

UNESCO, (1984). *Ground water in hard rocks*. Project 8.6 of the International Hydrological Programme. UNESCO, Paris.

United State Water Resource Council, (1980). USWC

United State Geological Survey, (1999). USGS

United States Geological Survey, (2013). USGS

UNEP and WRC, (2008). Freshwater under threat: *Vulnerability Assessment of Freshwater Resources to Environmnetal Change*. UNEP-WRC publication. Water Research Commission, South Africa.

Van Tonder *et al*. (2002). *Manual on pumping test analysis in fractured rock aquifers.* Report no. 1116/1/02, Water Research Commission, Pretoria, South Africa.

WHO/UNICEF, (2000). *Global Water Supply and Sanitation Assessment 2000 Report*, New York, Geneva: Joint Monitoring Programme for Water Supply and Sanitation (JMP).

Vakpo, K.E. (2013). *Assessment of the water quality and sustainability of a borehole for a small town water supply scheme in Mim-Kyemfre, in the Kwahu Afram plains north district.* Tarkwa, Ghana.

Vsaleboa consulting, (2010)*. Hydrogeological Assessment and Aquifer Recharge Potential within the Lephalale (Ellisras) Local Municipality Area*. South Africa.

Willard, F.C. (1988). *Applied Hydrogeology*, 3rd ed. Englewood Cliffs, NJ: PrenticeHall.

Williams *et al*. (1999). *Sustainability of Ground-Water Resources*. U.S. Geological Survey Circular 1186. Denver, Colorado.

Williams *et al.* (2004). *Methods and hydrogeologic data from test drilling and geophysical logging surveys in the Lawrenceville, Georgia, area*: U.S. Geological Survey Open-File Report 2004-1366, CD–ROM.

Winter *et al.* (1998). Ground water and surface water— A single resource: U.S. Geological Survey Circular 1139, 79 p.

Wright, E.P. (1992). *The hydrogeology of crystalline basement aquifers in Africa*. Geol. In Wright E.P and Burgess W.G (eds) Geological Society Special Publication, London. 66:1-28.

Xiabin, S. (2014). *Testing and evaluation of artesian aquifers in Table Mountain group aquifers.* Department of Earth Sciences, University of Western Cape, Cape Town, South Africa.

APPENDICES

APPENDIX A

Norms for Drinking Water according to SANS 241:2011 Standard

Determinand	Risk	Unit	Standard Limits[a]

Physical and aesthetic determinands			
Free chlorine	Chronic health	mg/L	≤ 5
Monochloramine	Chronic health	mg/L	≤ 3
Colour	Aesthetic	mg/L Pt-Co	≤ 15
Conductivity at 25 °C	Aesthetic	mS/m	≤ 170
Odour or taste	Aesthetic	—	Inoffensive
Total Dissolved Solids	Aesthetic	mg/L	≤ 1 200
Turbidity [b]	Operational	NTU	≤ 1
	Aesthetic	NTU	≤ 5
pH at 25 C [c]	Operational	pH units	□5 –≤ 9.7
Chemical determinands — macro-determinands			
Nitrate as N [d]	Acute health - 1	mg/L	≤ 11
Nitrite as N [d]	Acute health - 1	mg/L	≤ 0,9
Sulfate as SO_4^{2-}	Acute health - 1	mg/L	≤ 500
	Aesthetic	mg/L	≤ 250
Fluoride as F^-	Chronic health	mg/L	≤ 1,5
Ammonia as N	Aesthetic	mg/L	≤ 1,5
Chloride as Cl^-	Aesthetic	mg/L	≤ 300
Sodium as Na	Aesthetic	mg/L	≤ 200
Magnesium Mg	Aesthetic	mg/L	≤70
Calcium Ca	Aesthetic	mg/L	≤150
Zinc as Zn	Aesthetic	mg/L	≤ 5
Chemical — micro-determinands			
Antimony as Sb	Chronic health	µg/L	≤ 20
Arsenic as As	Chronic health	µg/L	≤ 10

Cadmium as Cd	Chronic health	µg/L	≤ 3
Total Chromium as Cr	Chronic health	µg/L	≤ 50
Cobalt as Co	Chronic health	µg/L	≤ 500
Copper as Cu	Chronic health	µg/L	≤ 2 00
Cyanide (recoverable)	Acute health - 1	µg/L	≤ 70
Iron as Fe	Chronic health	µg/L	≤ 2 00
	Aesthetic	µg/L	≤ 300
Lead as Pb	Chronic health	µg/L	≤ 10
Manganese as Mn	Chronic health	µg/L	≤ 500
	Aesthetic	µg/L	≤ 100
Mercury as Hg	Chronic health	µg/L	≤ 6
Nickel as Ni	Chronic health	µg/L	≤ 70
Selenium as Se	Chronic health	µg/L	≤ 10

(SANS 241: 2011)

APPENDIX B

Pump testing results

PROJECT			Senakwe										
BOREHOLE No			H07-2014		**AVAIL. DRAWDOWN**				55,74		**Coordinates**		
BOREHOLE DEPTH			83 m		**PUMP DEPTH**				77,5 m		**LAT**		S23.52961
STATIC WATER LEVEL			21,76 m		**PUMP TYPE**				WA22-2		**LONG**		E30.42848
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)		**0,80**	**1,77**	**3,36**	**5,80**					**2,90**	**1,82**		**1,82**
TIME(hrs)	**TIME(min)**												
	1,00	-0,14	-2,22	-4,98	-10,99			91,00	1,00	-36,64	-1,23	1201,00	-47,72
	2,00	-0,33	-2,30	-4,96	-19,23			46,00	2,00	-23,86	-1,34	601,00	-41,51
	3,00	-0,41	-2,40	-5,21	-22,38			31,00	3,00	-14,06	-1,42	401,00	-36,75
	5,00	-0,54	-2,58	-6,05	-30,08			19,00	5,00	-9,22	-1,58	241,00	-24,78
	7,00	-0,64	-2,73	-6,60	-37,28			13,86	7,00	-8,36	-1,79	172,43	-17,00
	10,00	-0,78	-2,92	-7,22	-45,98			10,00	10,00	-7,93	-2,11	121,00	-16,09
	15,00	-0,93	-3,18	-8,22	-66,14			7,00	15,00	-7,31	-2,44	81,00	-15,69
	20,00	-1,09	-3,48	-8,97				5,50	20,00	-7,06	-2,74	61,00	-15,43
	30,00	-1,33	-3,85	-10,02				4,00	30,00	-6,56	-3,22	41,00	-14,82
	40,00	-1,66	-4,25	-10,75				3,25	40,00	-6,15	-3,76	31,00	-14,40
	50,00	-1,71	-4,56	-11,45				2,80	50,00	-5,77	-4,04	25,00	-13,98
	60,00	-1,87	-4,80	-12,11				2,50	60,00	-5,56	-4,22	21,00	-13,70
	90,00							2,00	90,00	-5,10	-4,90	14,33	-13,05
	120,00							1,75	120,00	-4,92	-5,66	11,00	-12,33
	150,00							1,60	150,00	-4,64	-6,06	9,00	-11,77
	180,00							1,50	180,00	-4,36	-6,35	7,67	-11,21
	210,00							1,43	210,00	-3,96	-6,66	6,71	-10,94
	240,00							1,38	240,00		-6,96	6,00	-10,51
									300,00		-7,74	5,00	-9,96
									360,00		-8,63	4,33	-9,38
									420,00		-9,92	3,86	-8,85
									480,00		-10,22	3,50	-8,40
									540,00		-10,48	3,22	-8,07
									600,00		-10,8	3,00	-7,77
									720,00		-12,03	2,67	-6,99
									840,00		-14,11	2,43	-6,73
									960,00		-16,82	2,25	-6,54
									1080,00		-17,13	2,11	-6,21
									1200,00		-18,84	2,00	-5,88
									1320,00		-36,73	1,91	-5,33
									1440,00		-54,06	1,83	-4,91

PROJECT			Senakwe										
BOREHOLE No			H07-2015		**AVAIL. DRAWDOWN**				39,3		**Coordinates**		
BOREHOLE DEPTH			66 m		**PUMP DEPTH**				60 m		**LAT**		S23,52407
STATIC WATER LEVEL			20,7 m		**PUMP TYPE**				WA22-2		**LONG**		E30.4302
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)		**0,70**	**1,10**	**2,20**						**0,99**	**0,80**		**0,80**
TIME(hrs)	**TIME(min)**												
	1,00	-0,09	-0,93	-12,11				91,00	1,00	-31,90	-0,55	1201,00	-33,35
	2,00	-0,11	-1,07	-16,96				46,00	2,00	-27,52	-0,59	601,00	-29,86
	3,00	-0,12	-1,19	-20,32				31,00	3,00	-23,08	-0,64	401,00	-26,80
	5,00	-0,23	-1,35	-28,38				19,00	5,00	-15,18	-0,71	241,00	-21,62
	7,00	-0,27	-1,46	-35,39				13,86	7,00	-7,58	-0,76	172,43	-17,35
	10,00	-0,31	-1,59	-37,40				10,00	10,00	-1,56	-0,87	121,00	-11,51
	15,00	-0,36	-1,75					7,00	15,00	-1,17	-1,06	81,00	-2,87
	20,00	-0,40	-1,89					5,50	20,00	-1,03	-1,16	61,00	-1,73
	30,00	-0,45	-2,79					4,00	30,00	-0,95	-1,24	41,00	-1,53
	40,00	-0,51	-4,80					3,25	40,00	-0,84	-1,31	31,00	-1,41
	50,00	-0,54	-6,45					2,80	50,00	-0,77	-1,39	25,00	-1,34
	60,00	-0,57	-7,98					2,50	60,00	-0,71	-1,50	21,00	-1,28
	90,00							2,00	90,00	-0,54	-1,93	14,33	-1,18
	120,00							1,75	120,00	-0,42	-3,60	11,00	-1,10
	150,00							1,60	150,00	-0,33	-4,48	9,00	-1,01
	180,00							1,50	180,00		-5,10	7,67	-0,99
	210,00							1,43	210,00		-5,61	6,71	-0,95
	240,00							1,38	240,00		-6,88	6,00	-0,92
									300,00		-8,59	5,00	-0,86
									360,00		-11,13	4,33	-0,80
									420,00		-13,01	3,86	-0,75
									480,00		-17,98	3,50	-0,70
									540,00		-18,87	3,22	-0,65
									600,00		-19,61	3,00	-0,60
									720,00		-21,98	2,67	-0,54
									840,00		-23,15	2,43	-0,49
									960,00		-30,7	2,25	-0,45
									1080,00		-32,83	2,11	-0,41
									1200,00		-34,09	2,00	-0,36
									1320,00		-34,48	1,91	-0,34
									1440,00		-38,02	1,83	-0,32

PROJECT			Madumane										
BOREHOLE No			H07-1685		**AVAIL. DRAWDOWN**				35,3		**Coordinates**		
BOREHOLE DEPTH			60 m		**PUMP DEPTH**				47,5 m		**LAT**		S23,62932
STATIC WATER LEVEL			12,2 m		**PUMP TYPE**				WA22-2		**LONG**		E30.39976
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)		**0,37**								**0,37**			
TIME(hrs)	**TIME(min)**												
	1,00	-3,91						91,00	1,00	-35,19		1201,00	
	2,00	-5,60						46,00	2,00	-35,07		601,00	
	3,00	-7,37						31,00	3,00	-34,96		401,00	
	5,00	-9,79						19,00	5,00	-34,42		241,00	
	7,00	-12,58						13,86	7,00	-33,81		172,43	
	10,00	-16,94						10,00	10,00	-33,12		121,00	
	15,00	-23,78						7,00	15,00	-32,94		81,00	
	20,00	-31,19						5,50	20,00	-32,23		61,00	
	30,00	-35,24						4,00	30,00	-31,34		41,00	
	40,00							3,25	40,00	-30,40		31,00	
	50,00							2,80	50,00	-29,60		25,00	
	60,00							2,50	60,00	-28,90		21,00	
	90,00							2,00	90,00			14,33	
	120,00							1,75	120,00			11,00	
	150,00							1,60	150,00			9,00	
	180,00							1,50	180,00			7,67	
	210,00							1,43	210,00			6,71	
	240,00							1,38	240,00			6,00	
									300,00			5,00	
									360,00			4,33	
									420,00			3,86	
									480,00			3,50	
									540,00			3,22	
									600,00			3,00	
									720,00			2,67	
									840,00			2,43	
									960,00			2,25	
									1080,00			2,11	
									1200,00			2,00	
									1320,00			1,91	
									1440,00			1,83	

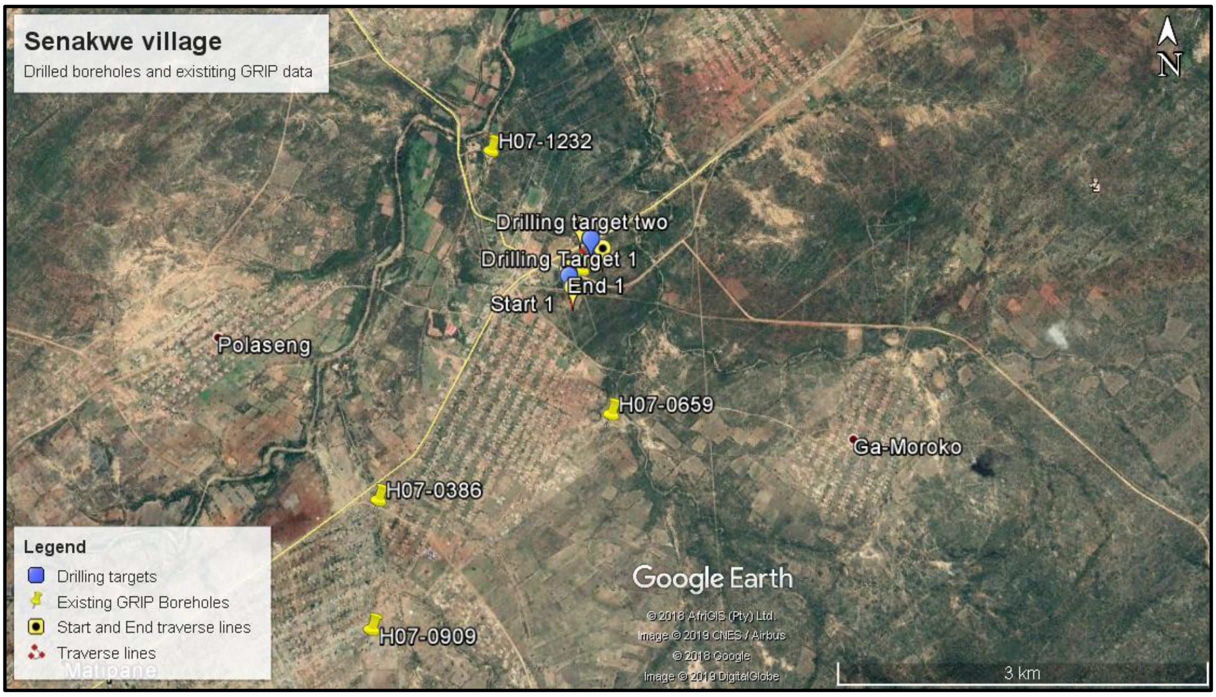
PROJECT			Babanana										
BOREHOLE No			H07-2016		**AVAIL. DRAWDOWN**				28		**Coordinates**		
BOREHOLE DEPTH			60	m	**PUMP DEPTH**				38	m	**LAT**		S23.70029
STATIC WATER LEVEL			10	m	**PUMP TYPE**				WA22-2		**LONG**		E30.39980
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)		**0,38**								**0,09**			
TIME(hrs)	**TIME(min)**												
	1,00	-5,02						91,00	1,00	-35,66		1201,00	
	2,00	-7,55						46,00	2,00	-27,88		601,00	
	3,00	-10,55						31,00	3,00	-25,11		401,00	
	5,00	-15,66						19,00	5,00	-24,55		241,00	
	7,00	-18,99						13,86	7,00	-15,22		172,43	
	10,00	-23,64						10,00	10,00	-14,22		121,00	
	15,00	-29,22						7,00	15,00	-13,25		81,00	
	20,00	-37,99						5,50	20,00	-12,11		61,00	
	30,00							4,00	30,00			41,00	
	40,00							3,25	40,00			31,00	
	50,00							2,80	50,00			25,00	
	60,00							2,50	60,00			21,00	
	90,00							2,00	90,00			14,33	
	120,00							1,75	120,00			11,00	
	150,00							1,60	150,00			9,00	
	180,00							1,50	180,00			7,67	
	210,00							1,43	210,00			6,71	
	240,00							1,38	240,00			6,00	
									300,00			5,00	
									360,00			4,33	
									420,00			3,86	
									480,00			3,50	
									540,00			3,22	
									600,00			3,00	
									720,00			2,67	
									840,00			2,43	
									960,00			2,25	
									1080,00			2,11	
									1200,00			2,00	
									1320,00			1,91	
									1440,00			1,83	

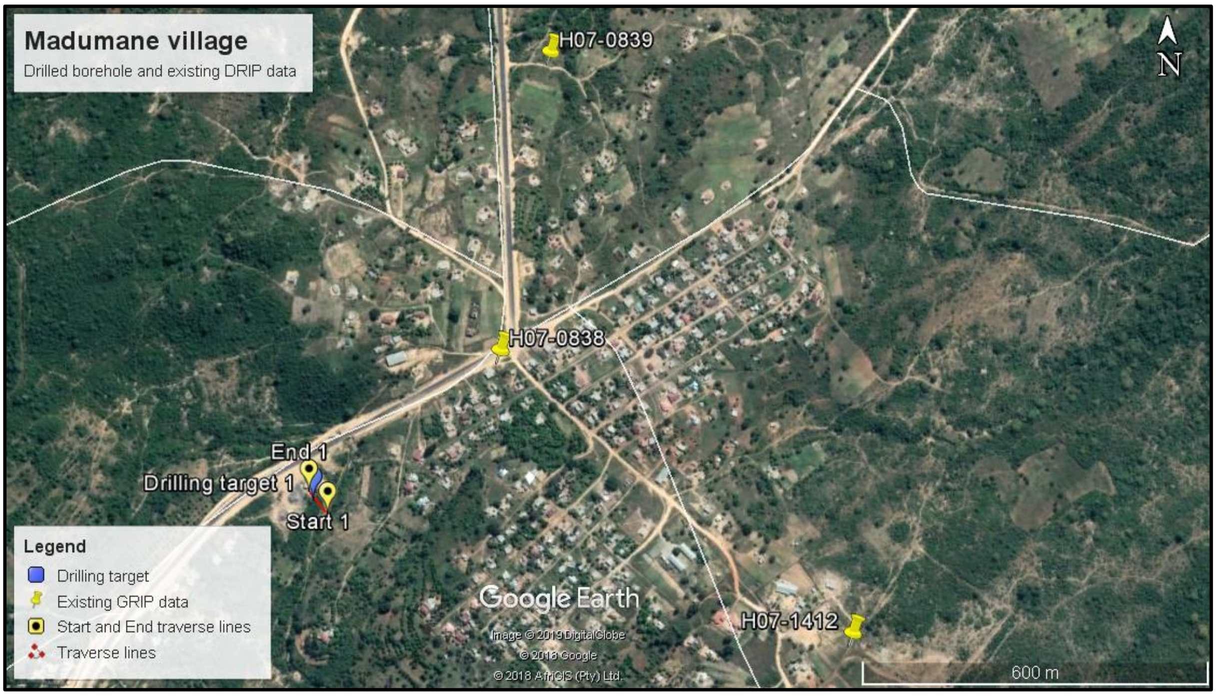
PROJECT	Mabyepelong Village												
BOREHOLE No			H07-2023		**AVAIL. DRAWDOWN**			39,28		m	**Coordinates**		
BOREHOLE DEPTH			58,5	m	**PUMP DEPTH**			53,5		m	**LAT**		-23,56823
STATIC WATER LEVEL			14,22	m	**PUMP TYPE**			BP23M			**LONG**		30,45712
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)		**0,37**	**0,60**	**1,20**						**0,72**	**0,44**		**0,44**
TIME(hrs)	**TIME(min)**												
	1,00	-0,25	-5,74	-14,72				188,00	1,00	-36,80	-1,16	1441,00	-35,06
	2,00	-0,42	-5,87	-15,19				94,50	2,00	-34,67	-1,32	721,00	-33,32
	3,00	-0,58	-5,99	-16,30				63,33	3,00	-32,45	-1,51	481,00	-31,91
	5,00	-0,86	-6,32	-20,00				38,40	5,00	-28,39	-1,76	289,00	-29,33
	7,00	-1,13	-6,62	-24,27				27,71	7,00	-25,00	-2,05	206,71	-27,24
	10,00	-1,47	-7,05	-30,99				19,70	10,00	-20,52	-2,48	145,00	-24,32
	15,00	-1,96	-7,70	-38,12				13,47	15,00	-15,01	-3,04	97,00	-19,40
	20,00	-2,44	-8,30					10,35	20,00	-14,54	-3,60	73,00	-15,89
	30,00	-3,22	-9,38					7,23	30,00	-13,61	-4,77	49,00	-14,98
	40,00	-4,13	-10,31					5,68	40,00	-12,81	-4,91	37,00	-14,72
	50,00	-4,85	-12,31					4,74	50,00	-11,91	-5,64	29,80	-14,57
	60,00	-5,54	-13,96					4,12	60,00	-10,97	-6,56	25,00	-14,41
	90,00							3,08	90,00	-9,89	-8,08	17,00	-13,83
	120,00							2,56	120,00	-8,86	-8,98	13,00	-13,22
	150,00							2,25	150,00	-8,08	-9,95	10,60	-12,26
	180,00							2,04	180,00		-12,05	9,00	-11,78
	210,00							1,89	210,00		-14,17	7,86	-10,82
	240,00							1,78	240,00		-15,61	7,00	-10,52
									300,00		-17,21	5,80	-9,56
									360,00		-18,03	5,00	-8,99
									420,00		-21,63	4,43	-8,23
									480,00		-24,96	4,00	-7,85
									540,00		-27,88	3,67	-7,12
									600,00		-32,73	3,40	-6,40
									720,00		-37,66	3,00	-5,50

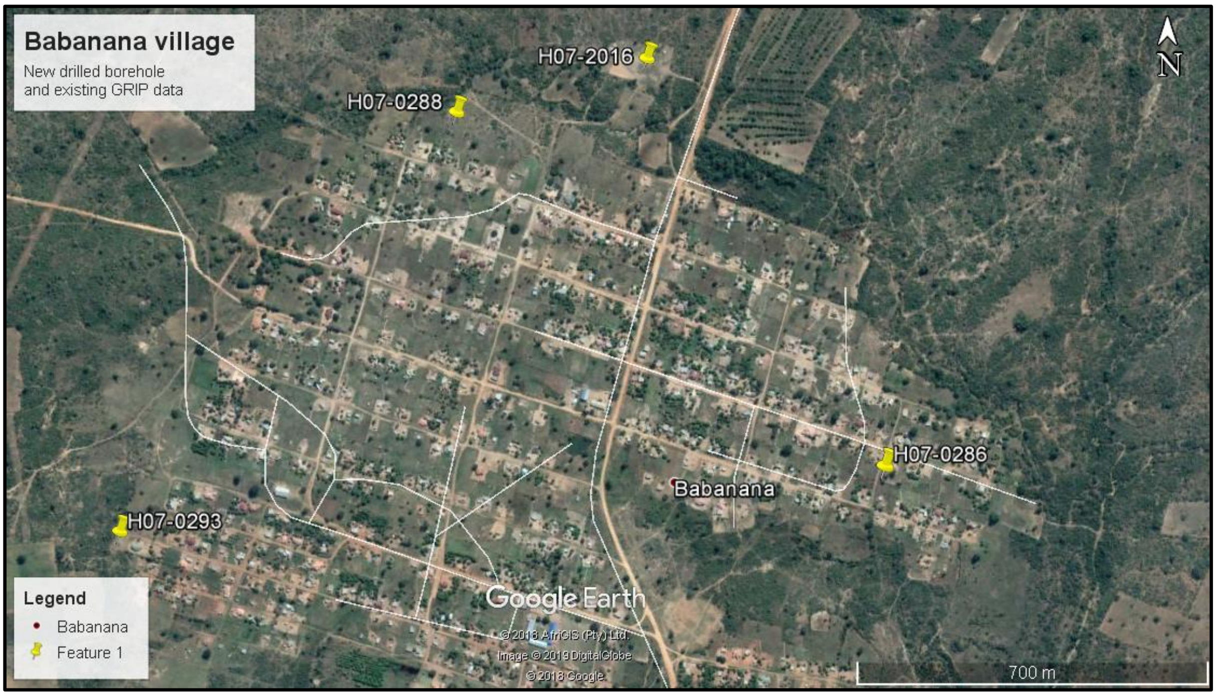
PROJECT	Mabyepelong Village												
BOREHOLE No		H07 - 2022			**AVAIL. DRAWDOWN**				48,6	m	**Coordinates**		
BOREHOLE DEPTH			57,07	m	**PUMP DEPTH**				53,5	m	**LAT**		-23,56502
STATIC WATER LEVEL			4,9	m	**PUMP TYPE**				BP23M		**LONG**		30,44335
		STEP 1	**STEP 2**	**STEP 3**	**STEP 4**	**STEP 5**	**STEP 6**	**T/T'**		**RECOVERY**	**CD**	**T/T'**	**RECOVERY**
AVERAGE YIELD (l/s)			**0,31**	**0,57**						**0,44**	**0,00**		
TIME(hrs)	**TIME(min)**												
	1,00		-1,13	-33,46				281,00	1,00	-46,99		2881,00	
	2,00		-2,13	-34,47				141,00	2,00	-46,10		1441,00	
	3,00		-2,78	-35,90				94,33	3,00	-45,25		961,00	
	5,00		-3,96	-38,65				57,00	5,00	-43,63		577,00	
	7,00		-4,94	-41,14				41,00	7,00	-42,28		412,43	
	10,00		-6,53	-44,53				29,00	10,00	-40,30		289,00	
	15,00		-9,28	-47,03				19,67	15,00	-37,62		193,00	
	20,00		-12,37					15,00	20,00	-35,23		145,00	
	30,00		-18,66					10,33	30,00	-30,87		97,00	
	40,00		-24,01					8,00	40,00	-26,68		73,00	
	50,00		-28,44					6,60	50,00	-22,47		58,60	
	60,00		-32,03					5,67	60,00	-19,04		49,00	
	90,00							4,11	90,00	-8,71		33,00	
	120,00							3,33	120,00			25,00	
	150,00							2,87	150,00			20,20	
	180,00							2,56	180,00			17,00	
	210,00							2,33	210,00			14,71	
	240,00							2,17	240,00			13,00	
	300,00							1,93	300,00			10,60	
									360,00			9,00	
									420,00			7,86	
									480,00			7,00	

APPENDIX C

Borehole locality Maps for GRIP






Babanana village
New drilled borehole and existing GRIP data
H07-2016
H07-0288
N
H07-0286
Babanana
H07-0293
Legend
● Babanana
Feature 1
Google Earth
© 2018 AfriGIS (Pty) Ltd.
Image © 2019 DigitalGlobe
© 2018 Google
700 m

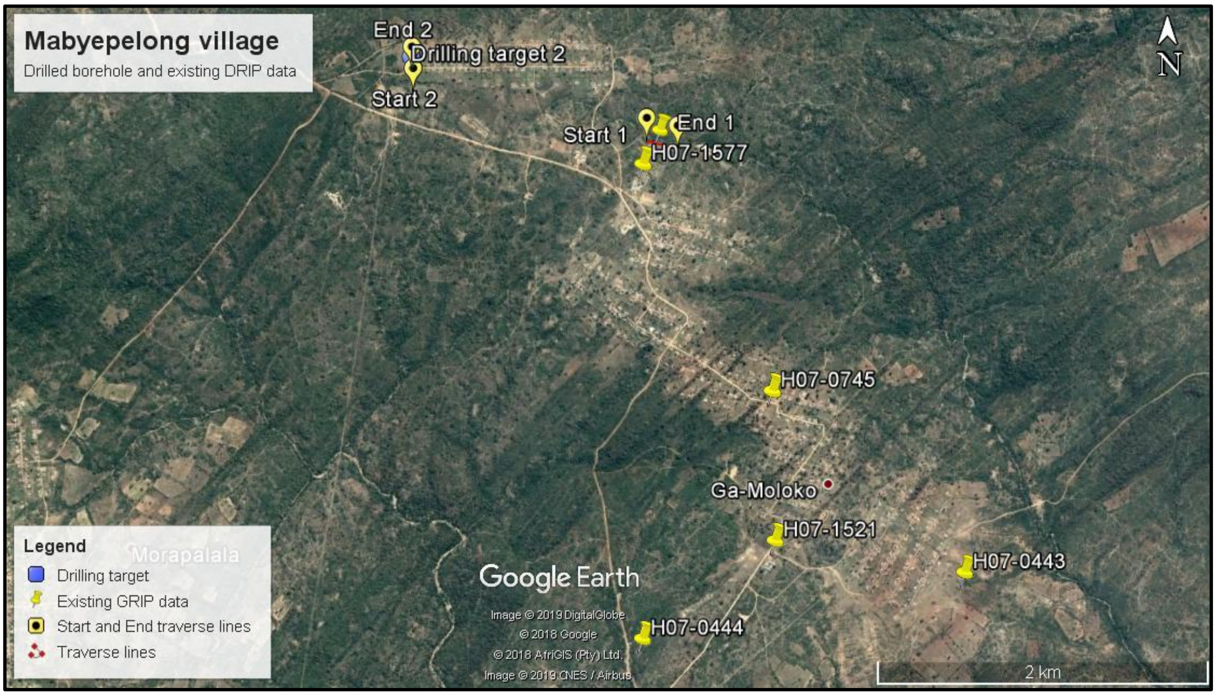

Mabyepelong village
Drilled borehole and existing DRIP data
End 2
Drilling target 2
Start 2
N
Start 1
End 1
H07-1577
H07-0745
Ga-Moloko
H07-1521
H07-0443
H07-0444
Legend
Morapalala
Drilling target
Existing GRIP data
Start and End traverse lines
Traverse lines
Google Earth
Image © 2019 DigitalGlobe
© 2018 Google
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Image © 2019 CNES / Airbus
2 km