

Prefeasibility Study for Managed Aquifer Recharge within
the Greater Kruger National Park, Limpopo Province,
South Africa

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Declaration

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

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



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Summary

The Greater Kruger National Park (GKNP) is located in South Africa, which is a relatively dry country and among the 20 most water-scarce countries in the world. Two study sites for a prefeasibility study are situated along the western borders of the GKNP, located within the private game park boundaries of Olifants West Nature Reserve (Balule) and Timbavati Game Reserve (Motswari), north of Hoedspruit. Warm summer with seasonal rainfall on hot afternoons and winters that are mild and dry with almost no rainfall characterises the climate of the study areas. Except for Water Research Commission (WRC) reports and selected geological reports on regional geology surrounding the study areas, few hydrogeological studies have been conducted in the study areas.

This dissertation investigates the prefeasibility of progressing to a full feasibility study for Managed Aquifer Recharge (MAR) through a combination of literature investigations and diagnosis of multiple field visits to collect hydrogeological information within the study areas. National guidelines on MAR have been consulted throughout the dissertation and study to guide the investigation on the potential for success to feasibility within the study area for MAR. The study involved an in-depth hydrocensus of both study sites to identify all possible boreholes, as well as establish a monitoring network of selected boreholes to monitor the effect of regional groundwater use on the hydrogeological setting. Geochemical analysis was conducted on both groundwater sites and surface water sites to class the water quality against water types and drinking water guidelines for usage within communities and game reserves/lodges. Geophysical surveys and available literature were assessed to characterise the hydrogeological flow regimes within the study areas, to develop a conceptual model for further understanding of the study areas hydrogeology, as well as to complete specific elements of a prefeasibility study check-list.

In accordance with the prefeasibility check-list, many aspects were investigated to determine the success and need for a MAR scheme. Water level monitoring of selected boreholes indicated that over a period of two-and-a-half years, an overall decrease in the water table for boreholes at a higher elevation. This decrease in water level indicated that the aquifer is dewatering as a result of either below average annual rainfall recharge or over-abstraction of groundwater users of the aquifer. Chemistry results of groundwater and surface water sites indicated that the surface water (or source water) is much more desirable than the groundwater, which is typically characterised by elevated electrical conductivity (EC), fluoride (F) and nitrate (NO₃) across both study sites. Surface water was more ideal and only displayed elevated aluminium.

Through geophysical methods and literature studies, potential MAR sites were identified for both study areas, whereby an Aquifer Storage Transfer and Recovery (ASTR) method can be implemented for recharging groundwater into dolerite dykes and mapped lineaments, upgradient of abstraction boreholes to increase water security and improve the natural groundwater quality setting. MAR schemes are initially more expensive to establish than conventional methods such as water treatment facilities, however, the annual operating expenses are much lower and can see a faster return on investment than treatment options. The MAR method proposed is non-invasive and opportunistic for flood water runoff from within drainage channels, whereby potential groundwater zones of MAR correlate to. It is recommended that this dissertation complete the purpose of a prefeasibility study and precedes a feasibility study in the future.

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LIST OF ABBREVIATIONS

ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
CAPEX	Capital Expense
CRD	Cumulative Rainfall Departure
CGS	Council of Geosciences
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical Conductivity (mS/m)
EIA	Environmental Impact Assessment
ELU	Existing Lawful Use
EM	Electromagnetic
EPAR	Enhanced Passive Aquifer Recharge
GKNP	Greater Kruger National Park
GW	Groundwater
HD	Horizontal Dipole
IGS	Institute of Groundwater Studies
MAR	Managed Aquifer Recharge
NGA	National Groundwater Archives
NEMA	National Environmental Management Act
NWA	National Water Act
OPEX	Operational Expense
SADC	Southern African Development Community
SAR	Sodium Adsorption Ratio
SAT	Soil Aquifer Treatment
SAWS	South African Weather Services
SW	Surface Water
T	Transmissivity (m ² /day)
TDS	Total Dissolved Solids (mg/L)
UFS	University of the Free State
VAT	Value Added Tax

VD	Vertical Dipole
WARMS	Water Authorisation and Registration Management System
WL	Water Level (mbgl)
WUL	Water Use License
WULA	Water Use License Application

LIST OF MEASUREMENT UNITS

Km	Kilometre
L/s	Litres per second
m	Metre
m ² /day	Cubic meters per day
mamsl	Metres above mean sea level
Mm ³	Mega cubics
mm/a	Millimetres per annum
mbgl	Metres below ground level
meq/L	Milliequivalents per litre
mg/L	Milligrams per Litre
mS/m	Millisiemens per meter
Ma	Million years
nT	Nanotesla
R/kL	Rands per kilolitre

CHAPTER 1: INTRODUCTION

1.1 Background

The Greater Kruger National Park (GKNP) is located in South Africa, which is a relatively dry country. It is amongst the 20 most water-scarce countries in the world (Woodford and Rosewarne, 2005). In general, the GKNP experiences higher rainfall in the summer months on hot afternoons and mild dry winters, which are almost void of any rainfall. The area is classified as having a tropical to subtropical climate (Petersen, 2012). Climatic trends during the period of 2015 – 2019 indicated that the rainfall in the region was below the long-term average and the region had experienced drought-like conditions. This drought period led to increased demand on groundwater supply, as shrinking surface water supply had tipped the conjunctive use scales of water distribution towards a more groundwater-dependent management system. Through this period, the travel and tourism industry continued to grow and accommodation at game lodges, private estates and town populations increased with it, leading to greater demand placed on water supply. The increased demand had a direct impact on the groundwater resource. Due to poor management and lack of groundwater knowledge in the area, lodges resorted to drilling new boreholes as existing boreholes either dried up or collapsed, these are all examples that no sustainable groundwater management practices are in place. Figure 1 is a good example of poor groundwater management, indicating three subsequent boreholes that had been drilled as a result of the previous borehole either drying up or collapsing.



Figure 1 – Typical example of poor groundwater management. Three boreholes were drilled adjacent to one another over approximately 15 years.

Groundwater has become the primary source of water in this region (Figure 2) as building dams are too expensive and the terrain does not support the construction or development of sufficient water storage. Drilling for groundwater is a common practice in the region as groundwater is readily

available, spatially convenient and can be treated to acceptable drinking standards. Additionally, boreholes are used to provide water supply to shallow surface dams for wildlife and animal viewing in remote areas, particularly during dry periods, such as winter.

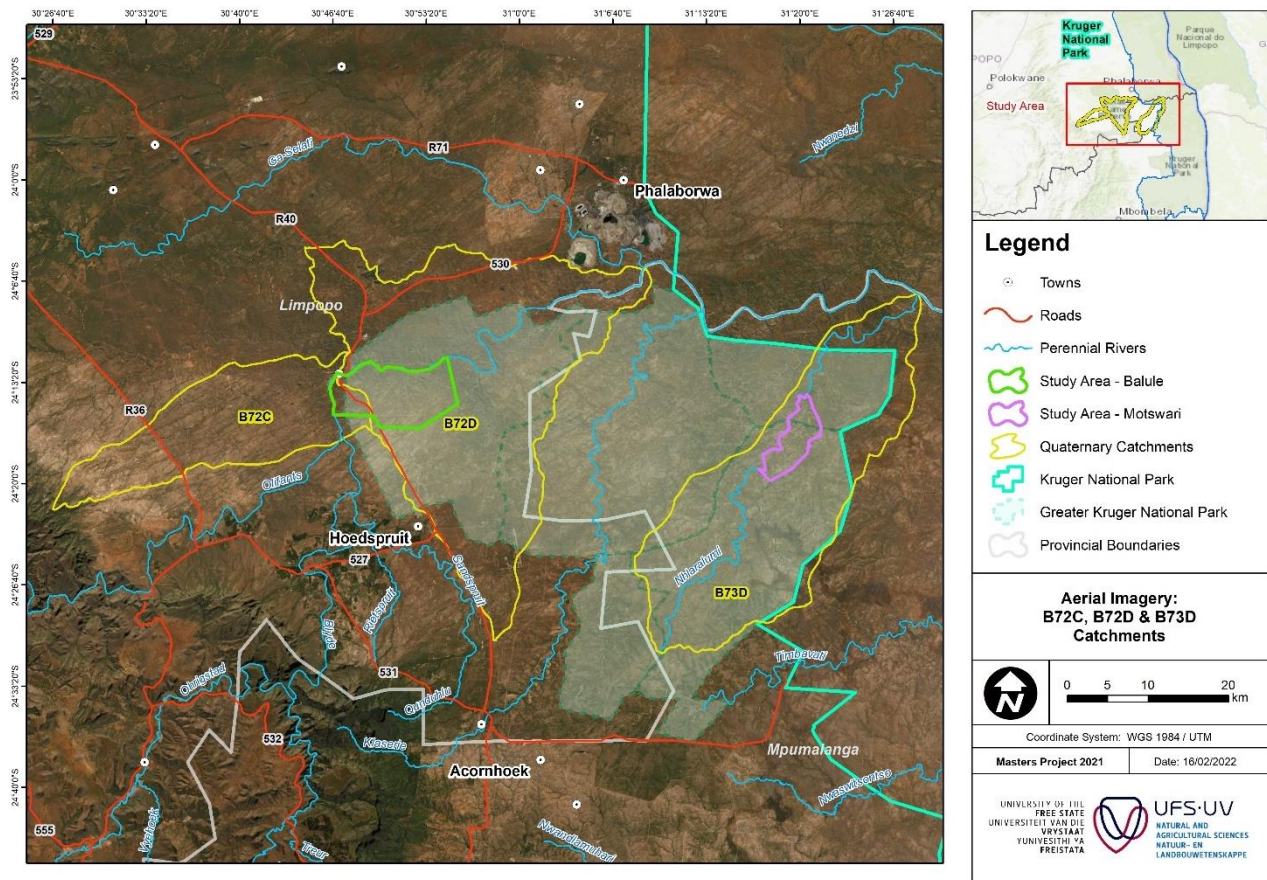


Figure 2 – Catchment Boundaries in Study Area.

Due to the increased demand on groundwater and reduced seasonal peak rainfall events during summer, a prefeasibility study for artificial recharge has been conducted to address these concerns. The purpose of this dissertation is two-fold. Firstly, to determine the prefeasibility of progressing to a full feasibility study in the study area for Managed Aquifer Recharge (MAR). Furthermore, to provide a means of characterising the hydrogeological setting of the GKNP and ensuring the longevity of the groundwater supply, followed by recommendations to ensure the correct training and groundwater management strategy is implemented to safeguard the water supply. There is a large lack of groundwater knowledge within the general population of the area and upskilling will be a key part of a MAR scheme.

Groundwater in South Africa as a whole is misunderstood by those outside of the profession. It is underutilised and yet in some cases, it is also over exploited. In most sub-Saharan African countries, groundwater use remains below 5% of the national groundwater supply, however, in South Africa, 65.4% of renewable groundwater is used (Cobbing and Hiller, 2019). Groundwater schemes are quick and affordable to implement. They are particularly effective when implemented in a combination with other moving parts of a project cycle or a dispersed scenario (du Toit and Verster, 2017). This was a summary of observation on the state of groundwater affairs in South Africa by Eberhard Braune, the director of Hydrogeology in 2000 at the Department of Water Affairs and Forestry. It is

hoped that this dissertation lends itself to increasing groundwater education and allowing others to increase their access to groundwater in a safe and sustainable manner.

1.2 Aims and Objectives

This research dissertation aims to characterise the hydrogeological conditions as part of a prefeasibility study to initiate Managed Aquifer Recharge (MAR) within the GKNP area. Each specific objective of the research study is listed below:

- To delineate and gain an understanding of the study areas based on a detailed desktop study and review of existing literature and case studies.
- Identify and delineate the geological as well as hydrogeological characteristics that control the occurrence and distribution of groundwater.
- To determine the extent to which Managed Aquifer Recharge is feasible.
- To describe the hydrogeological processes within the GKNP.
- Develop a simplified conceptual hydrogeological model of the study areas.
- Develop a basic understanding of the geochemistry within the study area and briefly discuss potential concerns, should there be any.
- Assessment and completion of a prefeasibility study as per the National Guidelines (DWA, 2009) to recommend a way forward to a feasibility study.

1.3 Managed Aquifer Recharge Prefeasibility

MAR is the process of artificially recharging the subsurface environment (Ebrahim et al., 2020) with an alternative water source. It is important to note that each artificial recharge project is site-specific and will come with its own set of individual challenges and objectives (DWA, 2009). MAR projects are separated into four (4) separate stages as outlined below:

- The **prefeasibility stage** will be for identifying the initial indication of the viability of the project and should also present a project plan and budget for a feasibility study.
- **Feasibility studies** are to determine whether the project will be a success by looking at certain controlling factors such as costs, budget and optimisation of the scheme.
- The **implementation stage** will be the construction of infrastructure, obtaining relevant legal applications for the start of such a MAR project.
- The **operation and maintenance stage** is for the constant monitoring and performance adjustments during the operation of the MAR scheme.

The details of this dissertation will focus on the prefeasibility stage of a MAR project as outlined in Table 1 (DWA, 2009). MAR can also be implemented as a passive method, whereby there is an initial artificial scheme design (drilling of boreholes, borehole construction and infrastructure, etc.), followed by passive methods of increasing the groundwater recharge and monitoring the groundwater system and its response to the changes made, through non-invasive methods. This can be seen as Enhanced Passive Aquifer Recharge (EPAR) or opportunistic aquifer recharge, whereby it takes place as the occasion sees fit. These will be discussed further in the dissertation.

Table 1 – Prefeasibility study check-list (DWA, 2009).

Success Criteria	Check-list
1. The need for an artificial recharge scheme.	<ol style="list-style-type: none"> 1. What are the primary and secondary objectives? (E.g., Primary, increase security of water supply by ensuring the aquifers are full prior to the onset of the dry season; secondary, water treatment). 2. Is artificial recharge the best option to meet the primary objective? (Better options may be, for example, to expand the existing wellfield, develop a new aquifer or introduce better water conservation measures). 3. Will artificial recharge meet the primary objective? (E.g., if the aquifer is full prior to the onset of the dry season, will it provide the envisaged security?)
2. The source water	<ol style="list-style-type: none"> 1. Roughly what volume of water is available for recharge? 2. When is it available?
3. Aquifer Hydraulics	<ol style="list-style-type: none"> 1. Will the aquifer receive the water? 2. Is there sufficient space in the aquifer to receive the water? (E.g., if you need to store 1Mm³ before the onset of the dry season, will the aquifer be able to receive that volume? 3. Is the aquifer permeable enough to receive it at the planned supply rate? (E.g., if you need 10 x 10 L/s injection boreholes, are there enough drilling targets or existing boreholes that will allow for these rates?) 4. Will the water be retrievable when you want it? Or will it flow downgradient and away from the planned abstraction area?
4. Water Quality	<ol style="list-style-type: none"> 1. Is the source water quality suitable for recharge? E.g., Is the water not too turbid, saline or rich in organic material? Are there any particular worrying determinants, like heavy metals, disinfection by-products etc. that could affect the final water quality? 2. Describe the natural groundwater quality. 3. Will <i>in situ</i> blending likely improve the natural groundwater quality or make it worse? Estimate the concentrations of key determinants in the final water quality. 4. Comment on clogging concerns.
5. The artificial recharge method and engineering issues	<ol style="list-style-type: none"> 1. How will the water be transferred into the aquifer? 2. What infrastructure will be needed to treat, recharge and extract the water? 3. What are the engineering issues and how significant are they?
6. Environmental Issues	<ol style="list-style-type: none"> 1. What are the potential environmental benefits, risks and constraints?
7. Legal and regulatory issues	<ol style="list-style-type: none"> 1. Are there legal constraints? E.g., Securing source water rights etc. 2. Is there an existing groundwater license and what are the conditions regarding use? 3. What type of authorisation is required from DWA to do the feasibility tests?
8. Economics	<ol style="list-style-type: none"> 1. How much will the feasibility study cost? 2. Roughly how much will the scheme cost? 3. Roughly how much will 1 m³ of supplied water cost and how does this compare to other options of water supply?
9. Management and technical capacity	<ol style="list-style-type: none"> 1. What skills will be necessary to manage, operate and maintain the scheme and are they available or obtainable?

Success Criteria	Check-list
10. Institutional arrangements	<ol style="list-style-type: none"> 1. Who will be responsible for supplying the source water? 2. Who will pay for the source water? 3. Who will ensure that its quality is suitable for recharge? 4. Who will regulate the scheme?

The check-list in Table 1 will be further discussed later in this dissertation as it is completed and the study areas will be assessed against each success criteria.

1.4 Research Methodology

To address the above-mentioned aims and objectives of the study, the following steps were taken:

- All available geological and hydrogeological reports were gathered on the study area and data were combined and further studied for a better understanding and knowledge of the groundwater system.
- A desktop study was then completed on the area to delineate the potential water-bearing structures and formations with known borehole locations.
- Field work was conducted in June 2019, March and October 2020 and April 2021 to gain sufficient knowledge of the study area and collect the following information:
 - Detailed hydrocensus to identify and map all known boreholes (production, historical and monitoring).
 - Collection and interpretation of water level and geochemical information.
 - Basic field mapping to delineate geological structures.
- Groundwater and surface water samples were collected from hydrocensus boreholes to analyse for major ion species, minor trace elements and metals. This was done for the following reasons:
 - 1. Determine if groundwater quality was suitable for the water supply.
 - 2. Understand the basic surface water / groundwater interaction in the region.
 - 3. Identify if source water for MAR will have the potential for borehole clogging in future MAR studies.
- Surface geological and geophysical (Electromagnetic and Magnetic) mapping was conducted in areas of interest for geological structures/formations that may be groundwater bearing and potential future recharge sites for MAR.
- All the collected data were analysed to develop a conceptual hydrogeological model of the GKNP and the completion of a prefeasibility MAR study.

1.5 Dissertation Structure

This masters dissertation will be structured as follows:

- **Chapter 1** gives an introduction to the research, outlines the aims and objectives, provides the background to a MAR prefeasibility study, describes the methodology outlined to address the aims and objectives of the study, then completes with a structure of the dissertation.
- **Chapter 2** is a review of the available literature that is appropriate to the dissertation as well as provides relevant case studies that apply to the dissertation. The literature review will cover the study area in a geological as well as hydrogeological sense and case studies that focused on the region and that are project-specific.

- **Chapter 3** will provide a description and details on the site study area in terms of regional setting, climate, relief and surface drainage, geology and recharge within the GKNP. These are important items for the reader to understand the purpose of this dissertation.
- **Chapter 4** covers the materials and methods chosen in this study. It explains methods used to further understand the feasibility of a MAR study and to understand the hydrogeological characteristics of the study area. Chapter 4 also includes a brief outline of equipment and techniques used to collect information that is pertinent to the prefeasibility study questions.
- **Chapter 5** describes the results obtained from the periods spent in the field, exploration studies conducted, hydrogeological mapping, interpretation of geochemical results and geochemical analysis based on water samples taken in the study area. Chapter 5 goes further to a discussion of the results, which is important to determine the prefeasibility of future MAR studies done in the study area and to understand the subsurface hydrogeological conditions in the GKNP.
- **Chapter 6** focuses specifically on the prefeasibility study check-list and method of introducing source water to the MAR scheme. The chapter provides feedback per success criteria (Table 1) as required by the check-list to implement a successful artificial recharge scheme and can be used to assist in a future feasibility study.
- **Chapter 7** will cover a summary of the dissertation, focusing on the potentials for concern as well as support to continue with MAR feasibility studies. Recommendations on sustainable management practices and opportunities for future work and investigation will also be included in this chapter. The dissertation will be closed with references, a summary and appendices.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

South Africa is a water-scarce country with limited and strategic groundwater resources in the country (Murray et al., 2007). The distribution of reliable groundwater is varied and dependant on geology, location, topography and available budget to access the groundwater. South Africa is composed of three different aquifers; approximately 10% of South African aquifers are porous (Primary) aquifers, while the remaining 90% of South African aquifers are fractured rock (secondary) aquifers (DWA, 1998). A small portion of South African aquifers are dolomitic and are typically characterised by karst topography.

Primary aquifers are susceptible to drought conditions, as they are generally found in shallow systems, along the edges of river courses (e.g., Crocodile River) or coastal sands such as Lamberts Bay, Atlantis and Langebaan. Primary aquifers are typically characterised by unconsolidated material of no more than 30 meters thick, such as grains of sand and clay. According to the Department of Water Affairs Groundwater dictionary (DWA, 2011), primary aquifers can yield appreciable volumes of groundwater, yet require crucial management as they are highly vulnerable. Fractured rock aquifers (secondary aquifers) are more commonly occurring in South Africa (approximately 90%), they stretch across large distances and are capable of holding larger volumes of water. The fractured rock aquifers are the aquifer type that is most commonly targeted for groundwater supply in South Africa. Groundwater flow is predominantly through open fault structures, weathered zones (high permeability horizons), fractures/fissures and joints. The interstices between which groundwater flows were formed after the rock was formed (DWA, 2011) and therefore referred to as secondary fracturing.

The main focus of this literature review was on the overarching aspects of the dissertation, characterising the hydrogeological setting of the GKNP and identifying the area as a possible site for future feasibility studies to MAR. Characterising the hydrogeological setting is done through available literature written on the study area and MAR literature that is focused on the process of completing a prefeasibility study and the steps taken in similar settings. Field data and site visits were additionally used to assist in characterising the hydrogeological setting and assessment of a prefeasibility study.

2.2 The Hydrological Cycle

Groundwater is water within the saturated zone and forms part of the hydrological cycle. The hydrological cycle is the continual process of water circulating between land, ocean and atmosphere. The generalisation of the hydrological cycle is that water will be moved and distributed by all possible water paths within the atmosphere, biosphere, lithosphere and hydrosphere (Salas et al., 2014).

All water contained within the earth will move through different stages of the hydrosphere at varying rates depending on which stage of the cycle it is at. Water will move from the hydrosphere (ocean/seas) into the atmosphere. This process is powered through the sun's solar energy and interpreted as evaporation and transpiration. From the atmosphere, water is transferred to the lithosphere by precipitation (rainfall) and then followed into groundwater recharge through the process of infiltration along a hydraulic gradient to discharge areas. It must be highlighted that the hydrological cycle is not a beginning or end and is in continual motion with varying rates of

circulation depending on which stage of the hydrological cycle (Salas et al., 2014) as well as based on the setting of each stage in its position on the planet.

Groundwater recharge and the length of the hydrological cycle are dependent to a great degree on the geology and subsurface characterisation. Figure 3 indicates how recharge and groundwater flow pathways can vary in length, distribution, time and depth. Groundwater flow through confining beds such as clay or competent rock will be slow and is shown as vertical flow paths.

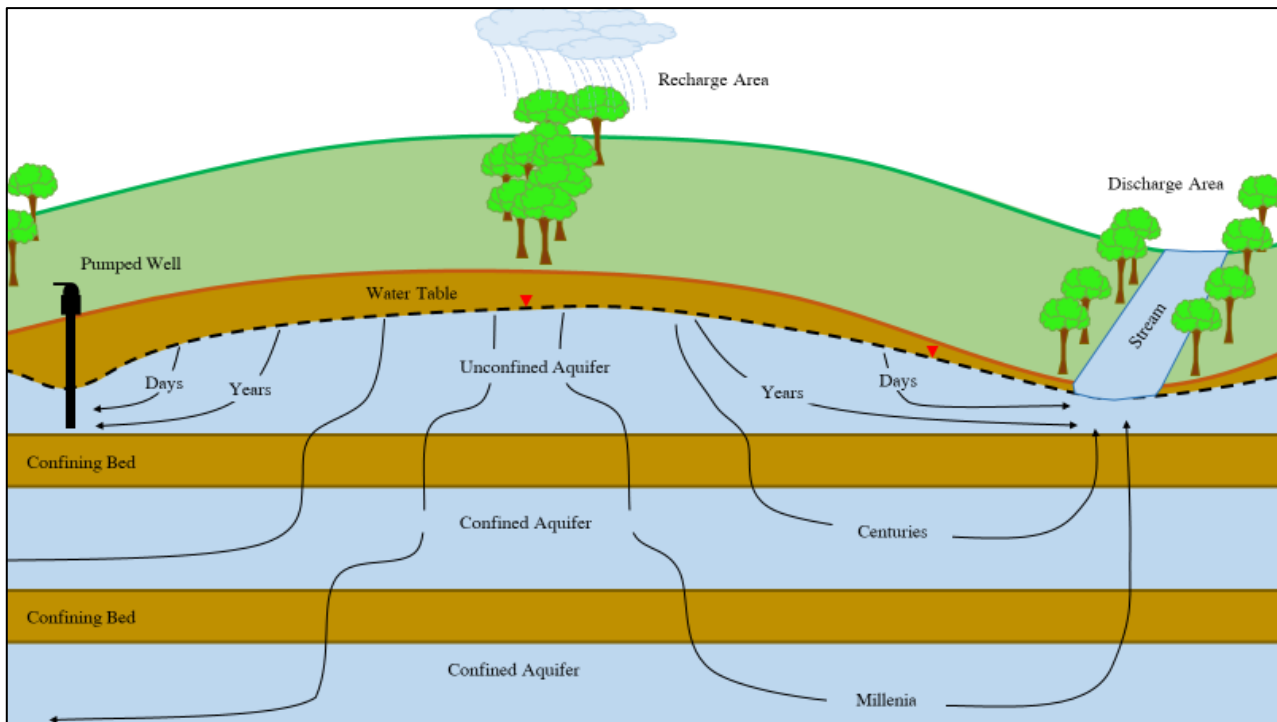


Figure 3 – Illustration showing the variation between groundwater pathways in length, depth and time modified after Winter et al. (1998).

With regards to any MAR scheme, the initial recharge of the scheme is seen as rainfall through natural processes to enter the groundwater system and in effect recharge or restore the system to natural processes. Managed, or artificial recharge is to do it in a manner that will increase this recharge cycle through artificial processes (passive or mechanical) and increase annual recharge percentages.

2.3 Aquifer Systems of the Greater Kruger National Park

An aquifer is defined as a geological formation that has structures or textures that support groundwater and appreciable groundwater flow movement through them (DWA, 2011). A formation or group of formations that are saturated and capable of holding a viable supply of groundwater, as well as supporting groundwater movement is what makes aquifers such an important geological feature of any location. Within the chosen study area, are a combination of two different aquifer systems, namely primary (porous) and secondary (fractured) aquifers.

A primary aquifer, or commonly known as a porous aquifer, accounts for a small portion of the GKNP, as it is most commonly found along the banks of the river systems (Olifants River) and on larger flood plains that can flood seasonally with the associated rainfall. More commonly identified within the study area are secondary fractured aquifers. This is described as a composite aquifer,

determined by weathered, faulted and fractured structures (du Toit and Verster, 2017). Major controlling secondary fractured groundwater features that may lead to increased water supply are the dolerite dyke swarms that trend in a North-Westerly direction through the entire study area (Petzer, 2009). These younger age intrusive features are more competent, low permeability rocks and can be seen as controllers of the landscape, as river courses are often redirected when intercepting a dolerite dyke intrusion. Mège and Rango (2009) described basaltic dykes as being important for directing and storing groundwater in semiarid regions and can even store water through the dry season after recharge in the wet seasons (Mège and Rango, 2010). Within this dissertation's study area, dolerite dykes were encountered rather than basaltic dykes, however, due to the similar nature of intrusion it is assumed that they support similar groundwater flow characteristics as a dolerite dyke is a finer-grained variant of basaltic dykes, both would have intruded the host rock under high pressure and temperature, through an existing fracture or zone of weakness (DWA, 2011).

Springs are seasonal appearances and can vary in strength throughout the year, springs are often found where dolerite dykes have intruded into the host rock of the region. This intrusion can cause an upwelling of water and daylight into springs, through the fractures and weathered zones between the dyke and host rock. Limited volumes of groundwater can be discretely discharged to rivers through springs (le Maitre and Colvin, 2008).

2.4 Structural Geology

Structural geology is among the most important aspect of any hydrogeological investigation. Faulting, fracturing, weathering and folding lead to a priority in groundwater flow preference which has a follow-on effect with groundwater quality and supply (Cook and Gordon, 2003; Guihéneuf et al., 2014).

The structural characteristics of the controlling geology in the study area have been the topic of multiple studies taken place, with a particular focus on groundwater exploitation and the internal characterisation of the aquifer system (du Toit and Verster, 2017). Generally, the majority of the archaean granitic crust composed of granites, tonalites and granitoids which have been intruded by the younger dolerite dykes and are the controlling geological feature within the study area. These structural features will control groundwater flow by either acting as a conduit or barrier to flow, through more competent rocks prohibiting the flow of groundwater. Geological features such as the dolerite dykes and faults cause fracturing when the younger intrusive or deformation intruded into the older granites or gneiss host rock. This would have then heated and deformed at the point of contact to create preferential flow paths to store and allow the flow of water (Petzer, 2009).

The definition of a fracture is any reasonable continuous and through-going planar, commonly on length scales of centimetres to tens or hundreds of meters along which there has been imperceptible "pull-apart" movement more or less perpendicular to the fracture surface (Davis et al., 2011). Fractures can be further defined by the mode of deformation or displacement into three different types, namely: shear or sliding, scissoring or tearing and extensional or opening fractures (Davis et al., 2011). These three different deformations can be seen graphically in Figure 4.

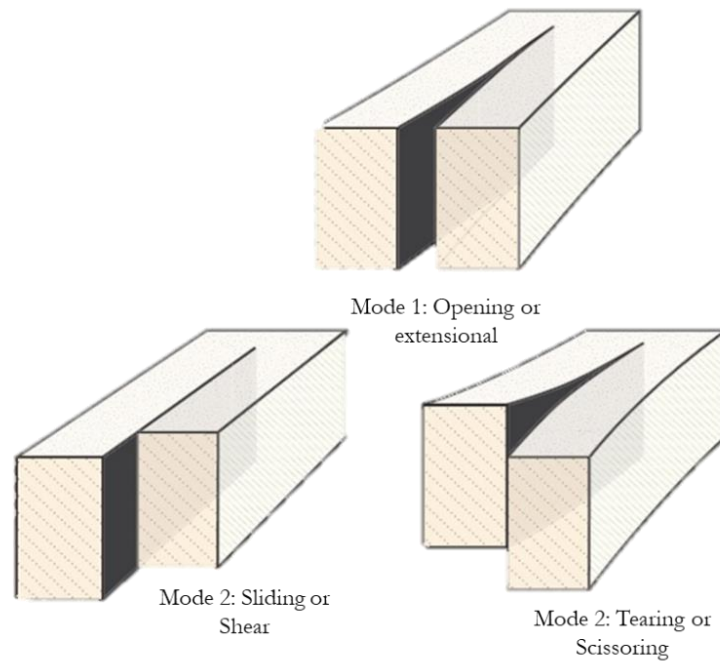


Figure 4 – Types of Fractures (Davis et al., 2011).

The baked or fractured zone is where younger dolerite dykes would have intersected into the host rock geology (Figure 5), which is characterised by brittle deformation structures which would have weathered through time as a result of the flow of water through these zones. The width of these damaged zones can vary depending on the lithological units that have been intersected, as the dolerite dykes would have intruded to the host rock, the much hotter intrusive would have baked the host rock at the point of contact, later creating preferential flow zones and increased weathering as a result. However, it is generally accepted that dyke lineaments would have a positive influence on groundwater productivity (Holland, 2012). Groundwater quality and structural occurrence of lineaments have a correlating control on one another, groundwater quality is good in areas of high lineament density, shown in the structural framework of Dasht-e Arjan region that the various faults and lineaments act as deep and shallow recharge sites (Sarikhani et al., 2014).

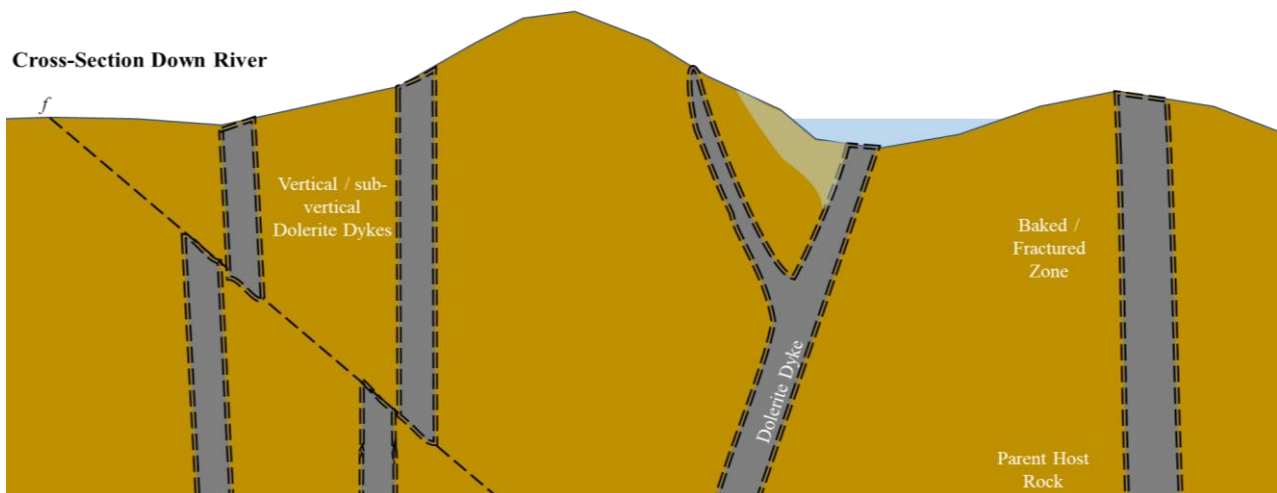


Figure 5 – Cross-section graphic illustration of multiple dyke intrusions and fault displacement.

2.5 Fracture Flow

An aquifer that can yield sustainable economic volumes of water that is characterised by fractures, jointing and weathering throughout the aquifer is classified as a secondary or fractured aquifer. When this is observed in host rock material, the increased porosity and hydraulic flow causes the increase of permeability along a preferential flow path at higher rates, such as through the brittle and fractured makeup of a dyke that has intruded into the host rock (DWA, 2011).

Porosity within a rock matrix can be classified as; primary, secondary or double porosity. Primary porosity is the porosity reserved from lithification deposition. Secondary porosity is created after the alteration of a rock, commonly through either faulting, folding and dissolution (Freeze and Cherry, 1979). Double porosity, as seen in Figure 6, is a combination of both primary and secondary porosity. Porosity is defined by the ratio of available void space to the total volume of rock (DWA, 2011).

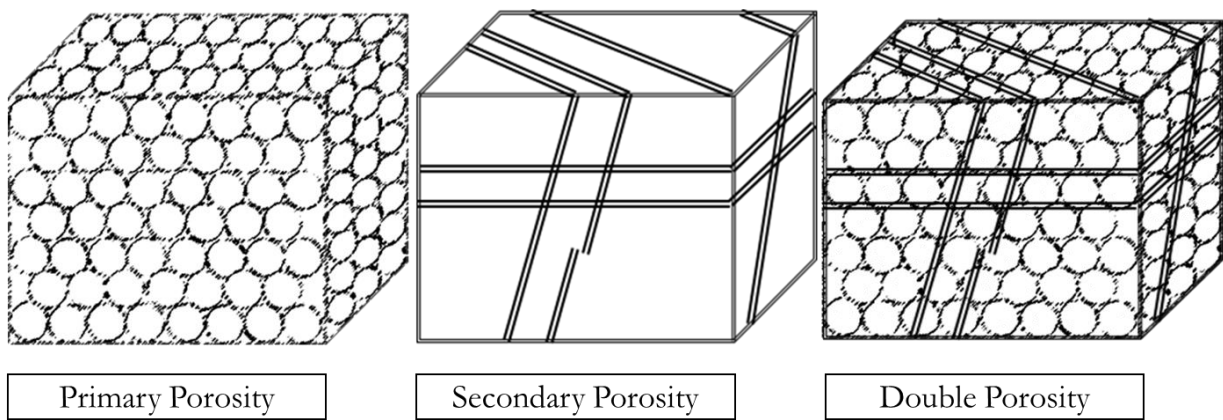


Figure 6 – Primary, secondary and double porosity graphic illustration (WSM Leshika Consulting (Pty) Ltd, 2020).

Darcy’s law is an equation that describes the flow of a fluid through a porous medium and can be used to characterise the amount of flow in both porous and fractured aquifers (Kruseman et al., 2000). The equation to calculate Darcy’s flux (V) is indicated in Equation 1:

$$V = \frac{Q}{A} = K \frac{dh}{dl} \quad (1)$$

$V =$ Darcy Flux	$Q =$ Discharge Rate
$A =$ Cross-sectional area (perpendicular to the flow direction)	$dh =$ $h_2 - h_1$ (head loss between two points in a system)
$dl =$ Distance between two points (length)	$dh/dl = i =$ hydraulic gradient
$K =$ Constant of proportionality (Hydraulic Conductivity)	

Fracture connectivity is a factor in any secondary aquifers, this refers to when fractures are connected into a network that connects water flow. Connectivity plays a controlling role in the flow and storage of a groundwater system. Cook (2003) has listed different terminations to a fracture network.

- Fractures that abut other fractures.
- Fractures that cross one another.

- Blind fractures that terminate into the host rock matrix.

Groundwater flow within a fractured network is important for the understanding of the direction in which groundwater will naturally flow. In the sense of a MAR scheme, the source water must not flow through the fracture network away from the intended extraction point or end-user.

2.6 Managed Aquifer Recharge in South Africa

The Southern African extent to existing MAR, is particularly behind in relation to many other countries and regions. According to a study published in 2018, an attempt was made to quantify the volume of MAR on a global scale, as well as to illustrate the percentage growth of MAR types (Dillon et al., 2018). Southern Africa recorded a growth of 5.2% in average annual MAR volume per decade from 1965 to 2015. With Southern Africa recording an approximate volume of 4,500 Mm³/year, only 0.2% of this was used for MAR. It is expected that the actual volume of groundwater used per year is higher. Southern Africa contributed approximately 0.1% to global MAR capacity, with the 5 states of India contributing the most (30.9%), followed by the USA (25.8%). However, in a positive comparison, Southern Africa recorded higher growth than the USA (5.2% versus 4.7%) in increased MAR use between 1965 – 2015. As can be seen in Figure 7, Africa falls well short of most other regions.

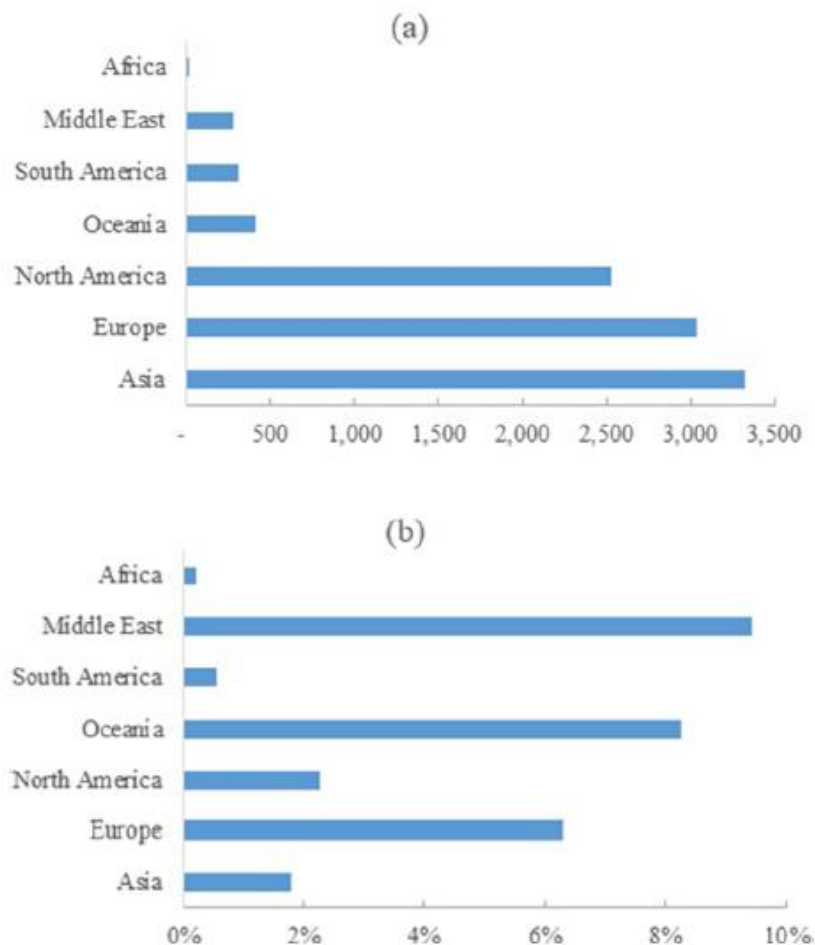


Figure 7 – Reported MAR capacity in 2015 by region expressed (a) volumetrically (Mm³) and (b) as a percentage of groundwater use (Dillon et al., 2018).

2.6.1 Managed Aquifer Recharge Methods

There are multiple forms of different methods used to infiltrate water into the subsurface, some of these methods are occasionally combined into a hybrid of methodologies, yet they all allow the same result – an increased volume of water being introduced to a subsurface system, above average. MAR, however, is adapted to site-specific circumstances that are required and it is typically governed by the aquifer, topography, land use and future intended uses of the recovered water (Dillon et al., 2009). A summary and explanation of standard methods has been broken down and shown in Table 2, Figure 8 and Figure 9.

Table 2 – Summary of different MAR methods and techniques (Dillon et al., 2009).

MAR Method	Description
Aquifer Storage and Recovery (ASR)	Injection of source water into a borehole (or well), followed by recovery from the same well.
Aquifer Storage, Transfer and Recovery (ASTR)	Similar to ASR, however, the injection water and recovery water are from different boreholes. Used as an additional treatment tool as water has a longer residence time in the aquifer.
Infiltration ponds	Surface water is diverted into off-stream basins and channels, where water is allowed to then soak through an unsaturated zone to the underlying unconfined aquifer.
Infiltration galleries	Buried trenches in permeable soils, allowing infiltration through an unsaturated zone to an unconfined aquifer, usually via slotted pipes.
Soil Aquifer Treatment (SAT)	Sewerage effluent that is treated is infiltrated into the subsurface through infiltration ponds to facilitate the removal of pathogen and nutrient removal. The water is later recovered through abstraction wells.
Percolation tanks or recharge weirs	Water detained up in ephemeral streams through a dam, will infiltrate the unconfined aquifer and enhance storage within.
Rainwater harvesting for aquifer storage	Water from roofs is collected and then diverted into a borehole to increase storage within the local aquifer, water can then be retrieved later when it is required. This method can be applied on a small scale through many sources (rooftops), an example of this currently taking place is in Hermanus (DWAF, 2010).
Recharge releases	Flood water is detained in ephemeral streams through the construction of dams. Following this will be the slow release of water into the streambed, matching the infiltration to aquifers below.
Dry wells	Water is infiltrated to deeper water levels through shallow dry wells, allowing further infiltration of good water quality to an unconfined aquifer at depth.
Bank filtration	Intentional groundwater extraction from a borehole that is near to a surface water body, essentially inducing infiltration from the surface water body through the subsurface.
Dune filtration	Infiltration of water within sand dams and then extraction from boreholes that are downgradient of the sand dams, this works well for better water quality improvement. A local example of this is through the MAR scheme designed at Sedgfield (DWAF, 2010).
Underground dams	Ephemeral streams can have a trench constructed where basement highs already restrict flow, the trench is constructed and backfilled with low permeability material to help retain and store flood waters, the water is then most often restored for stock water.

MAR Method	Description
Sand dams	These dams are typically constructed in ephemeral stream channels within arid areas, sediment is then trapped during flood or flow events, slowly the sand dam grows bigger naturally and creates an aquifer for groundwater storage.

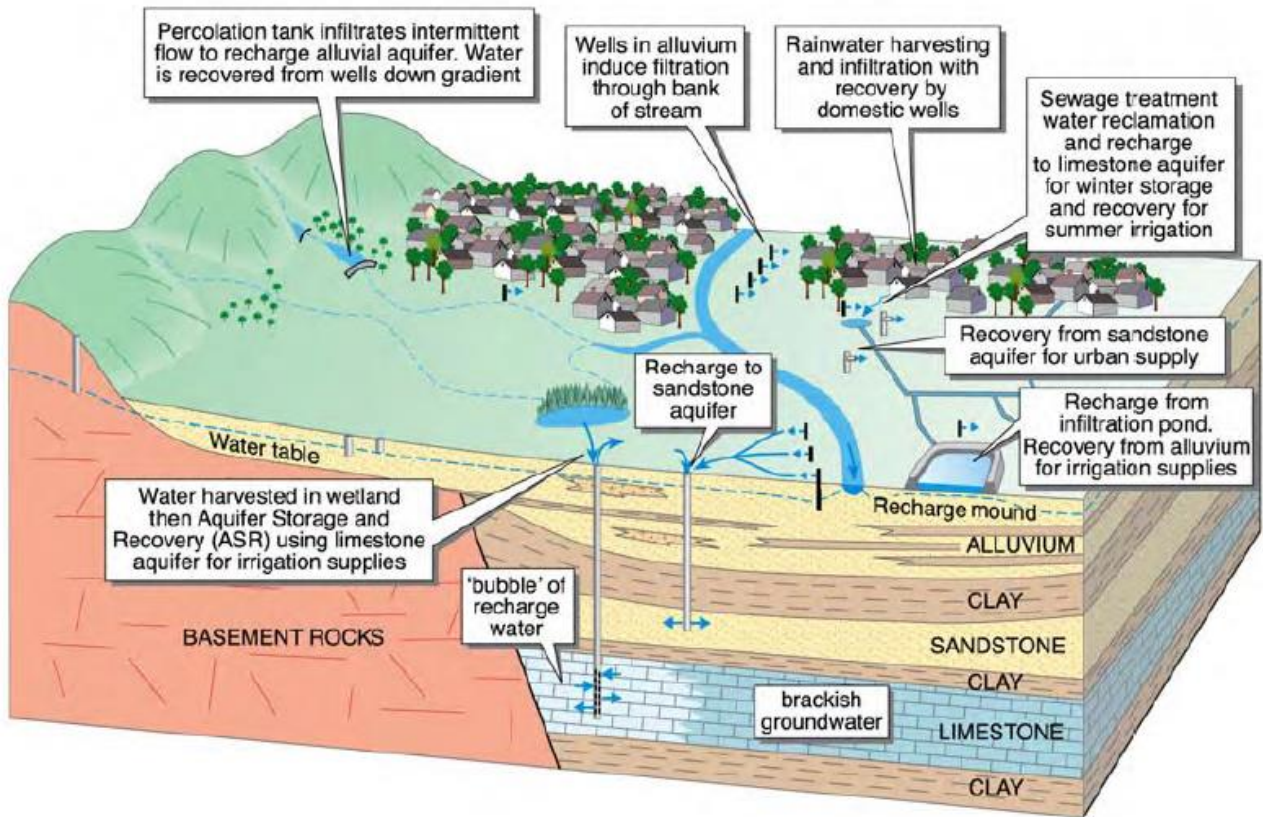


Figure 8 – Graphic illustration showing the different methods of MAR being implemented within a variety of settings (Dillon et al., 2009).

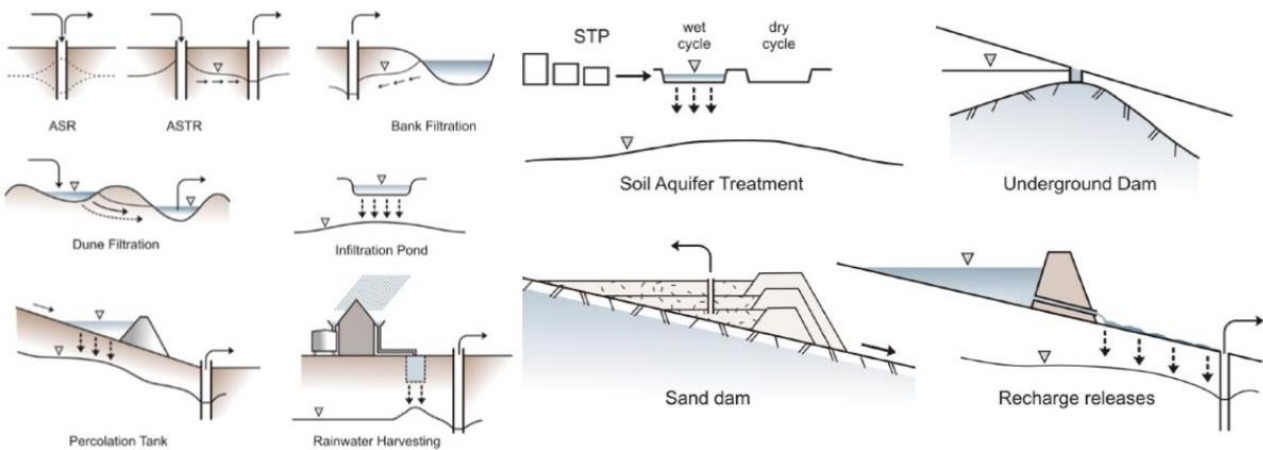


Figure 9 – Schematic illustration of different MAR types (Dillon et al., 2009).

2.6.2 Case studies of Managed Aquifer Recharge in South Africa

South Africa currently has the highest number of recorded MAR sites in Africa. 17 active MAR sites were noted in the publication: “*Managed Aquifer Recharge in Africa: Taking Stock and Looking Forward*” (Ebrahim et al., 2020). This equates to approximately a third of all MAR sites in Africa (52 in total). The most common form of MAR in South Africa was Open Borehole Injection (12 of the 17 sites). The most common need for MAR was to meet the increasing demand for water in summer as well as secure water during drought conditions, for example in Calvinia, Northern Cape (Ebrahim et al., 2020). The most common final use of the recovered water was for domestic purposes. Three of the active sites have been explained further below. The oldest active MAR scheme (Atlantis wellfield scheme) is outlined first, followed by two methods of MAR that are relevant to this dissertation. The Elandsfontein Phosphate mine (ASTR) and the Kharkams MAR flood water scheme. Their relevancy is described further in this dissertation.

2.6.2.1 Atlantis Water Resource Management Scheme – Basin Infiltration

The Atlantis wellfield scheme was implemented after studies indicated that the Atlantis Aquifers' natural yield was insufficient to sustain the long-term water supply for the town of Atlantis (Tredoux and Cain, 2010). Water recycling then formed part of the management scheme through infiltration ponds, shown in Figure 10. The scheme is into its 50th year, since project inception and first hydrogeological study in 1972 (Tredoux and Cain, 2010).



Figure 10 – Atlantis infiltration basin (Tredoux and Cain, 2010).

The recharge basins are filled with stormwater and wastewater, which then settles and infiltrates into the Atlantis aquifer's artificial recharge infiltration basins. The Witzand wellfield is downgradient of the artificial recharge basins, water is then pumped out of this wellfield to the town of Atlantis. Additionally, further downgradient is a series of coastal recharge basins to prevent salt water intrusion to the Witzand wellfield (Tredoux and Cain, 2010). This is shown spatially in Figure 11. It is estimated that on average 7,500 m³/day is recharged upgradient of the Witzand wellfield in the infiltration basins. In the 1990's, while the scheme was undergoing refurbishment of the wastewater treatment works, borehole water levels dropped and led to over-pumping of the production boreholes resulting in clogging of the boreholes, rehabilitation remains the only solution to this problem (Tredoux and Cain, 2010).

The Atlantis MAR scheme remains a good South African example of a scheme that is cost-effective and has been proven successful over time, supplying water to both residential and industrial areas of Atlantis for more than 40 years. Effective management, monitoring and rehabilitation is an important contributor to the scheme's success (Tredoux and Cain, 2010).

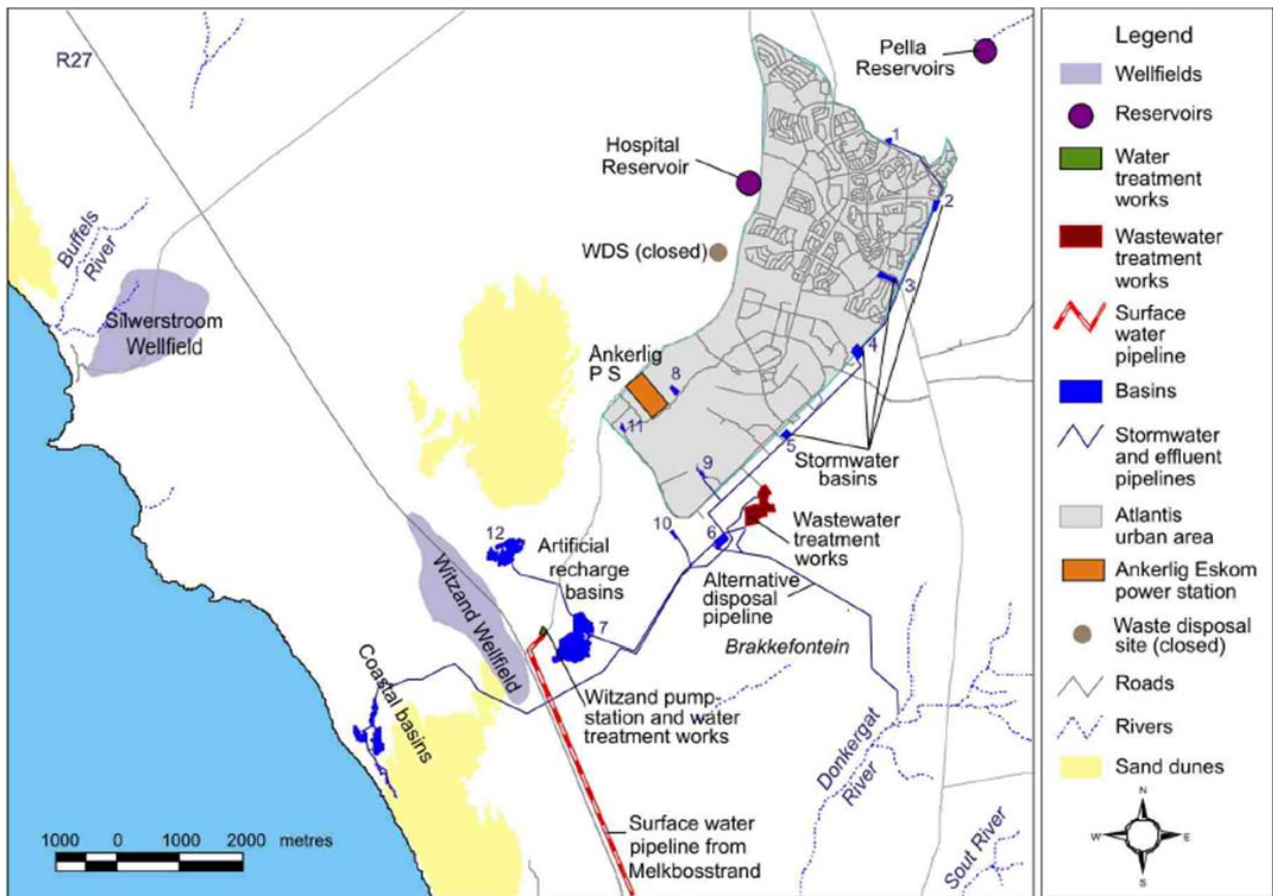


Figure 11 – Layout of the Atlantis Water Resource Management Scheme wellfields and recharge basins (Tredoux and Cain, 2010).

2.6.2.2 Elandsfontein Phosphate Mine – Environmental MAR

The Elandsfontein phosphate mine is located on the west coast of South Africa, approximately 20 kilometres from the coastal town of Langebaan. The scheme is focused on ensuring the continued natural groundwater flow within the Elandsfontein aquifer from the North-East, further towards the Langebaan lagoon, South-West of the mine (GEOSS, 2021). The scheme has a total of 20 injection boreholes specifically for reinjecting pit water (Figure 12), this is abstracted to dewater the mine pit for mining purposes. The mine is licensed to reinject approximately 25 Mm³ for the length of their Water Use License (WUL), at varying rates depending on years of production and operational status. Further to the injection boreholes, the mine has drilled and equipped monitoring boreholes dedicated to the monitoring of water quality and levels as a result of dewatering and reinjection of the groundwater. The source water for this MAR scheme is sourced from dewatering pit water abstracted upgradient, then pumped into a holding tank, whereby through gravity it is reinjected into the same aquifer, downgradient of the open pit. This is done through a series of injection boreholes (GEOSS, 2016). Figure 13 shows how the downgradient monitoring boreholes (~1.0 – 1.5 km) display a rising water level as a result of reinjection and stable EC measurements, this data is recorded monthly. The

measured water levels have risen by 2.53 m on average between SNP05 and SNP06 since the start of recharge in February 2017 (GEOSS, 2021).



Figure 12 – Elandsfontein injection line (GEOSS, 2016).

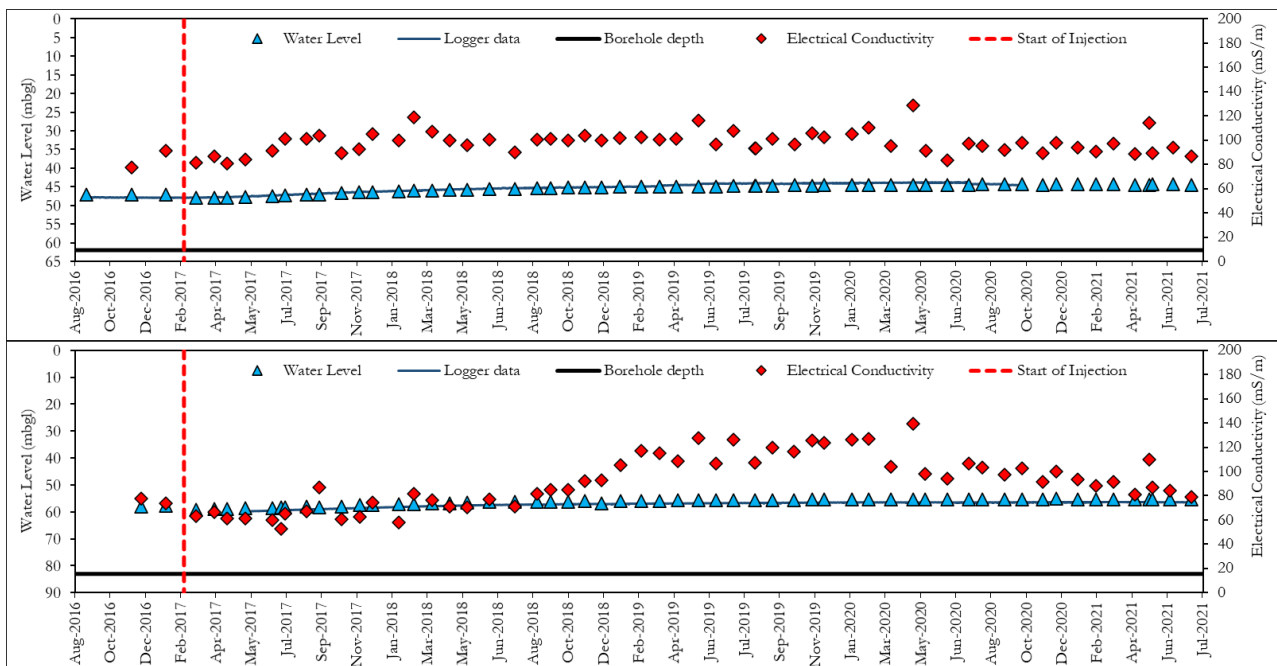


Figure 13 – Water level and EC monitoring graphs from downgradient monitoring boreholes, SNP05 (top) and SNP06 (bottom) (GEOSS, 2021).

The Elandsfontein mine recharge scheme is a result of dewatering required within the upper aquifer for mining purposes (GEOSS, 2016). Water is pumped out of the mining pit via 36 dewatering boreholes and an in-pit sump, with reinjection taking place downgradient of the pit, capable of injecting at a rate of 15 L/s (depending on dewatering rates). The water is injected into the upper aquifer through gravity flow via the MAR method, ASTR. The purpose of the MAR scheme is to offset environmental impacts due to dewatering and forms part of the mine’s mitigation strategy and is successful. The distribution of the Elandsfontein Phosphate mines monitoring, dewatering and injection borehole network can be seen in Figure 14.

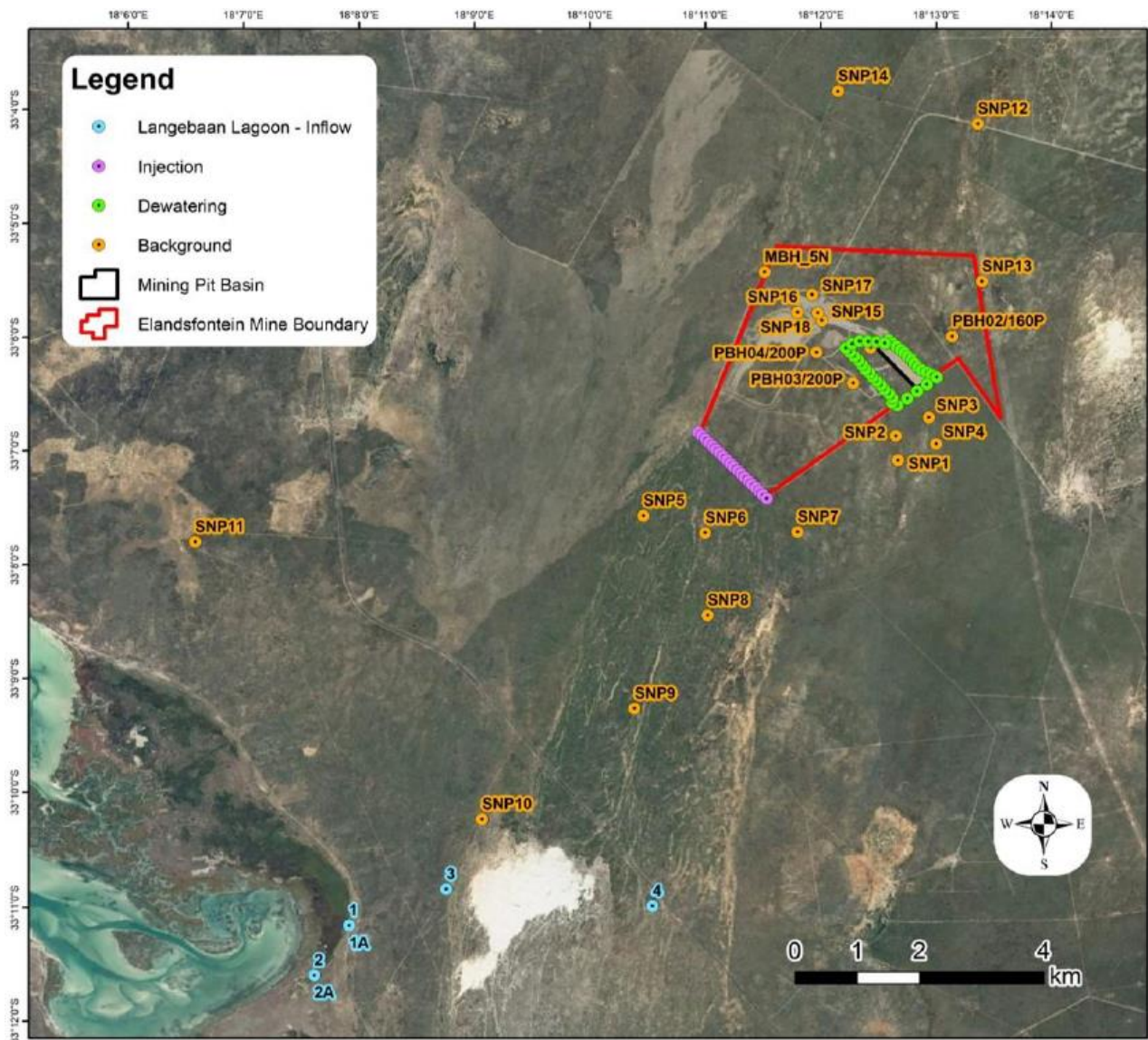


Figure 14 – Regional Setting of the Elandsfontein Phosphate mine within the mining boundary and illustrating the extensive monitoring network, injection sites and dewatering boreholes around the mine pit (GEOSS, 2021).

2.6.2.3 Kharkams, Namaqualand – Flood water MAR

The Kharkams MAR scheme was commissioned in 1995 and on average 0.005 Mm^3 groundwater is recovered per year. The methodology used is simple and affordable, on average a volume of 1 L/s is being recharged into the groundwater aquifer system (Braune and Israel, 2021). The scheme makes use of excess flood water that requires filtration of debris and clay before it can be recharged. The small town of Kharkams required MAR as a result of over-abstraction within the bedrock secondary aquifer (granites and gneiss). Water levels within the aquifer indicated a dropping level trend and water quality worsened as a result of concentrated dissolved salts (Braune and Israel, 2021). A complication with the scheme was the problems associated with clogging, this was handled by including a sand filter within the river bed (Figure 15).

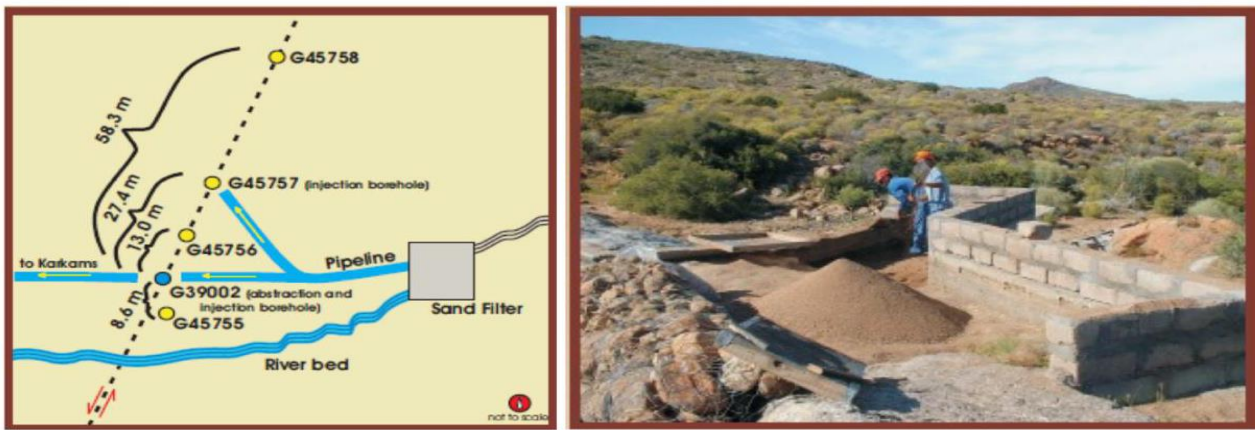


Figure 15 – Kharkams MAR scheme layout (left) with sand filter (right) within the river bed (Braune and Israel, 2021).

Between 1999 to 2001, a series of controlled injection tests took place. One particular test lasted 138 days and the volume of water injected into the borehole was more than two times the calculated sustainable yield ($2,400 \text{ m}^3/\text{annum}$) of the borehole. Figure 16 shows how the water quality improved from a maximum of 280 mS/m, down to a minimum of 40 mS/m, eventually stabilising between 60 to 70 mS/m in the groundwater. The success of the MAR scheme shows in improved water quality. It was concluded that although the scheme never had any cost developments determined, the technology and methodology used were less than the cost of treating water or developing other sources (Murray and Tredoux, 2002).

The Kharkams MAR scheme was used as the closest successful approximation to the proposed aquifer recharge method for this dissertation, as the objectives of the scheme are similar and the geological and environmental settings are parallel with one another. Fresher surface water injection to the groundwater system has been successful in this scheme and it is hoped that a similar impact will be observed within the GKNP. This dissertation is the first stepping stone to achieving equal success as that which was given to the Kharkams scheme.

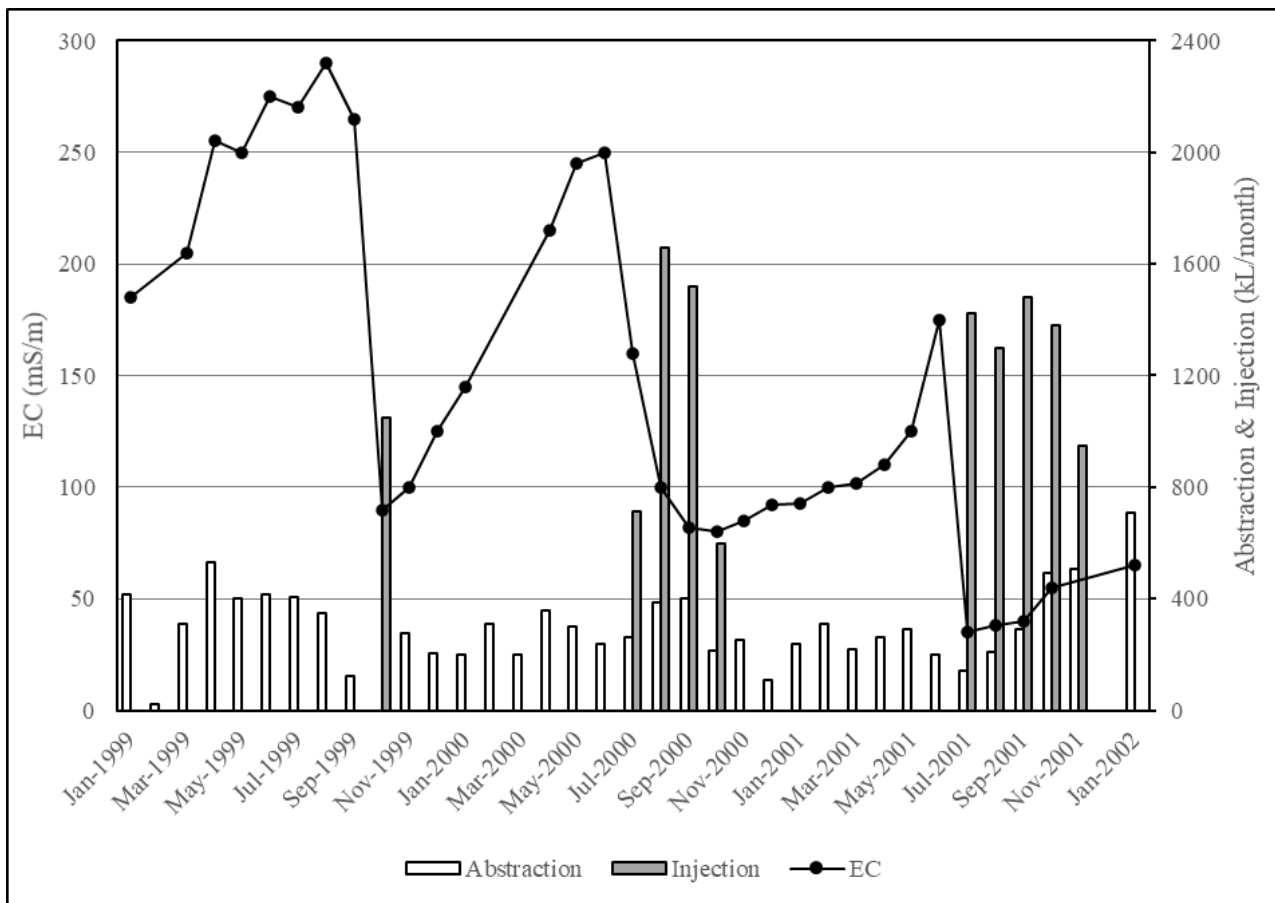


Figure 16 – Water Quality improvement as a result of injection water to Kharkams MAR scheme (Murray and Tredoux, 2002).

CHAPTER 3: SITE DESCRIPTION

3.1 Regional Setting

The two study areas are situated to the west of the Kruger National Park, located within the private game park boundaries of Olifants West Nature Reserve (Balule) and the Timbavati Game Reserve (Motswari). The town of Hoedspruit is to the south of both study sites, this can be seen in Figure 2 and Phalaborwa is to the North of Balule.

Motswari falls within the quaternary catchment B73D. This quaternary catchment has a general authorisation of 75 m³/ha/year. The primary land use in this area is wildlife conservation for tourism. Motswari has no permanent perennial rivers and only some non-perennial to ephemeral rivers that flow for short periods in summer after intense rainfall events.

Balule falls within the quaternary catchments B72D and B72C. These quaternary catchments have a general authorisation of 75 m³/ha/year. The dominant form of land use in this area is wildlife conservation for tourism and to a smaller degree, trophy hunting in some parts. Balule Nature Reserve is intersected by the Olifants River that flows from South-West to North-East in Figure 18. The perennial Olifants river is seen as a major hydrogeological boundary within the study area of Balule.

The study areas as a regional context are shown in Figure 17 and Figure 18, these have been superimposed onto aerial photography.

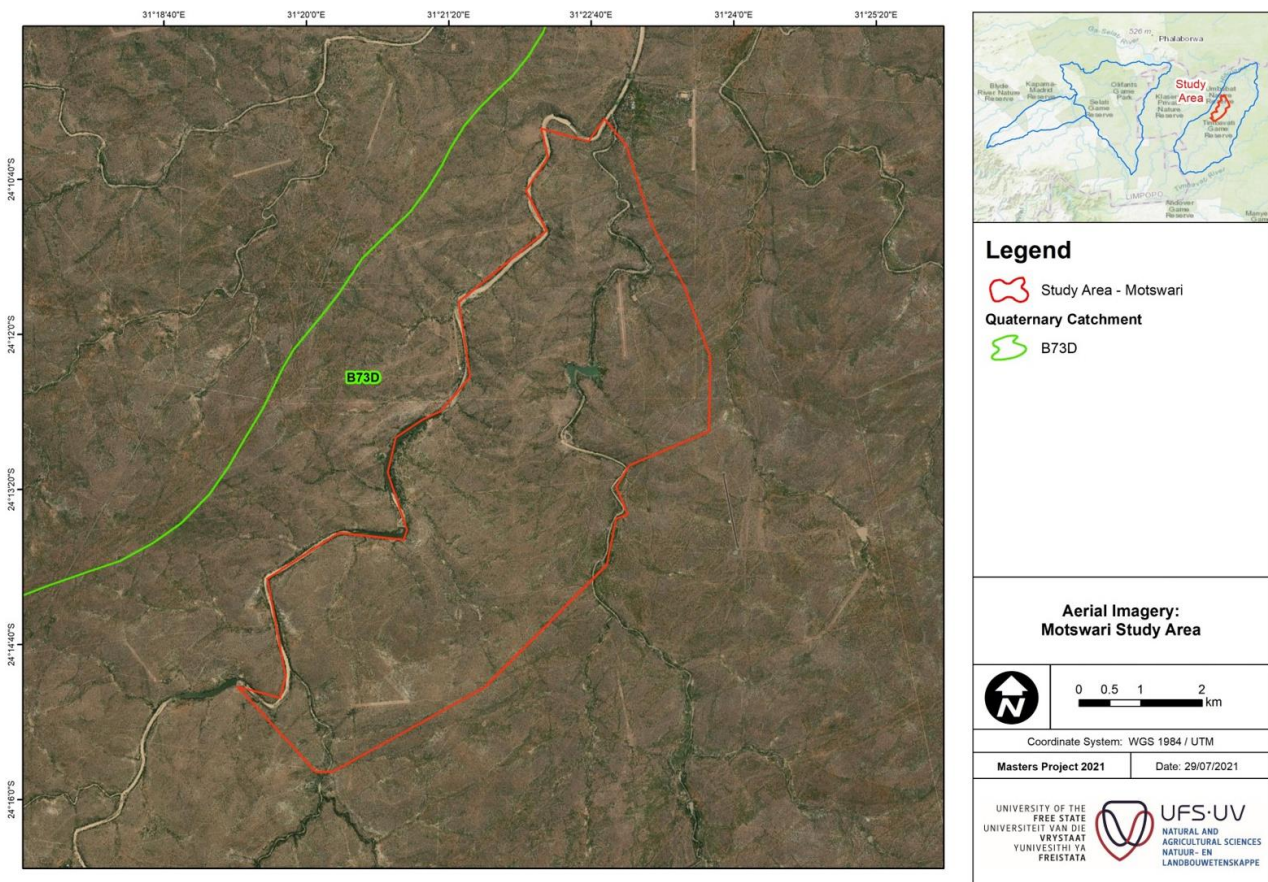


Figure 17 – Motswari Study Area location within Quaternary Catchment B73D.

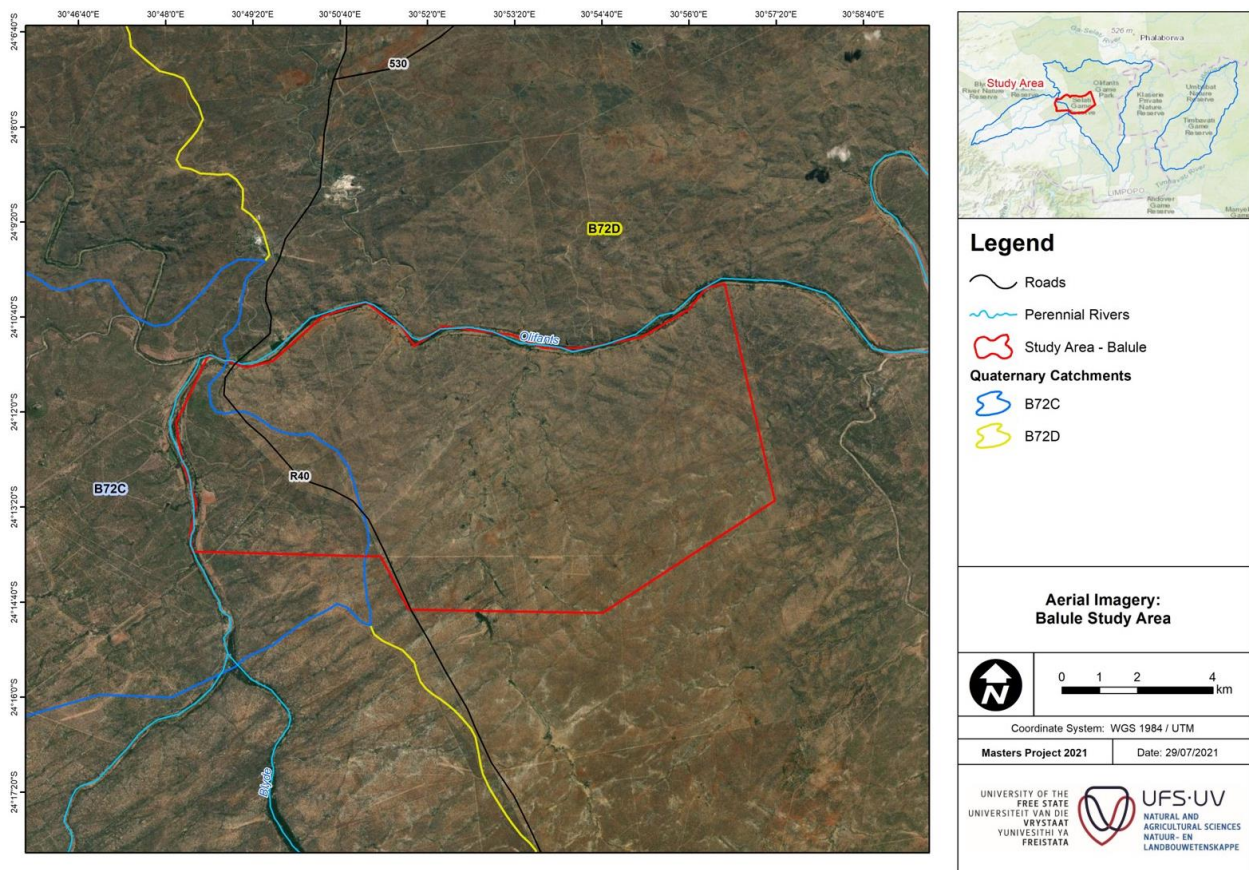


Figure 18 – Balule Study area within Quaternary Catchments B72C and B72D.

The two study areas were selected based on feedback from discussions with stakeholders and their willingness to form part of the study. The shapes of both study areas are limited to land ownership and access, hence the irregular shapes and boundary restraints of the Olifants river in Figure 18. The Balule study area extends across two quaternary catchments, as the land ownership extended towards the west and across the R40. This additional area allowed for more access to the Olifants river as well as potential monitoring sites.

3.2 Climate

The study area experiences a warm summer with seasonal rainfall on hot afternoons. Winters are mild and dry which is almost void of any rainfall. Figure 19 indicates the daily minimum and maximum air temperatures, provided by the South African Weather Services (SAWS) from the weather station at the Hoedspruit Air Force Base, from 1st January 2014 until 05 May 2021. It must be noted that there was a portion of temperature data loss from the SAWS between August 2016 and July 2017, these data gaps could partially be filled in using other nearby weather stations, however not completely.

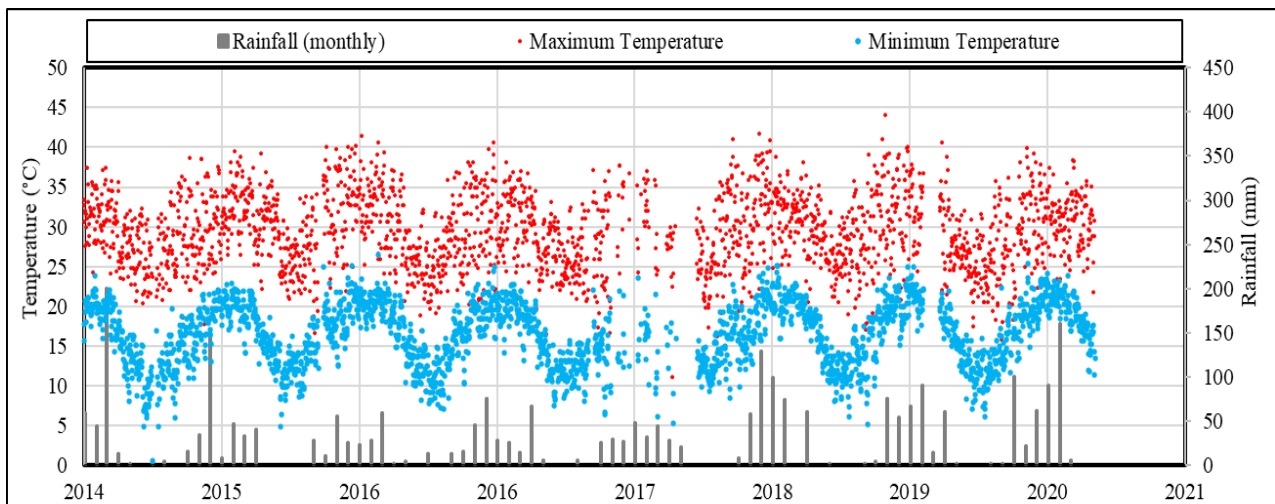


Figure 19 – Daily SAWS maximum and minimum temperature and monthly rainfall.

The annual rainfall at the study site is approximately 421 mm. Average monthly evaporation rates have been plotted in Figure 20 against monthly rainfall averages, evaporation data has been derived from McCartney et al. (2004). In Figure 20 it can be seen that monthly evaporation exceeds the monthly rainfall throughout the entire year. The ratio of evaporation to rainfall is greater in the winter months than in summer.

Figure 21 shows monthly total rainfall distribution as well as a moving 12-month average for Balule through an automated weather station for Olifants West Nature Reserve from 1985 till October 2021, this source location is on the border of Hoedspruit to the north, all rainfall shown in Figure 21 is local rainfall captured. Rainfall in this region takes place mostly in the hotter summer months of November to February, whilst most of the winter is drier. During winter months, the groundwater supply plays a vital role in meeting water requirements for water supply and ensuring that the game lodges and small communities have access to water for drinking, washing and recreational (e.g., swimming pools and watering holes) purposes.

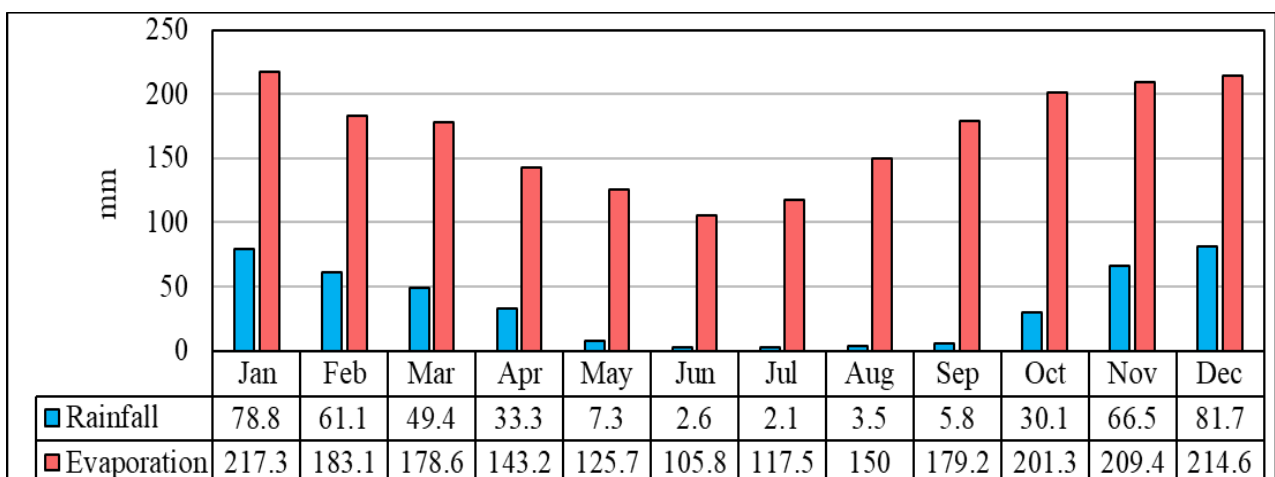


Figure 20 – Monthly rainfall and evaporation average of study areas (McCartney et al., 2004).

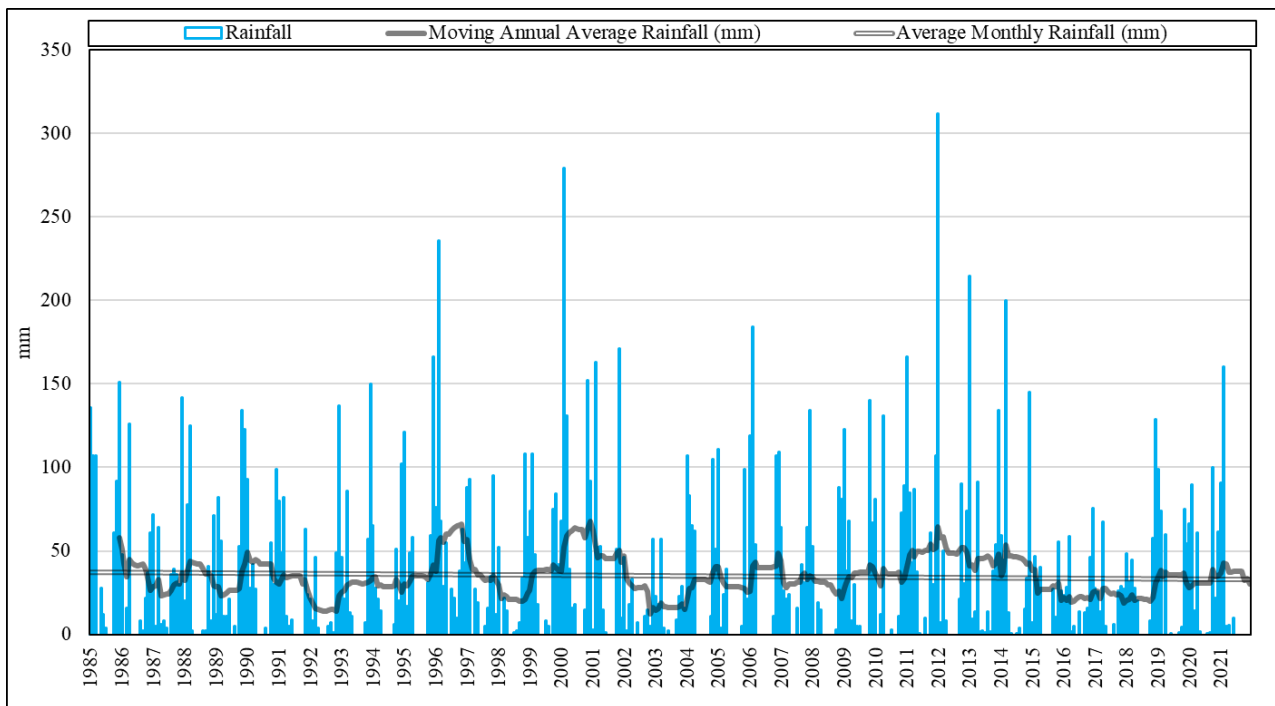


Figure 21 – Historical rainfall recording and average monthly and 12-month moving average.

3.3 Relief and Surface Drainage

The present landscape of Southern Africa is a result of complex combinations of isostatic readjustments glacio-eustatic oscillations in the sea level (Venter and Bristow, 1986). The study areas are located in a low relief area, with drainage lines covering and shaping the landscape through the long-term process of fluvial erosion. Multiple non-perennial rivers flow across both study areas with varying degrees of flooding during the summer season after high-intensity rainfall events.

The Motswari study area is composed of non-perennial drainage lines that flood for short periods following heavy downpours. The primary drainage direction for this area is from South to North, shown by the higher-lying (white-brown) in the south and dropping elevation towards the North of the study area (Figure 23).

The Balule study area has one prominent perennial river flowing from west to east, the Olifants River. Several non-perennial rivers flow into the Olifants from the Balule Reserve. These flow from the higher-lying areas in the south towards the Olifants in the North (Figure 24). The Olifants River has vigorously incised itself and by the active retreat of its headwaters, cut through the Great Escarpment to the West of Balule (Venter and Bristow, 1986).

An example of the flooding drainage lines can be seen in Figure 22, after a strong downpour in early-2021. Both study areas can be described as displaying a dendritic pattern (Venter and Bristow, 1986).



Figure 22 – Floodwater flowing through drainage line after a high-intensity rainfall event.

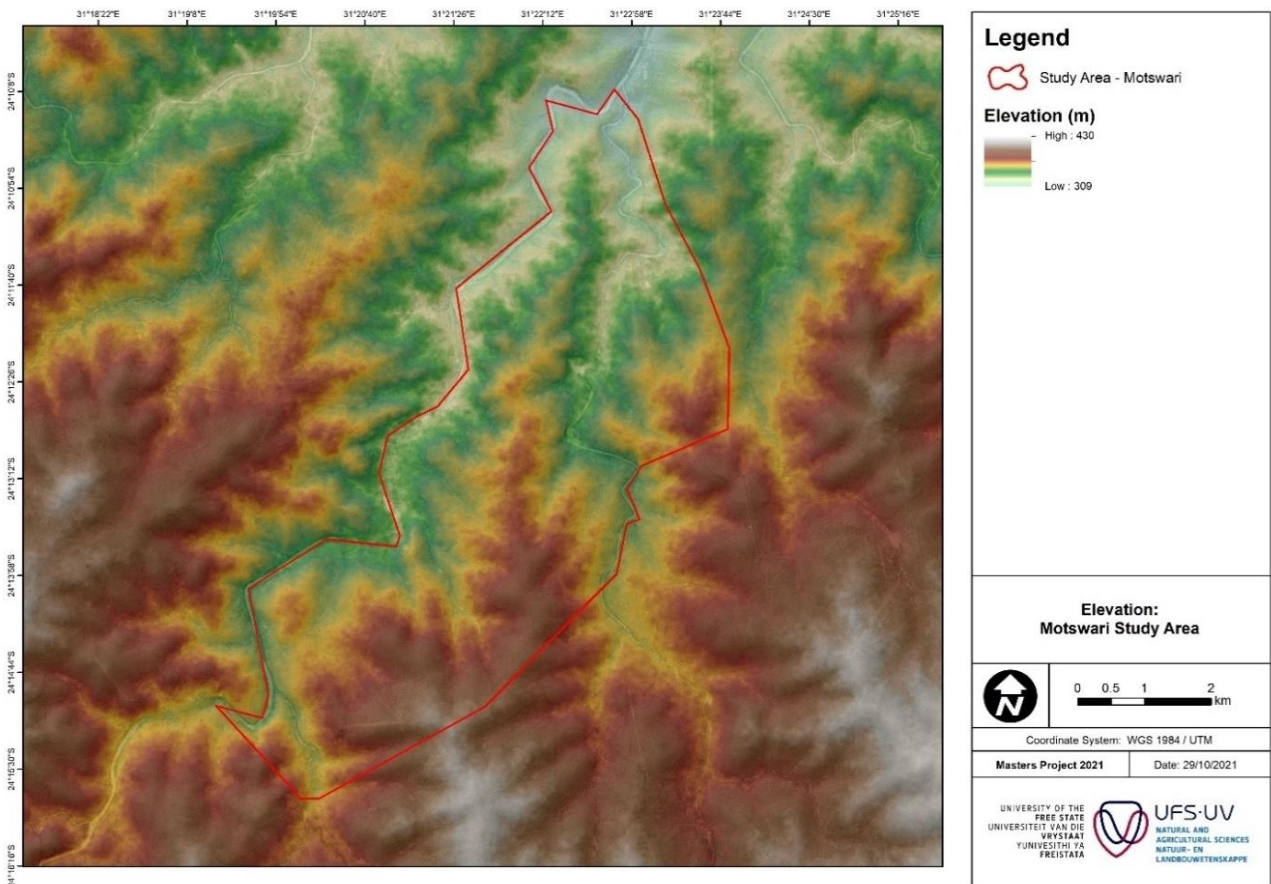


Figure 23 – Elevation interpolation of Motswari study area (mamsl).

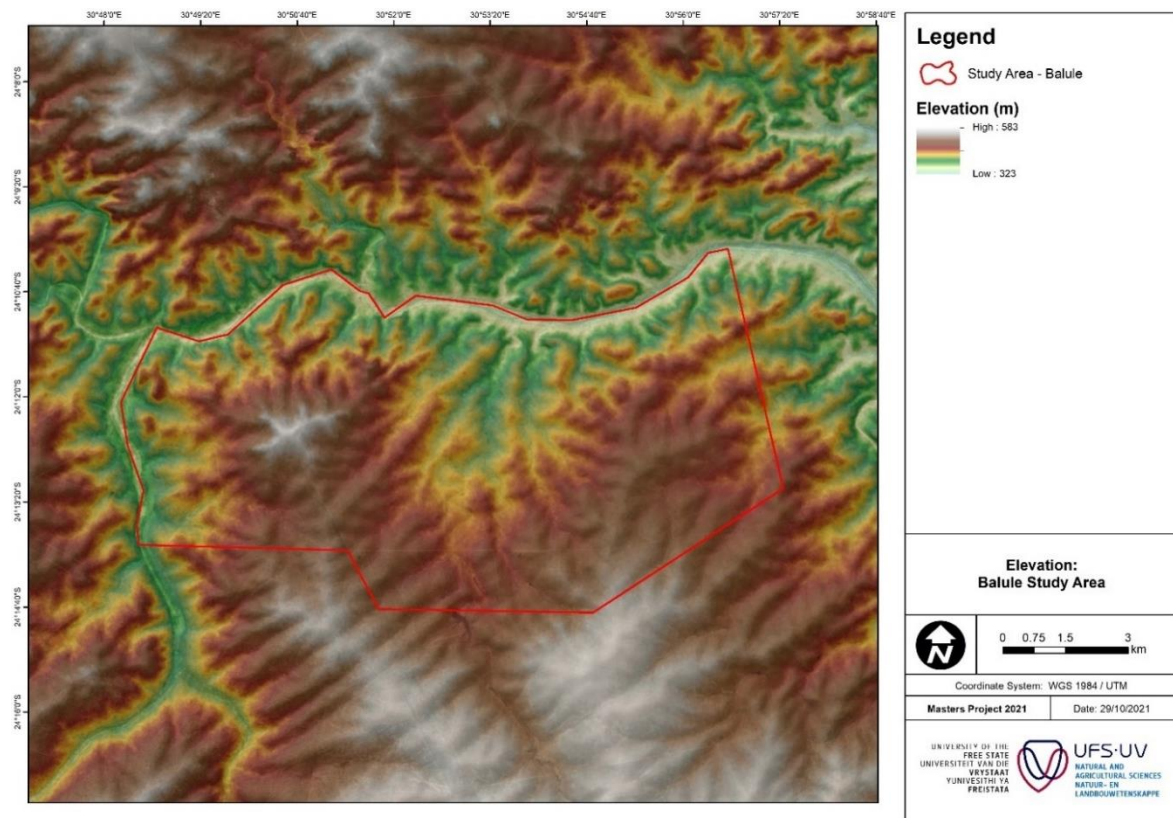


Figure 24 – Elevation interpolation of Balule study area (mamsl).

3.4 Recharge in the Greater Kruger National Park

Recharge in the study area is an important component of the hydrological cycle. Petersen (2012) completed a full study on a conceptual understanding of the recharge processes in the Kruger National Park, which forms part of the eastern GNKP. Petersen (2012) used two methods to identify the groundwater recharge processes as well as define when and how the recharge occurs. Cumulative Rainfall Departure (CRD) and stable isotopes were two of the studied methods. The CRD reflects the natural balance of groundwater within a system by studying the combined effects of both recharge and losses. A summary of the Petersen (2012) study is listed below:

- The impact on groundwater should be kept to a minimum as it plays a major role in sustaining a functional ecosystem.
- Groundwater was identified as a major environmental indicator that needed to be monitored.
- Groundwater recharge in the study area occurred primarily during the rainy summer months of November to February, with almost no recharge in the dry months of the remaining parts of the year.
- Recharge was only observed to have an impact on rainfall events of 100 mm or more, this was illustrated by the shallow groundwater levels after the major rainfall periods in 2000.
- Stable isotope samples collected indicated that there was evaporation before any infiltration to the groundwater, as the study area experienced high evaporation rates, smaller rainfall events were insignificant to recharge
- Recharge events to the aquifers only reflect in alternating wet and dry cycles that can last for between 6 to 14 years. The analysis showed that periods when there are low rainfall years, can contribute to dropping groundwater levels and little recharge.

- It is only during major rainfall events every 100 – 200 years that the aquifer will recharge fully. During below-average rainfall years, the water levels within the groundwater system will show a decline.
- Along with the western granitic areas of the study area within the Petersen (2012) research, similar to this dissertation, the dominant recharge mechanisms are through indirect recharge. Groundwater recharge takes place through preferred pathways, particularly rivers, streams and flood plains, these locations act as sinks for recharge. Major perennial rivers were seen as effluent river systems that are constantly being fuelled by groundwater flowing into the rivers and surface water systems

As part of this dissertation, localised rainfall recharge rates as a percentage (%) are calculated in comparison to similar studies. Nemaxwi et al. (2019) determined that 0.5% of annual rainfall was recharged to the groundwater. Higher recharge rates were noted in areas of higher elevation or mountainous areas, while lower-lying areas had lower recharge (Nemaxwi et al., 2019). DWAF (2006) estimations plotted the recharge in the study area to be between 3 to 6 mm/a (0.7 to 1.4% of mean annual recharge).

Drought conditions can be quickly identified in Figure 21 by plotting the moving 12-month average against the annual average. The years of 2015 – 2019 correlated to the previous drought conditions experienced in the region with below-average rainfall, preceded by an extended period of above-average rainfall from 2011 – 2015. Notably also when 2012 floods devastated the entire GKNP region (Getaway, 2020). The floods in February 2000, can also be noted in the moving 12-month average in Figure 21.

3.5 Regional Geology

The geological survey of South Africa (now the Council for Geoscience) has mapped the area at 1:250 000 (Council of Geoscience, 1986; Walraven, 1989). The primary geology of the area is listed in Table 3. The map reference for this geological area is 2430 – Pilgrims Rest and has been plotted on Figure 25 and Figure 26.

Table 3 – Complete Geology of Study Area (Council of Geoscience, 1986).

Age (Era)	Ma	Code	Formation / Pluton	Description
Jurassic (Period)	200 – 150	Jd	Dolerite Dyke	Intrusive Rocks - Minor Ultrabasic rock, fine-grained Dolerite (Dykes), commonly porphyritic.
Vaalium	3091 +/- 5	Vh	Harmony Granite	White, coarse-grained plagioclase granite, coarse-grained and pegmatitic near margins.
Swazium	3063 – 3118 +/- 5	Zm	Makhutswi Gneiss	Light grey massive, equigranular, medium to fine-grained rock consisting of quartz, plagioclase and biotite. Small amounts of microcline and sphene with the occasional inclusion of pegmatite veins
	3228 +/- 5	Zo	Gravelotte Group	Basic to ultrabasic lavas at the base (basaltic komatiite) to more acidic volcanic rocks at the top (felsic porphyritic tuffs), interlayered with conglomerates and quartzite

The geology of both study areas is comprised of the Archean granitic crust made of granites, gabbros and gneiss. Dolerite dykes have intruded into the host rock environment less than 200 million years

ago (Ma). The Gravelotte Group and Makhutswi Gneiss are the oldest rocks in the study area (Poujol et al., 2002). These rocks are the light grey migmatitic tonalite and granodiorites from the Paleoproterozoic era (Walraven, 1989). Additionally, to note on the geological map are the presence of mapped dolerite dykes which trend in a North-East to South-West direction (Council of Geoscience, 1986), similarly mapped lineament structures follow the same trend.

The regional geological landscape took millions of years to form, beginning in the Swazium era with the metamorphosed rocks of the Makhutswi Gneiss and basic to ultrabasic lavas of Gravelotte Group. Almost parallel with this timeline was the intrusion of the Harmony Granite pluton to the south of the Balule study area and its transition zone on the boundaries of the pluton. During the intrusion of these igneous rocks, the host rock would have experienced fracturing and baking as the intrusive would have placed it under high pressure and temperature. More recently in the geological timeline was the intrusion of dolerite dykes which would have contributed to more recent fracturing and faulting (Walraven, 1989).

Geology will be a key controlling factor in how the hydrogeological conditions within the entire study area will vary. Groundwater quality is dependent on water interacting with the host rock and residence time, pore spaces, fractures and fault zones. Borehole yields will rely on the permeability and porosity of the subsurface geology as different geological units will also have different recharge rates, storage capacities and permeabilities (Leyland and Witthüser, 2008). Groundwater is found where weathering and fracturing of the hard-rock formations extend into the saturated zones (Vegter, 2003).

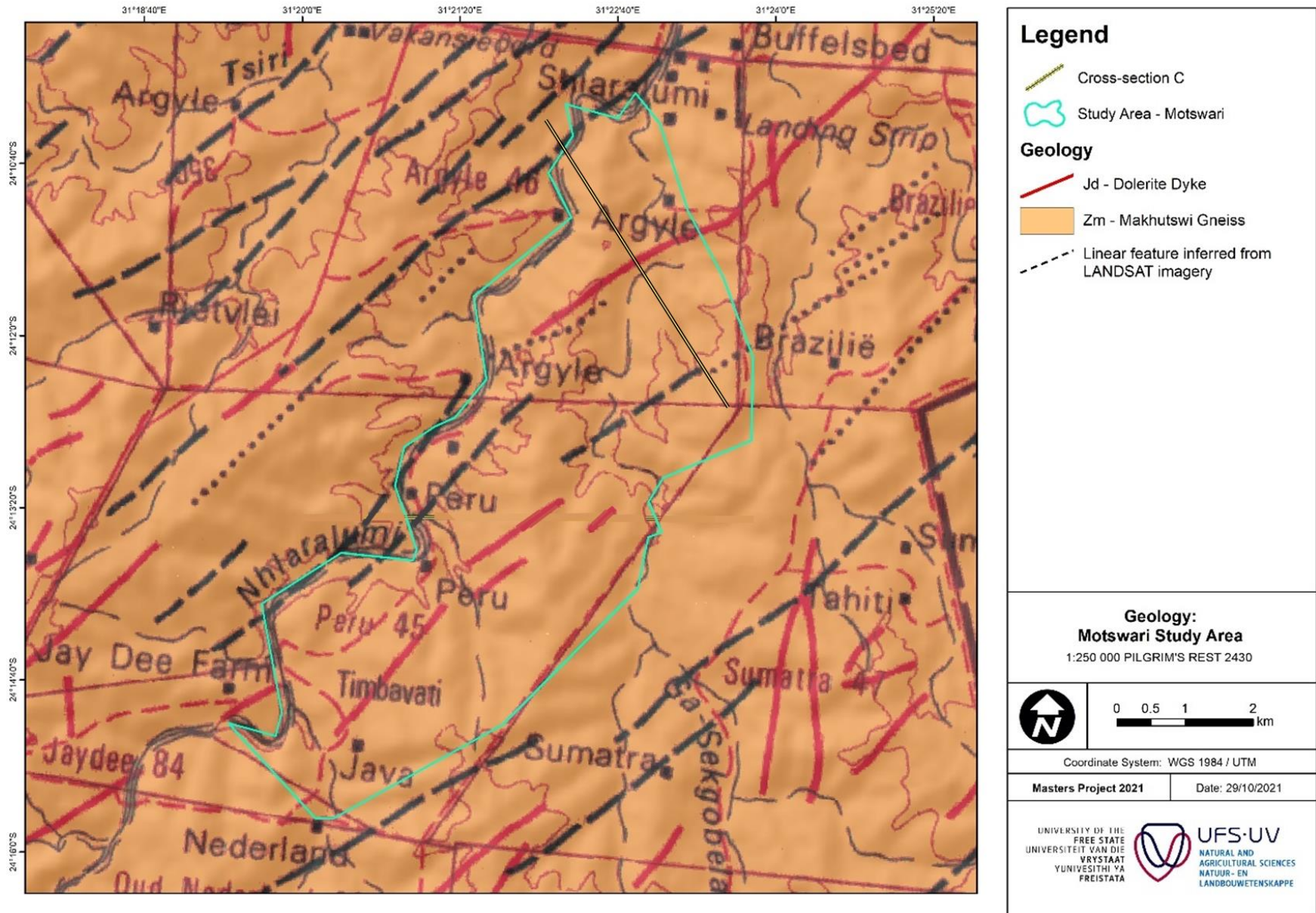


Figure 25 – Geology Map (1:250 000 Pilgrims Rest 2430) of Motswari Study Area.

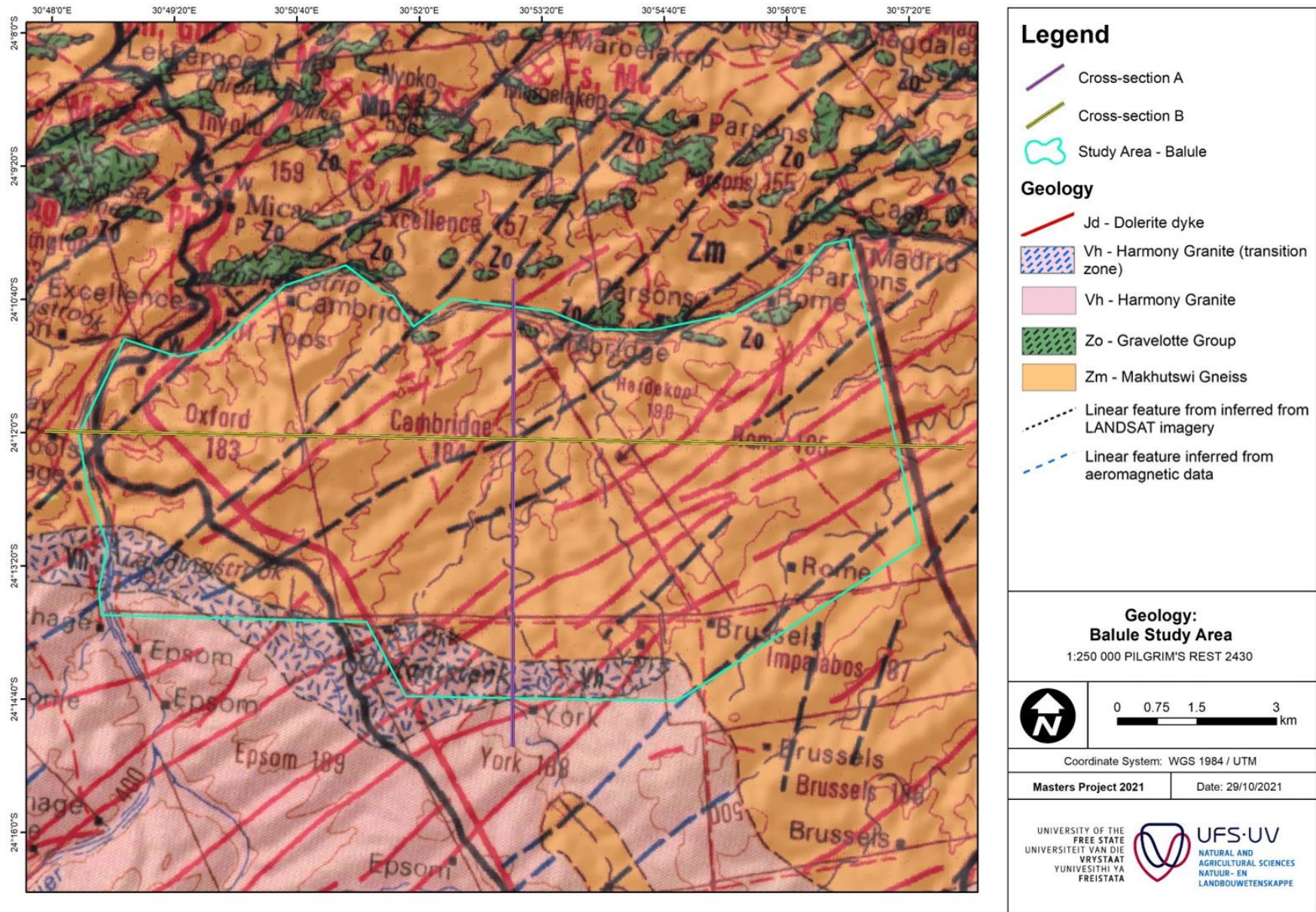


Figure 26 – Geology Map (1:250 000 Pilgrims Rest 2430) of Balule Study Area.

CHAPTER 4: METHODS AND MATERIALS

4.1 Introduction

The study made use of available existing information within the area and region. The study also involved a combination of field work and a review of available literature on the topic. Field work was conducted in accordance with known standards and best practices. Field work that was completed included; detailed hydrocensus, geological mapping, chemical sampling of groundwater and surface water and near-surface geophysical surveys.

4.2 Desktop Study and Hydrocensus

A desktop study was part of the initial phase of the study, which included an examination and overview of the following information to gather an understanding of the groundwater system before having to enter the field. The following information was queried and sourced.

- National Groundwater Archive (NGA).
- Southern African Development Community (SADC) Groundwater Information Portal.
- Water Authorisation and Registration Management System (WARMS).
- 1:250,000 geological map and lineaments map provided by the Council for Geoscience (CGS).
- South African Airborne Magnetic data (CGS).
- Climatic data for the region.
- Previous hydrogeological and geological reports and literature.

Two areas of interest were identified for further study to investigate the potential for MAR, these two areas were shown in Figure 17 and Figure 18.

4.3 Geophysics

The two study areas of interest were reviewed based on their geological and hydrogeological settings. The review of the study areas focused on determining which geophysical methods were relevant for further interpretation and suited to the study area setting. Some limiting factors posed a challenge to geophysical studies conducted, such as occasional overhead power lines, electric fences or wild animals. The geophysical traverses were then adapted and most often moved or relocated. As most of the study areas were in wild, open areas with little to no infrastructure, it was relatively straightforward to conduct geophysical surveys. Due to limited time in the field and vast areas to cover, two methods were selected for further geophysical studies, the Magnetics method and the Electromagnetic method. The geoelectric methodology (resistivity study) was unable to be done, due to equipment limitations and time in the field, though it is recommended to be used for future studies, particularly for the siting of recharge and monitoring boreholes.

4.3.1 Magnetism method

The Magnetism method was carried out using an “Overhauser Magnetometer” meter, which is an individual one-man system that is attached to a person and allows continuous measurements of magnetic susceptibility at a point in space. During a magnetic survey, small localised anomalies are observed in the earth’s magnetic field, this can then be measured. Anomalies are identified by changes in the magnetic susceptibility of different rock types and relate to the concentration of ferromagnetic minerals within a rock. Sedimentary rocks have a low magnetic susceptibility, whilst intrusive magnetic rocks such as dolerite have a higher magnetic susceptibility (Telford et al., 1990). Magnetic methods are used to delineate the presence and orientation of dolerite dykes within the host rock. It is an effective method for associated groundwater targets that can control the hydrogeological processes within the subsurface.

Magnetometers are instruments that are used for measuring a magnetic field, by virtue of their sensitivity and range, they can measure both the changes in the magnetic field between two rocks and also the prominent anomaly that will be observed with a magnetic body such as a dolerite dyke (Roux, 1980). Magnetic methods are completed to delineate magnetic dykes which often provide a barrier and therefore zones for the accumulation of groundwater. Magnetic measurements are measured in the unit of nanotesla (nT). The Magnetism data was then overlaid with aerial imagery and the geological map to identify the dipping direction and dip of the dolerite dykes. An example of how magnetism data can be used is shown in Figure 27.

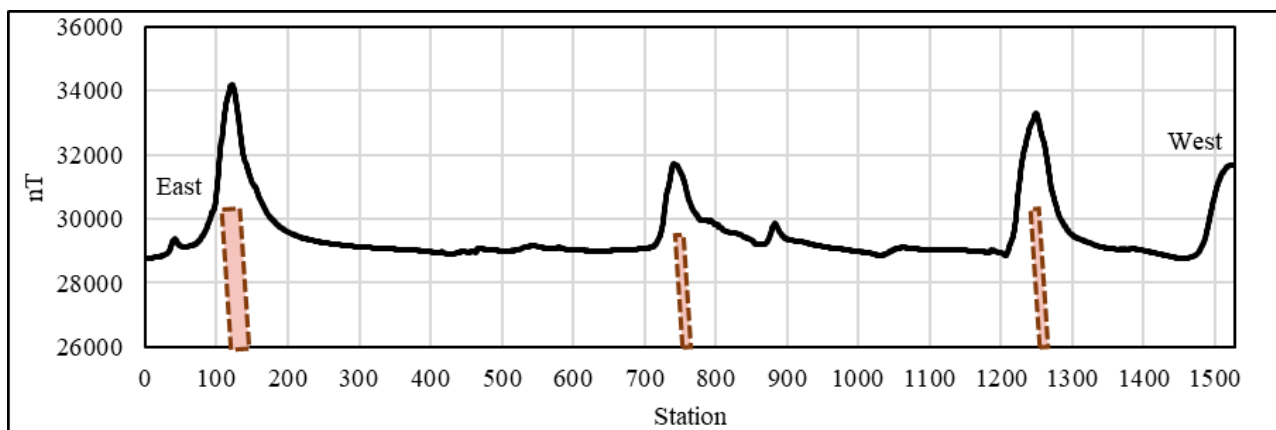


Figure 27 – Example of Magnetism anomaly and possible dyke intrusion dipping west.

4.3.2 Electromagnetic method

The Electromagnetic (EM) method was conducted using a “Geonics EM34-3” meter, which is a two-man portable system that measures the subsurface conductivity. The system is a medium-speed data acquisition system that can be used to gather subsurface conductivity data for the further understanding of a system. The Geonics system transmits an alternating EM wave with a known frequency into the subsurface using a “sender” coil. This varying magnetic component of the EM wave induces measurable electrical current flow in the subsurface area. An example of this is a weathered or fractured dolerite dyke contact that has intruded into the host bedrock, thereafter becoming saturated with groundwater and groundwater flow. The induced electrical current is then associated with its magnetic field, this can be measured with the “receiver” coil, in the presence of the primary magnetic field. The ratio between the secondary to the primary magnetic field is then

used to calculate the apparent subsurface conductivity. The subsurface conductivity measured has a direct correlation with formation porosity and groundwater salinity; for example, if the porosity of the formation or groundwater salinity increases, this will be shown as a higher subsurface conductivity measurement (Telford et al., 1990). EM measurements are measured in the unit of mS/m, for both a Vertical Dipole (deeper measurements) and Horizontal Dipole (shallower, near-surface measurements). An example of how EM data can be used for subsurface conditions is shown in Figure 28.

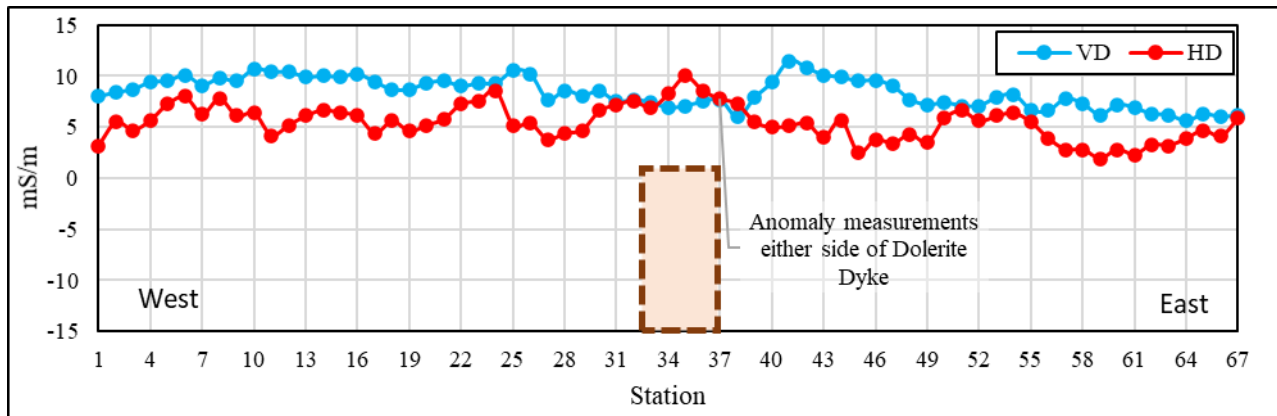


Figure 28 – Example of EM anomalies used to identify areas of higher or lower conductivity and relate to weathered or fractured zones within dolerite dyke intrusions, Horizontal Dipole (HD) is shown in red and the Vertical Dipole (VD) is shown in blue.

4.4 Geochemistry

Geochemistry is an important factor in developing groundwater for water supply, in regards to both suitability and sustainability. Geochemistry is an observable result of interaction between rainfall recharge and the aquifer systems. Various water types can result from interactions between rainfall, soil and host rock, speed of recharge can also affect the groundwater chemistry type. The chemical composition of groundwater and surface water can be used to determine a groundwater system's recharge source and establish the various aquifer units and their associated hydro-facies, that may be present in the study area. In the study, different approaches were taken to applying a geochemistry database, as both spatial geochemistry as well as time-series data has been collected, both graphical and statistical methods have been applied.

4.4.1 Sampling Method

Groundwater and surface water samples were collected either through the use of a plastic bailer (surface water) or a selective-depth bailer (groundwater). Where possible, the pump that was installed was switched on and allowed the groundwater system to purge until parameters stabilised, followed by collecting a sample. Sample parameters were selected according to DWAF (1996) water quality guidelines for domestic use as well as some additional parameters. All concentrations were measured in milligrams per litre (mg/L). The ionic balance calculation for all samples returned was within the acceptable threshold of $\pm 10\%$. All sample results were collated into a robust database to suit the requirements of the study.

4.4.2 Data Analysis and Interpretation

Electrical Conductivity (EC) is a measurement of salinity in the water, which is dependent on total ion concentration. Ionic presence in water allows the water body itself to conduct electrical current. Ease and ability of current to conduct in water are referred to as EC, essentially the more saline the water is, the higher EC will be recorded. EC is measured in mS/m. A general assessment of water quality can be done based on EC within the water. The water being used within the study area is being used for irrigation, drinking water, cleaning, refilling of pools and stock water for wildlife. Water samples additionally are compared against DWAF (1996) water quality guidelines for domestic use, except for microbiological parameters, as this was not possible to be completed with the available time frames. After samples were collected, they are submitted to the IGS analytical laboratory in Bloemfontein, Free State.

4.4.3 Graphical Data Interpretation

Within groundwater, several associations can be used to identify or value the water and the manner in which it can be used. A Piper diagram is one tool that can be used to classify water types and determine the water source. Major ionic species in water are sodium, potassium, calcium, magnesium, chloride, carbonate, bicarbonate and sulfate. The bottom left triangle (Figure 29) is composed of three variables and can then be in the association of six different variables by plotting three cations of calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium and potassium ($\text{Na}^+ + \text{K}^+$), these are then expressed as a percentage of total cations in milliequivalents per litre (meq/L), from this a single point is obtained within the triangle. Each apex of the triangles represents 100% concentration of one of the constituents. Similarly, to the bottom left triangle for cations, anionic concentrations are represented by chloride (Cl^-), sulfate (SO_4^{2-}) and carbonate and bicarbonate ($\text{CO}_3^{2-} + \text{HCO}_3^-$) (Piper, 1944).

A water sample is typically comprised of more than one constituent, as such a point from each diagram represents a percentage of each. The diamond-shaped field between the two triangles is used to represent the composition between both cations and anions. Groundwater flow through an aquifer will always interact with the minerals that are within the lithology, as such the groundwater will assume the composition of the host lithology. Hydrochemical facies are a classification of the dominant ionic composition within a water sample. As such there is also a potential of error that can be assumed with this classification, one of which being that the Piper diagram is only a representation of three cations and anions and the diagrams join these to the nearest parameter, overall reducing their effect.

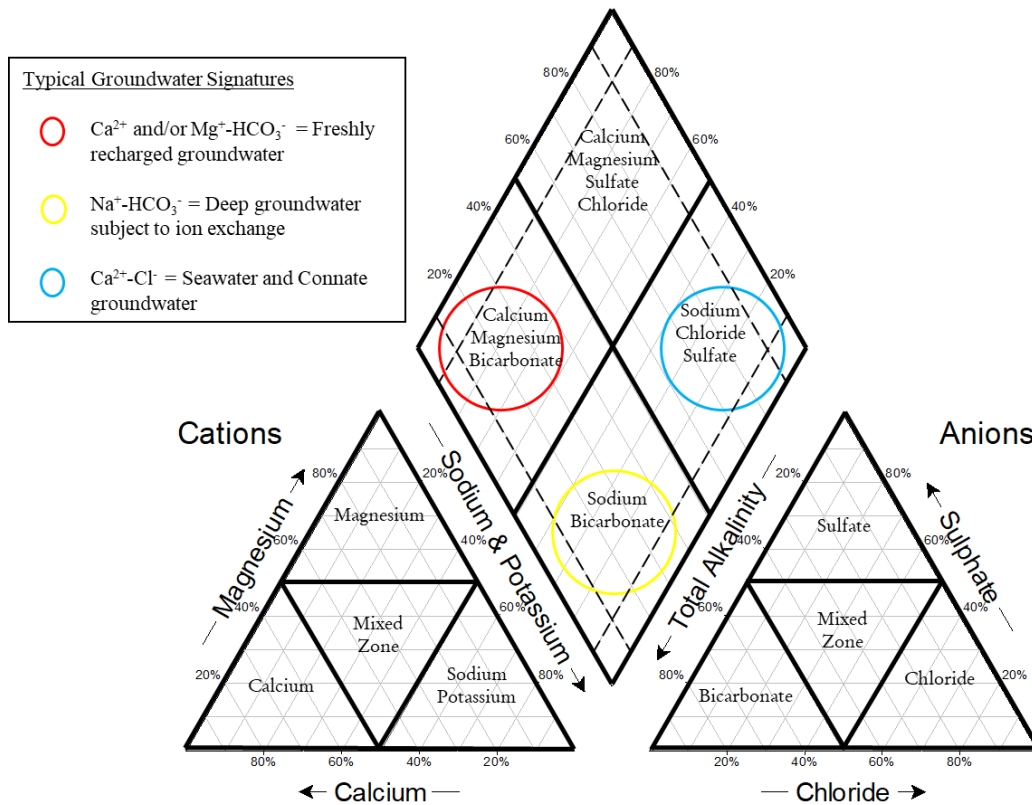


Figure 29 – Piper diagram with groundwater hydrochemical facies and processes responsible for composition (Piper, 1944).

4.5 Recharge Calculation – Chloride Method

In order to calculate volumes and percentages of rainfall recharged within the study areas, the Chloride method was used to determine the annual volume of groundwater recharge within the study areas. Chloride can reasonably be regarded as an inert element within the hydrological cycle and its source is derived from atmospheric deposition (Edmunds and Gaye, 1994). The chloride recharge calculation is shown in Equation 2:

$$R_d = \frac{P(C_p + C_d)}{C_{si}} \quad (2)$$

- | | |
|--|--|
| R_d = Direct Recharge (mm) | P = Long-term mean annual precipitation (mm) |
| C_p = Concentration of Chloride in rainfall (mg/L) | C_d = Concentration of Chloride in dry deposition (mg/L) |
| C_{si} = Average concentration of Chloride in groundwater (mg/L) | |

To determine the volume of groundwater recharged within a study area, R_d is multiplied by surface area within the study area. This is a basic calculation on groundwater recharge and is used as a baseline for determining annual recharge volumes within a study area. To calculate whether this is a sustainable volume of groundwater being recharged, it should be compared to the volume of water abstracted annually. The harmonic mean is used for the chloride methods recharge calculations.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

The majority of results in this dissertation are based on actual field measurements and data obtained from field work, with little raw data having been sourced from other studies and as such the results have a high degree of confidence. This chapter discusses all desktop and field results that were accumulated through the study. Where appropriate, the results have been classed against standards and through graphical and statistical data, discussion has been provided on the results.

5.2 Desktop Study

The results of the desktop study were limited, as the study areas are located within private nature reserves and only NGA data added any value to the study, the remaining data sources identified boreholes outside of the study areas (SADC Groundwater Information Portal and WARMS). There is inadequate knowledge of registering and legal water use for the area. Boreholes in general are often low-yielding and as such no efforts were made to license the groundwater by the users.

5.2.1 NGA Database

The results based on the desktop search of available boreholes were limited, the majority of the sites were last visited by governing bodies in the late 1990's. Since then, the boreholes and sites have not been maintained and the vegetation has overgrown the area, leading to loss of data, infrastructure and damaged sites. As a result of the limited NGA database search, the actual groundwork hydrocensus data was used for further collection of data, for example, water level measurements and collection of water samples. The full list of available NGA study sites is listed in APPENDIX A – DESKTOP STUDY SITES. Examples of two poorly maintained sites are shown below in Figure 30.



Figure 30 – Field photos of broken cement and borehole casings at two NGA sites.

In total, 72 sites were identified in the desktop search, with the majority of boreholes drilled between 1985 and 1991, the oldest borehole was drilled in late 1945. From engagement with the groundwater users in both study areas, it was communicated that more boreholes are likely to exist in the study

area than those identified. The ground-truth data were used for further assessments and data collection. The average blow yield of the boreholes reported by the NGA is 4.04 L/s, however from understanding the area and discussions with groundwater users, the sustainable yield is often less than the blow yield, which is likely why the boreholes tend to dry up. A summary table on desktop study data is shown in Table 4.

Table 4 – Statistical data summary on NGA for both study areas.

	Depth (mbgl)	Discharge (Blow Yield) (L/s)	Water Level (mbgl)	Water Strike (mbgl)	Casing Depth (mbgl)
Average	46.77	4.04	18.10	38.13	5.23
Maximum	106.00	40.00	50.00	70.00	10.00
Minimum	12.80	0.001	4.57	16.20	1.00
Standard Deviation	20.88	7.07	12.81	16.77	2.84
Median	42.00	1.90	11.88	37.00	6.00
Count	49.00	43.00	31.00	18.00	9.00

The spatial distribution of all the NGA sites per study area is shown in Figure 31 and Figure 32. Only a few of the available NGA data sites could be located although some correlated with nearby hydrocensus boreholes. In some cases, the NGA coordinates were linked to the entrance of a particular game lodge or land parcel. It was common practice for the governing body to associate the boreholes to a land parcel rather than give the exact coordinates of the borehole.

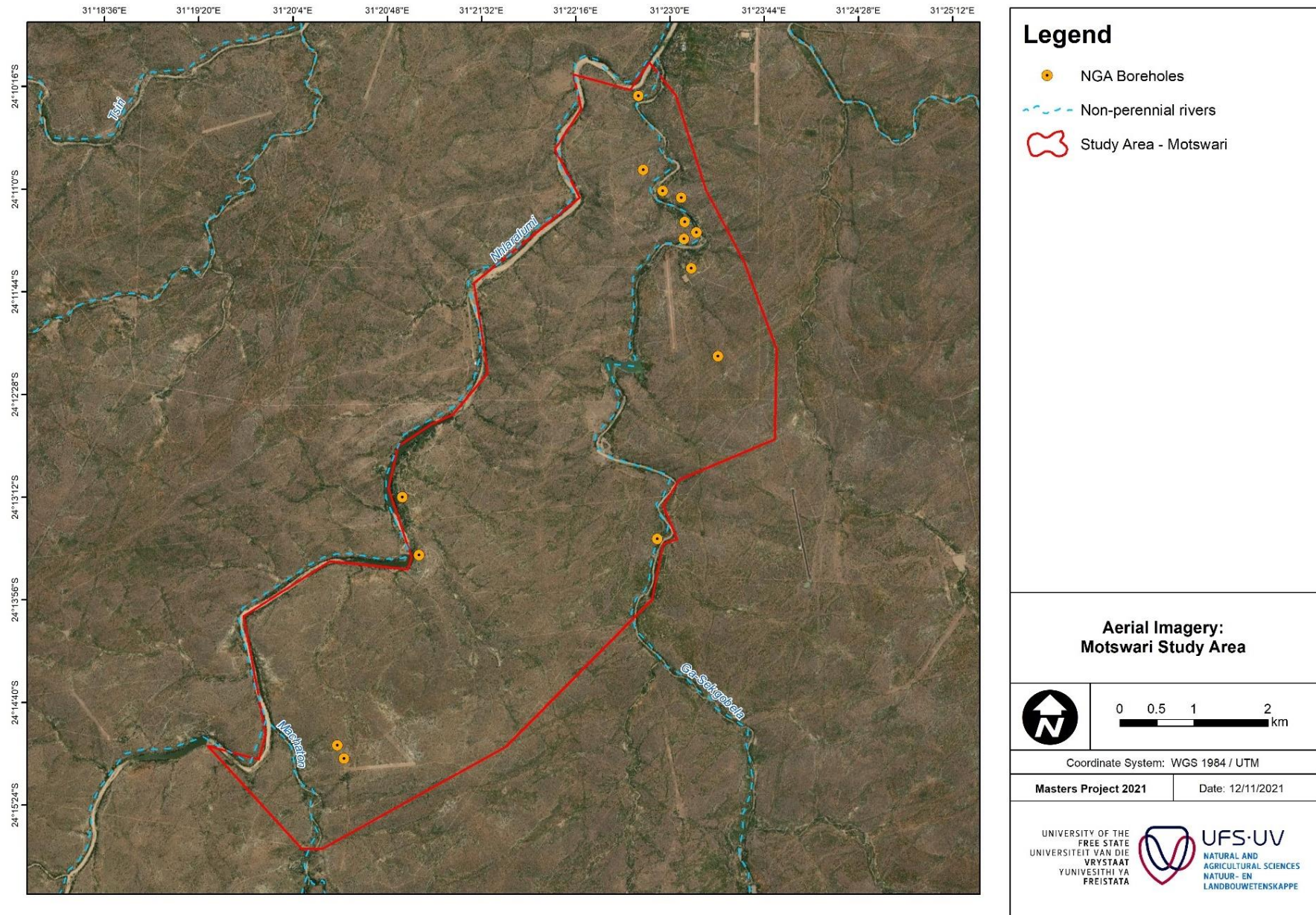


Figure 31 – Spatial distribution of identified NGA sites for the Motswari study area.

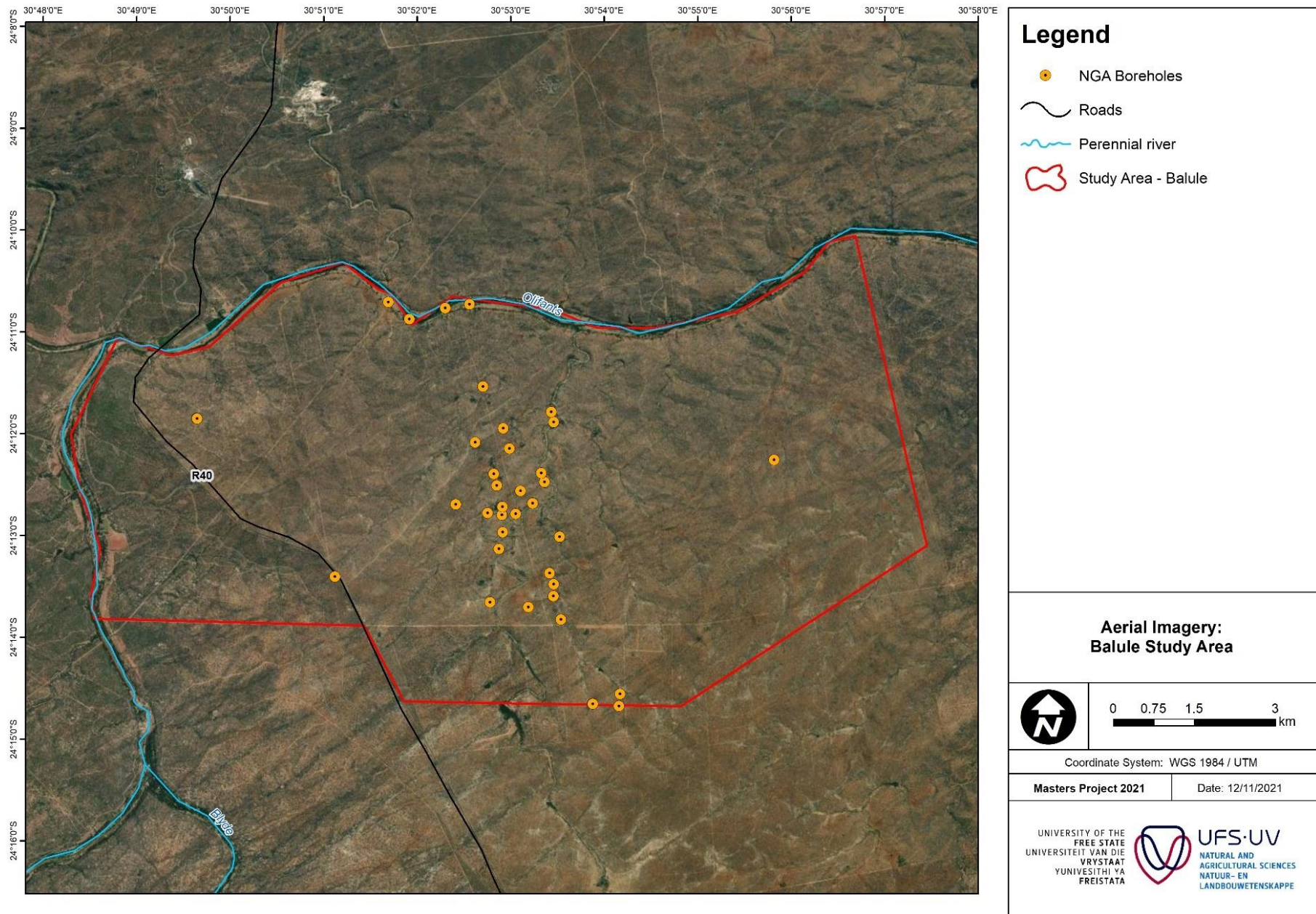


Figure 32 – Spatial distribution of identified NGA sites for the Balule study area.

5.2.2 Hydrogeological Characteristics / Hydraulic Parameters

Aquifer parameters such as hydraulic conductivity, transmissivity and storage are important factors to consider when a MAR scheme is to be implemented. To ensure that the recharge source water will not be lost downgradient and recharge an alternative site or that the source water will be able to enter into the groundwater system, the groundwater flow direction and aquifer transmissivity needs to be determined.

For a prefeasibility study, a general idea on aquifer parameters is important to know whether the water will be lost downgradient or whether the aquifer will accept the source water. Linear structures such as dykes or faults have a strong controlling factor over the success and appealing water chemistry in a borehole, due to increased ability for groundwater flow and shorter residence time, these structures can act as deep and shallow recharge sites (Sarikhani et al., 2014). The general strike direction of the dolerite dykes is in a North-East to South-West direction. Dykes should not be regarded as geologically different from the host rock that it intruded, rather it should be considered part of the same unit. Water-bearing characteristics must be viewed as neither a barrier nor a conduit, rather variable along their strike (Vegter, 2003).

For groundwater utilisation, groundwater users must not only consider the orientation of these dykes, but also the thickness (Petzer, 2009). Pumping tests in Botswana have shown that dolerite dykes thicker than 10 m's serve as groundwater barrier flows, although dykes that are narrower, tend to be more permeable due to the cooling joints and fractures that developed within them (Bromley et al., 1994). Other factors that can affect hydraulic conductivity are geometry, grain size and the degree of weathering.

Faulting within the Makhutswi Gneiss and at the contact of different lithological units are other areas where one can expect preferential flow pathways. From the specialist groundwater report of the Phalaborwa filling station (WSM Leshika Consulting (Pty) Ltd, 2020), a groundwater flow model was developed based on borehole yields in the surrounding areas of the Makhutswi Gneiss. The model that was developed, assigned an average transmissivity of $0.6 \text{ m}^2/\text{d}$ by multiplying the average blow yield of 0.1 L/s by six. This assigned value was found to be too low as water levels would rise above the surface within the model (WSM Leshika Consulting (Pty) Ltd, 2020). Based on topography and groundwater levels within the study areas, groundwater will follow the topography and flow downgradient. additionally, boreholes located at the bottom of a valley and flat areas have higher yields when compared to those at higher elevations (Holland, 2012).

Holland (2012) investigated the variability in transmissivity in hard-rock aquifers as a reliable source for rural water supply, a summary of this work is shown in Table 5. Higher transmissivity rates were found within the alluvium material, followed by boreholes that intercept dolerite and dolerite dykes. This work was found to be particularly useful in determining whether the source water can enter the groundwater system. Crystalline lithologies typically have low porosity (Holland, 2012) and it will be important for MAR sites to be selected carefully based on the best potential for success. Recharge boreholes must be sited into either the alluvium, dolerite dykes or water-bearing lineaments.

Table 5 – Summarised transmissivity (m²/day) values for the study area, in descending order of transmissivity and statistical average for Lowveld region (Holland, 2012).

Description	Average
Alluvium	55.7
Dolerite	29.1
Boreholes that intercept with dykes	23.6
Archean Gneiss	21.0
boreholes within 50-150 m of an inferred dyke	18.9
Granitic intrusive	6.5
Statistical average of borehole transmissivity within the study area (Lowveld)	25.19

5.2.3 Aerial Magnetics Interpretation

Further to the desktop study was a review of available South African airborne magnetic data, provided by the CGS (Council of Geosciences), of the study areas. The airborne magnetics data is shown in Figure 33.

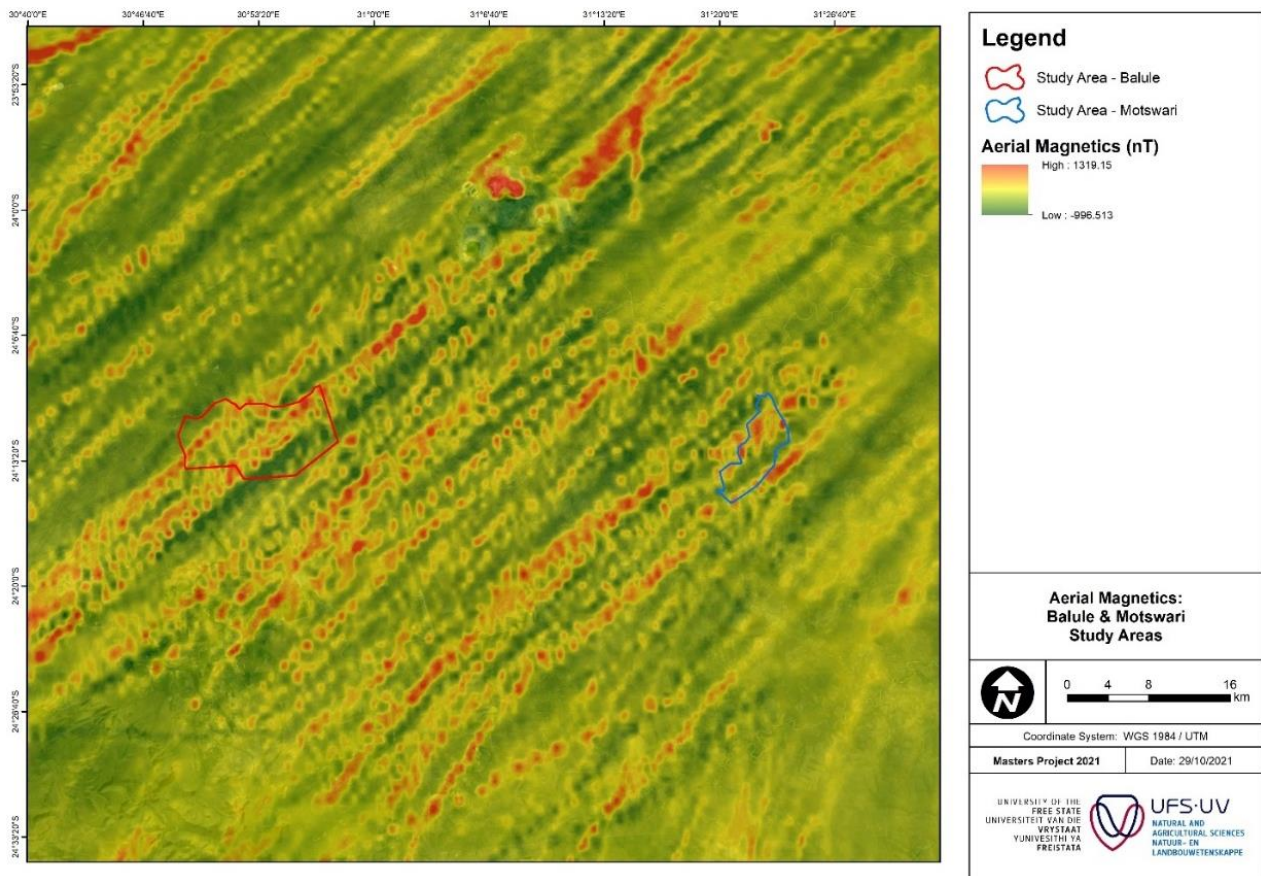


Figure 33 – Aerial Magnetics imagery of study areas.

The overlaying aerial magnetics data shows magnetic anomalies that trend North-East to South-West. This is similar to the dolerite dyke swarm trending direction from North-East to the South-West, indicated in Figure 25 and Figure 26. These aerial magnetics anomalies were investigated on a smaller scale using Magnetic and EM methods to identify potential future drilling positions for recharge boreholes and abstraction boreholes. The areas of higher magnetics susceptibility are shown on the

map in Orange / red colours, while areas with low susceptibility are green. The trending lineaments correlate to the dolerite dyke swarm structures of the geological maps, that intruded the host rock lithology. According to Holland (2012), the dyke swarms can be useful paleo-stress indicators of the principal stress direction at the time of intrusion.

5.3 Hydrocensus

From mid-2019 to April 2021, the hydrocensus database was continually developed and new boreholes were included into a network of available groundwater users and potential monitoring points. Monitoring points were then selected if no pumping infrastructure was installed within the borehole and if the borehole was easily accessible, these monitoring sites can be seen in Figure 34 for Motswari and Figure 35 for Balule. Monitoring is important to determine the seasonal variation in groundwater levels and identify how seasonal rainfall had an impact on associated groundwater levels. A table outlining all identified hydrocensus points is shown in Table 6. 20% of the boreholes were identified within the Motswari study area, more boreholes are located within Balule, which is much larger and has more game lodges. However, not all stakeholders and groundwater users were willing to participate in the hydrocensus. The spatial distribution of these hydrocensus sites can be viewed spatially in Figure 31 and Figure 32.

Table 6 – Hydrocensus results of Motswari and Balule.

Site Name	Co-ordinates (S, E)	Elevation (mamsl)	Borehole Depth (mbgl)	Field comments and groundwater user observations
Motswari Private Game Reserve – Hydrocensus				
M1	-24.18263, 31.39069	334	50	Production borehole, large seasonal chemistry variation.
M2	-24.18754, 31.38831	339	62	Reserve production borehole for lodge water supply.
M3	-24.17342, 31.37120	325	56	Production borehole within ~50 m of the river course.
M4	-24.17372, 31.37110	325	22	Decommissioned borehole, adjacent to M3, with the pump still installed.
M5	-24.17367, 31.37106	324	6	Collapsed borehole at approximate depth of 8 m.
M6	-24.19753, 31.39509	362	62	Monitoring borehole, adjacent to natural dam.
M7	-24.23673, 31.36690	374	-	Watering hole borehole, used for stock water.
M8	-24.24295, 31.33930	354	31	Unequipped monitoring borehole, within 100 m of a watercourse.
M9	-24.24957, 31.34365	359	20	Production supply borehole.
Balule Olifants West Nature Reserve – Hydrocensus				
Ba01	-24.15842, 30.94247	357	13	Production borehole within 80 m of the Olifants River.
Ba02	-24.21352, 30.90210	419	-	Production borehole, could not get access. Borehole well covered to protect from animals.

Site Name	Co-ordinates (S, E)	Elevation (mamsl)	Borehole Depth (mbgl)	Field comments and groundwater user observations
Ba03	-24.21340, 30.90008	418	40	Production borehole.
Ba04	-24.20722, 30.89066	407	35	Production borehole on a small flood plain within a river channel.
Ba05	-24.20593, 30.88913	411	-	Production borehole.
Ba06	-24.20797, 30.89907	411	18	Good borehole that was supposedly strong and high yielding, used for lodge water supply.
Ba07	-24.20639, 30.89708	406	80	Excellent monitoring borehole.
Ba08	-24.20491, 30.89342	403	-	The borehole collapsed and a beehive formed within the casing.
Ba09	-24.22334, 30.86449	460	86	Excellent monitoring borehole and welded partially closed.
Ba10	-24.21461, 30.81812	385	-	Sealed production borehole, supposedly strong and ~100 m from the Olifants River.
Ba11	-24.22770, 30.86850	462	166	Deep monitoring borehole.
Ba12	-24.22445, 30.86340	467	54	Excellent monitoring borehole and welded partially closed.
Ba13	-24.19004, 30.83752	405	37	Production borehole.
Ba14	-24.18976, 30.84357	411	36	Solar borehole pump serves as a good potential borehole for seasonal monitoring.
Ba15	-24.19796, 30.83933	439	59	Excellent monitoring borehole and covered by a lid to prevent access.
Ba16	-24.20357, 30.84422	464	87	Excellent monitoring borehole and covered by a lid to prevent access.
Ba17	-24.19982, 30.85396	499	110	Very deep borehole with reported low yields.
Ba18	-24.19982, 30.85396	363	175	Deep borehole, within 200 m of the Olifants River. Production borehole.
Ba19	-24.20524, 30.95574	435	-	Unknown borehole depth, good monitoring borehole.
Ba20	-24.22771, 30.92159	463	-	Historical production borehole that is decommissioned.
Ba21	-24.21618, 30.89303	425	19	Production borehole.
Ba22	-24.18900, 30.88939	406	40	Production borehole, hidden under the ground by approximately 40 cm.
Ba23	-24.17989, 30.89966	374	-	Production borehole within 40 m of the river course. Terrible borehole construction.
Ba24	-24.18006, 30.90016	371	59	Production borehole within 10 m of river course.
Ba25	-24.17957, 30.89921	378	58	Production borehole within 60 m of river course.
Ba26	-24.17369, 30.87823	369	-	Production borehole.

Site Name	Co-ordinates (S, E)	Elevation (mamsl)	Borehole Depth (mbgl)	Field comments and groundwater user observations
Ba27	-24.17666, 30.87317	397	62	Production borehole.
Ba28	-24.17489, 30.84682	395	43	Production borehole that ran dry.
Ba29	-24.19975, 30.89571	398	52	Production borehole.
Ba30	-24.19985, 30.89504	401	42	Production borehole.
Ba31	-24.18844, 30.87788	415	42	Decommissioned collapsed borehole.
Ba32	-24.23288, 30.91665	466	-	Production borehole.
Ba33	-24.22768, 30.91513	477	-	Production borehole.
Ba101	-24.20798, 30.89126	407	-	Excellent monitoring borehole within 10 m of a non-perennial river channel.
Ba201	-24.21855, 30.81951	382	-	Production borehole thought to be contaminated from nearby French drainage.
Ba202	-24.22771, 30.81878	383	60	Production borehole used for game lodge water supply.
Ba301	-24.17449, 30.84739	390	-	Replaced production borehole to Ba28 after it collapsed due to poor management.
Spring	-24.18333, 30.89862	376	-	Seasonal spring that supposedly flows stronger in winter, nearby dyke contact is prominent.

The hydrocensus phase of the groundwater study was successful in that a wide range of groundwater users and borehole sites were identified; water samples were collected at sample locations where possible and water levels were measured when possible. A summary of field parameters is shown in Table 7 and long-term (2½ years) monitoring data from selected monitoring boreholes are shown in Figure 39. No groundwater users were aware of their borehole yields as none of the boreholes had been yield tested, nor were there available drilling certificate logs. One spring was identified in the hydrocensus and was not being used for water supply.

Table 7 – Summary of field parameters across both study sites.

	Borehole Depth (mbgl)	WL (mbgl)
Average	55.69	17.83
Maximum	175.00	89.18
Minimum	6.00	4.30
Standard Deviation	37.22	16.20
Median	51.00	13.20
Count	32.00	37.00

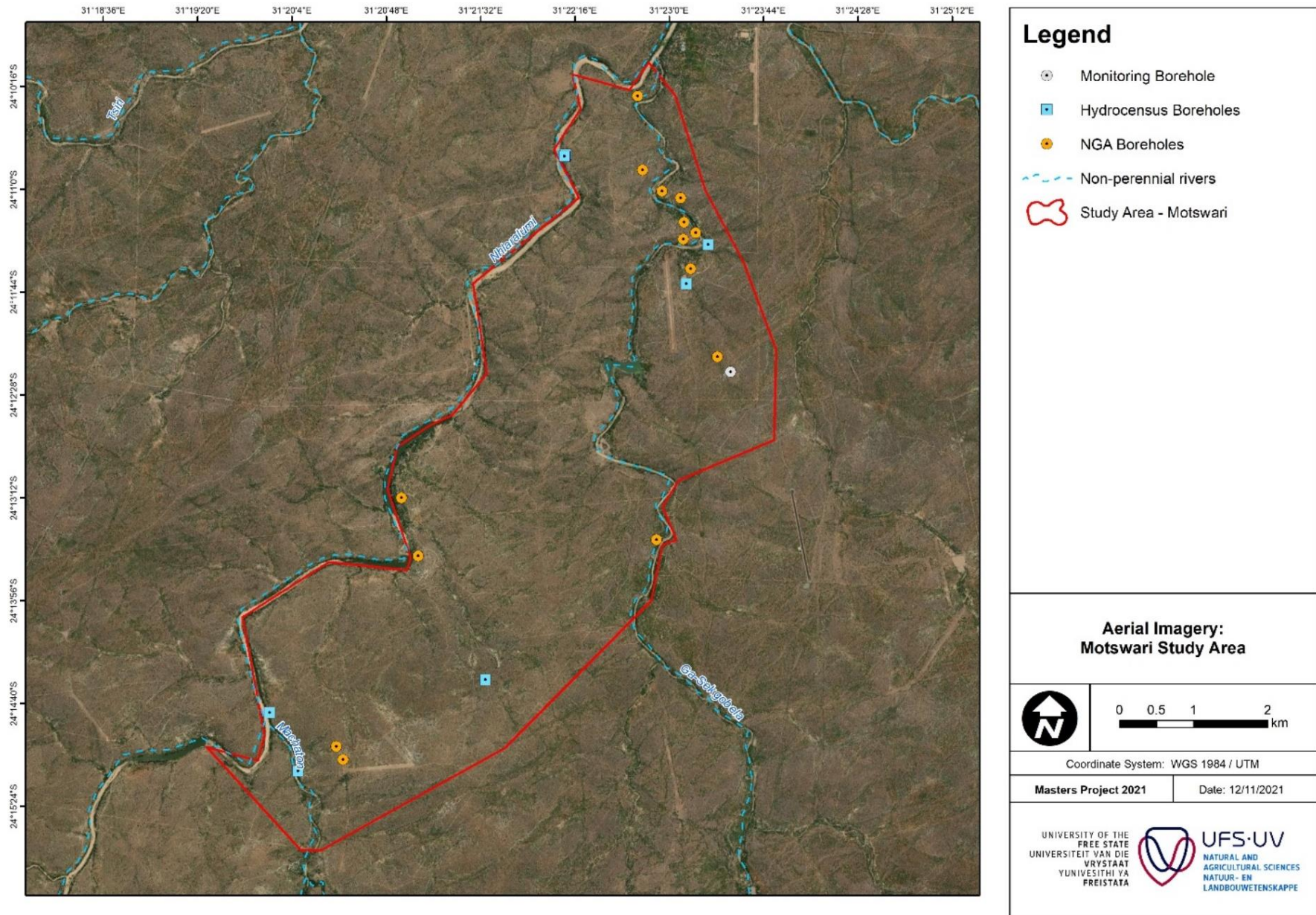


Figure 34 – Spatial distribution of identified NGA and hydrocensus sites for the Motswari study area.

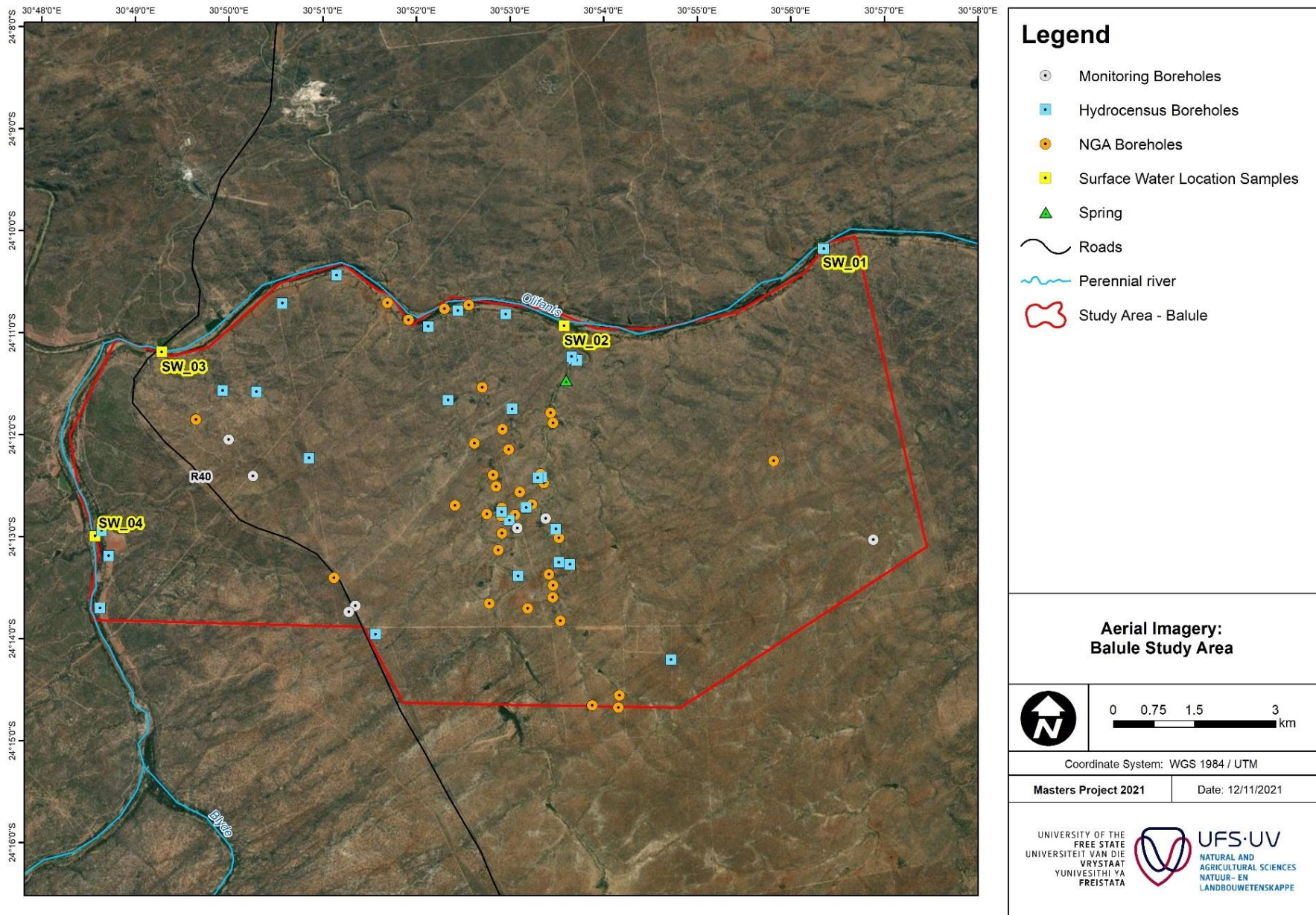


Figure 35 – Spatial distribution of identified NGA, hydrocensus and Olifants river surface sample sites for the Balule study area.

5.3.1 Water Levels

Groundwater levels were measured at 37 boreholes since mid-2019 at varying intervals. At some boreholes, only a single measurement could be recorded, while at others a dataset was developed of frequent water level measurements. The water levels were converted to mamsl and used to generate groundwater level maps (Figure 37 and Figure 38) per study area to determine groundwater flow directions. Not all boreholes were used for this interpolation as at some sites, the water level could not be measured due to a pump's baseplate or a blocked borehole.

Groundwater flow direction is generally from higher towards lower elevations and follows a similar path to drainage directions, which will also flow from a higher elevation to a lower elevation. This is confirmed and illustrated in Figure 36, indicating a good correlation between water level (mamsl) and surface elevation. The correlation between the two sites is 85% for both sites. The groundwater level flow map (Figure 37) for Motswari indicates that the flow direction is to the north. Similarly, for Balule, as shown in Figure 38, the groundwater flow direction is to the north and towards the Olifants River, suggesting that the river is groundwater-fed.

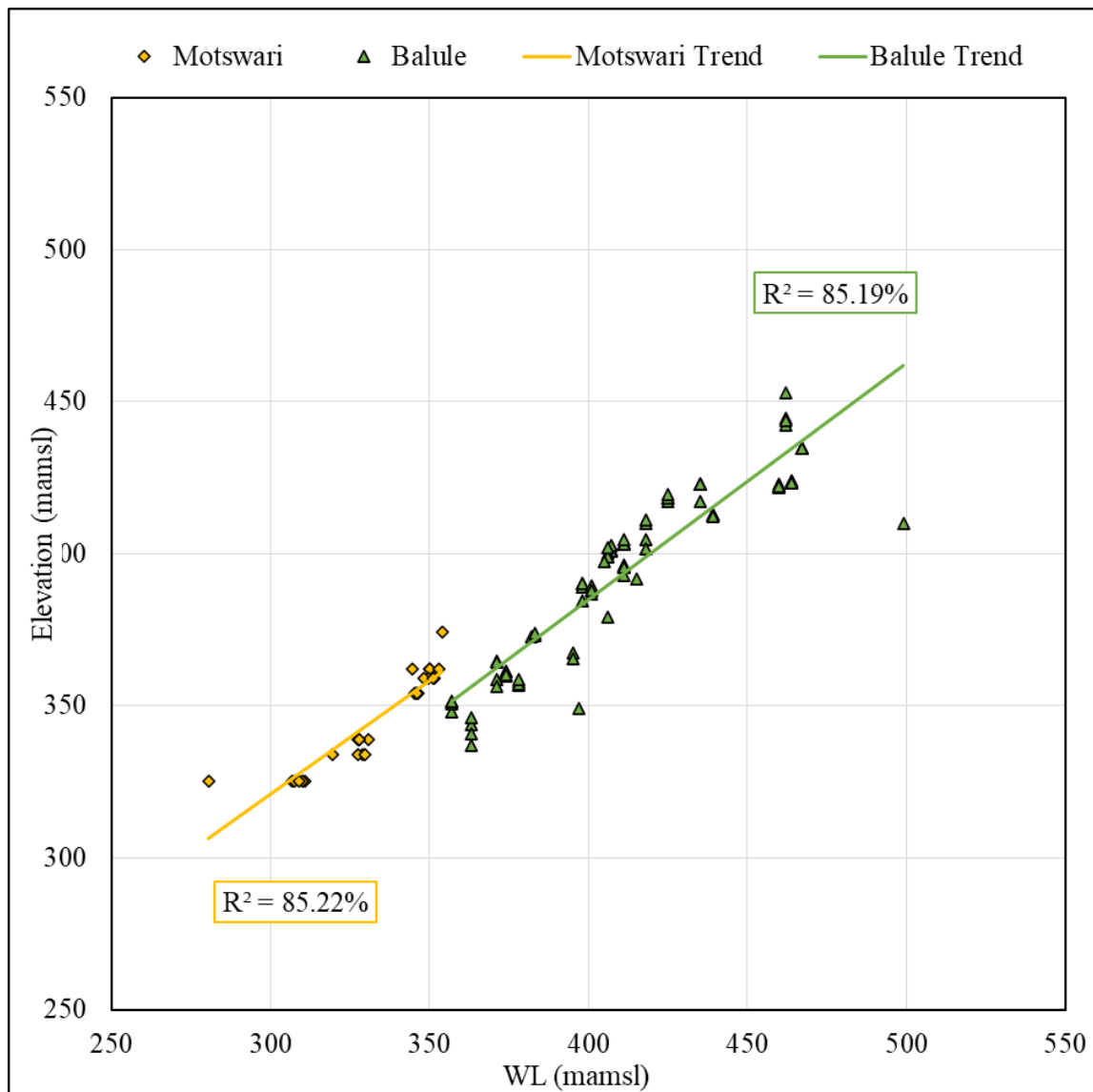


Figure 36 – Groundwater correlation between elevation and hydraulic head (mamsl).

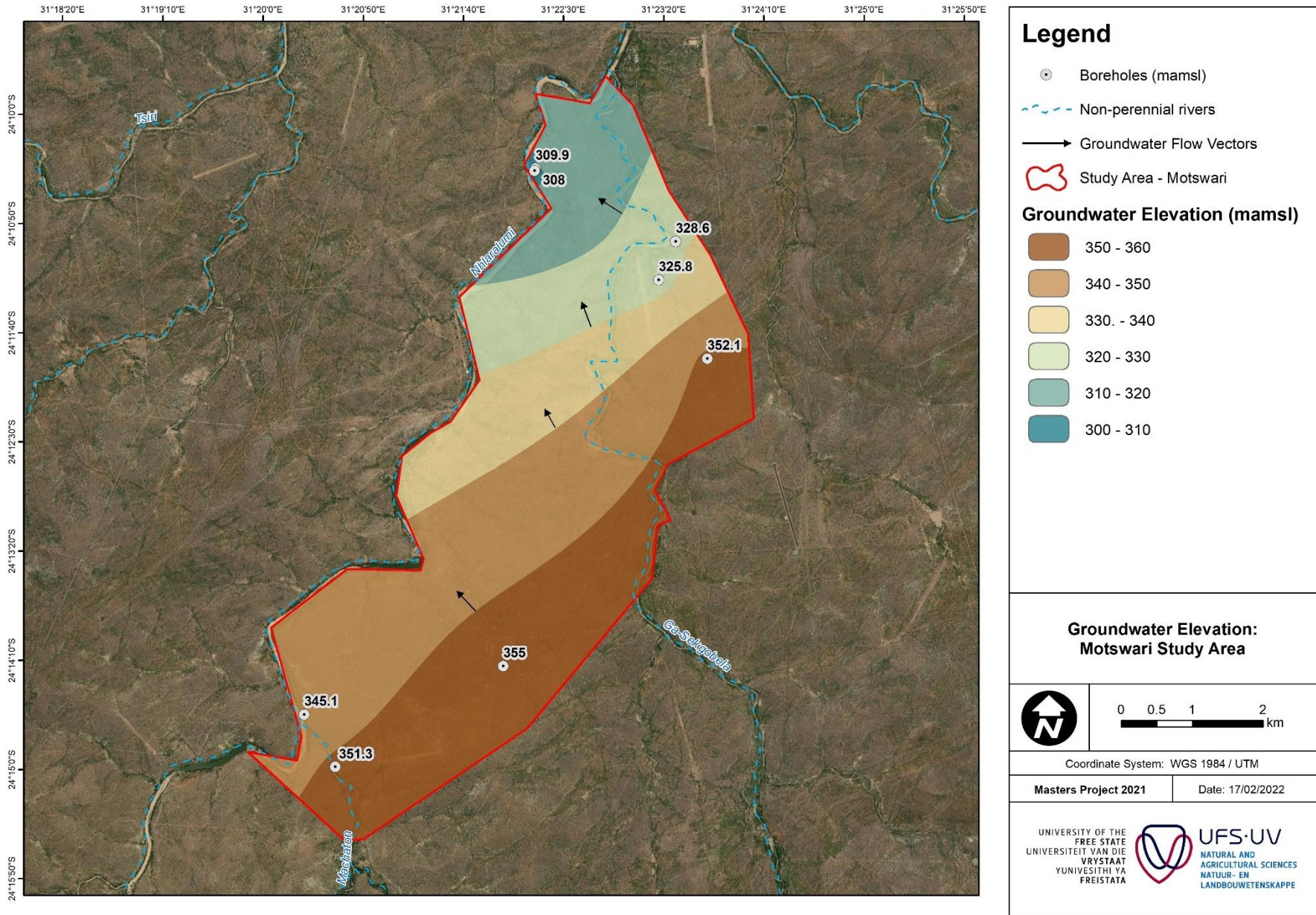


Figure 37 – Groundwater elevation map indicating flow directions for Motswari study area.

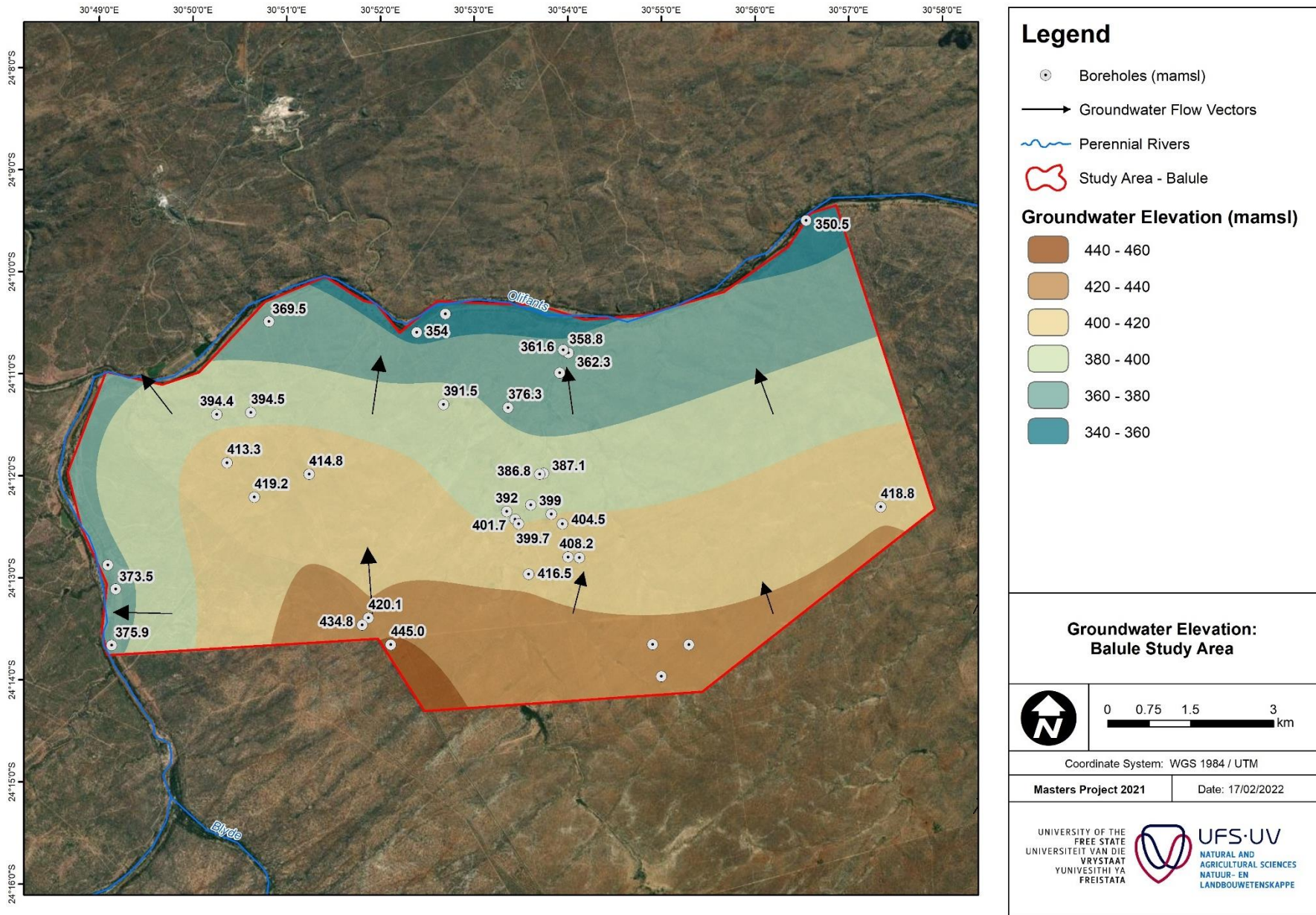


Figure 38 – Groundwater elevation map indication flow directions for Balule study area.

Frequent water level monitoring measurements are valuable for identifying potential trends, as can be seen from the long-term monitoring data in Figure 39. Water level monitoring initially took place every 4 – 6 months, this was increased to weekly from August 2021 at selected sites, after the author equipped the groundwater users with their own monitoring equipment in the form of a portable dipmeter (50 m).

Selected boreholes have been compared against monthly rainfall to indicate the dropping water level trend since mid-2019. These boreholes indicate the regional groundwater level fluctuation as they are not impacted by the pumping regimes of a production borehole. Figure 39 shows monitoring borehole water levels versus rainfall since the start of monitoring in 2019. The average water level drop is approximately 2.14 meters across these boreholes. This water level drop suggests that the aquifer is dewatering as a result of reduced rainfall recharge or increased water usage from the aquifer. The cause for water level drop may be due to game lodges drilling more boreholes, poor water management practices, reduced long-term rainfall recharge and over-abstraction of the resource.

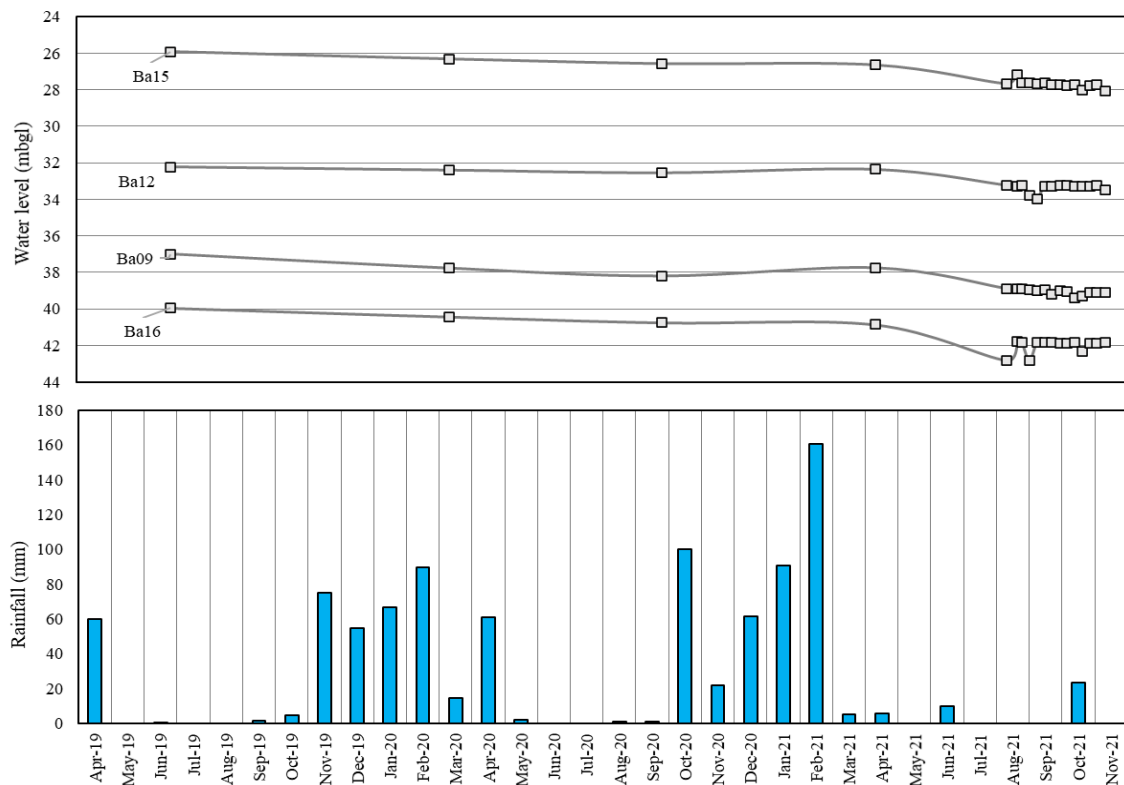


Figure 39 – Groundwater levels versus monthly rainfall of dedicated monitoring boreholes.

Many boreholes that were near to surface water features, responded well to localised rainfall. Such as boreholes near drainage channels, the Olifants River and small dams. Borehole M6, in particular, displayed this well.

Borehole M6 (Motswari study area) indicate an overall recovering water level of 8.35 m over two years (Figure 40). The rising (becoming shallower) water level was due to the nearby watering hole filling up with runoff stormwater in the rainy season and lasting through winter till the following rainfall season and recharging even further as the watering hole refilled with additional runoff water. Constant monitoring at this site (M6) ended in April 2021, due to the landowners no longer being

able to monitor the borehole independently. The distance between M6 and the nearby watering hole is 56 m, shown visually in Figure 41.

Groundwater level monitoring data is presented in APPENDIX B – WATER LEVEL MONITORING DATA.

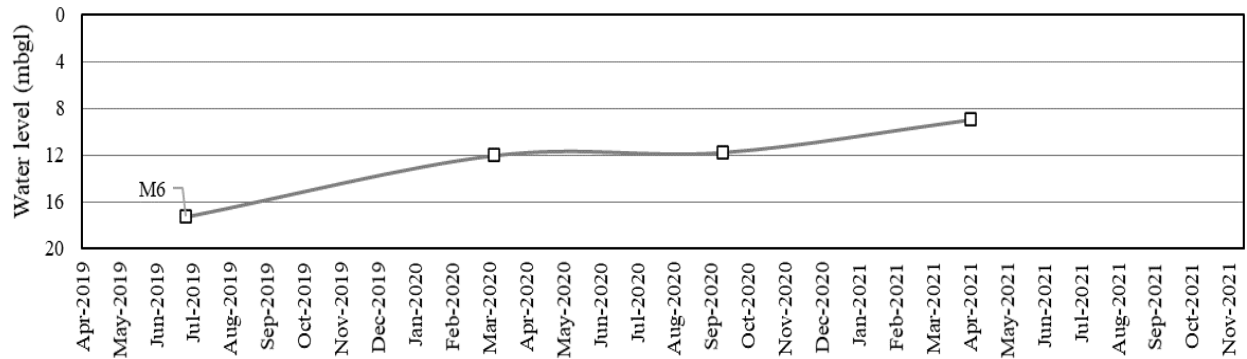


Figure 40 – Water level graph of borehole M6 (Motswari), indicating an extended recovering water level through winter 2020 and recovering closer to the surface in summer.

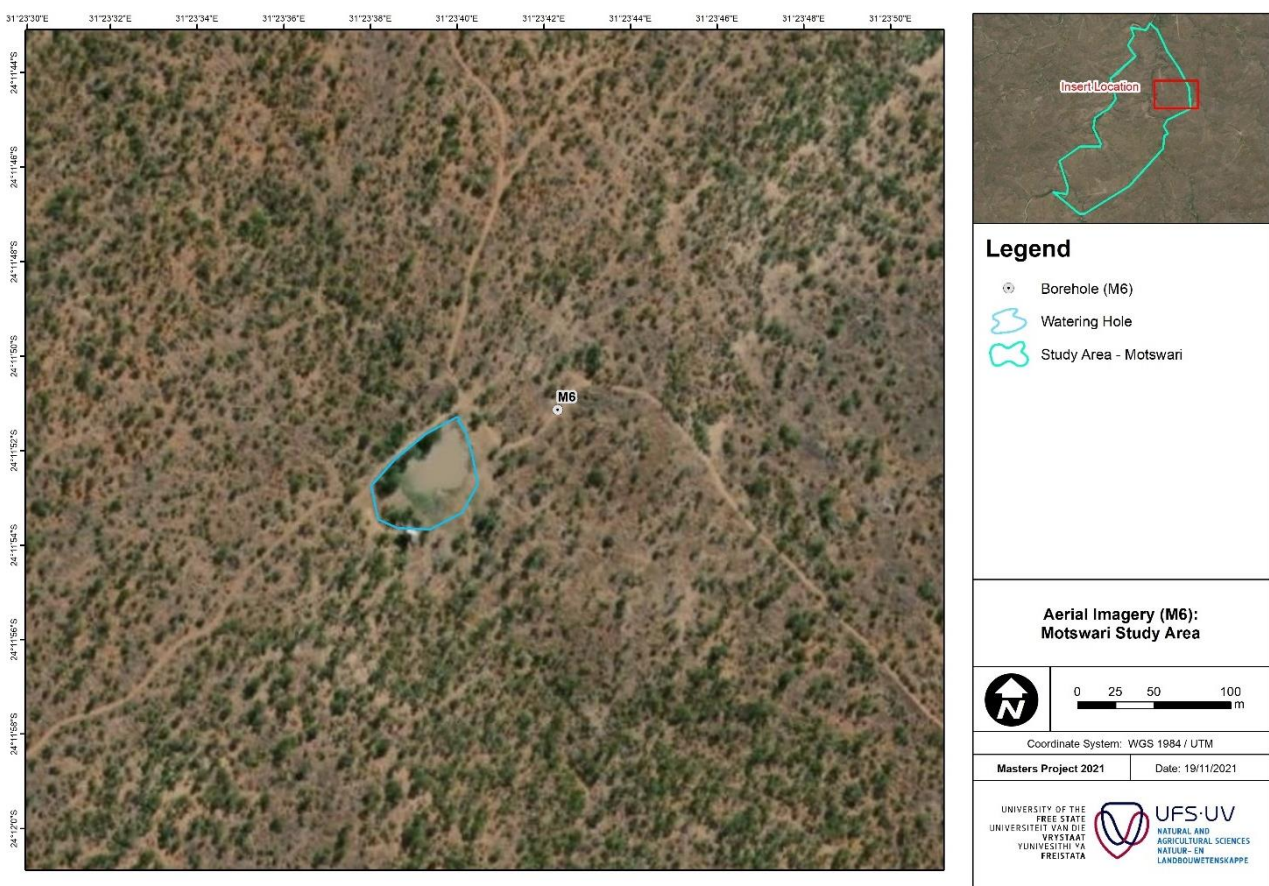


Figure 41 – Borehole M6’s location in comparison to a nearby watering hole that refills over summer from rainfall-runoff.

5.3.2 Water Quality

5.3.2.1 Hydrogeochemistry of study areas

Using available chemistry data from multiple site visits, the overall water quality within Motswari displayed a mixture of all water types. Balule also displayed a combination of all water types, except for a Sodium Bicarbonate water type at Ba11 and Ba09. The Piper diagrams showing all groundwater samples are shown in Figure 42 and Figure 43.

A full setlist of the chemistry data is available in APPENDIX C – LABORATORY CHEMISTRY RESULTS (IGS). The results have been compared against DWAF (1998) guidelines (Table 8) as some groundwater users utilise the water for consumption and extensively within lodges and camps.

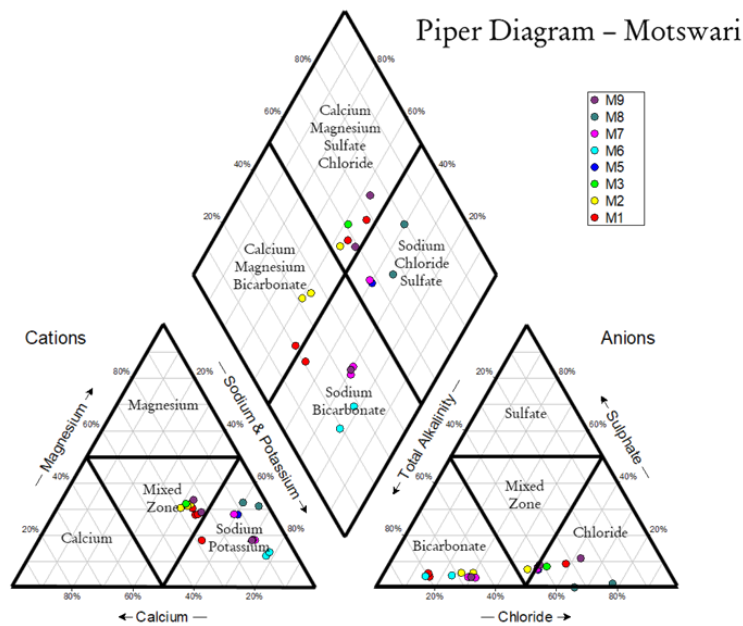


Figure 42 – Motswari Piper Diagram.

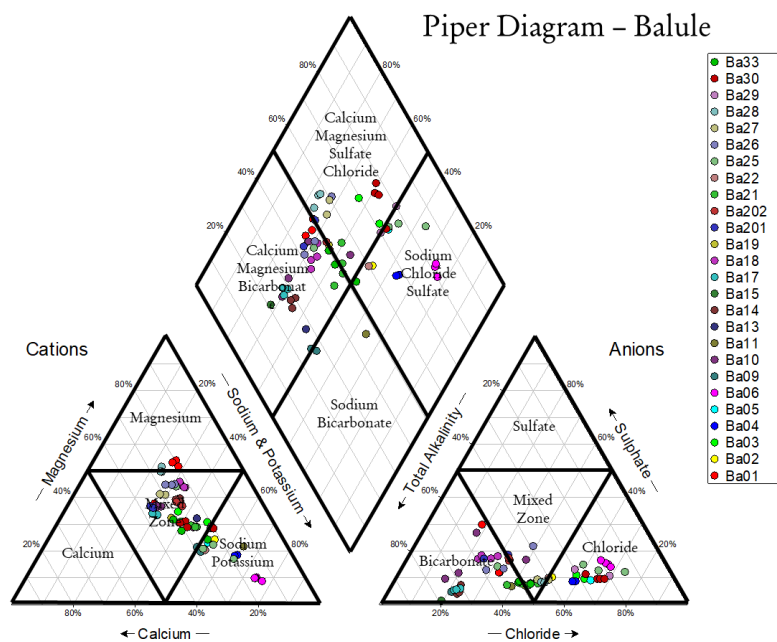


Figure 43 – Balule Piper Diagrams.

Table 8 – Classification table for groundwater results (DWAF, 1996).

Blue	Class 0	Ideal water quality, suitable for lifetime use
Green	Class I	Good water quality, suitable for use, rare instances of negative effects.
Yellow	Class II	Marginal water quality, conditionally acceptable. Negative effects may occur.
Red	Class III	Poor water quality, unsuitable for use without treatment. Chronic effects may occur.
Purple	Class IV	Dangerous water quality - totally unsuitable for use. Acute effects may occur.

From the chemistry results presented in APPENDIX C – LABORATORY CHEMISTRY RESULTS (IGS), it can be noted that the groundwater quality of both study sites is generally of marginal poor water quality (Class II to Class III) in terms of dissolved minerals for both study areas and accordance with DWAF (1996). A statistical summary of all groundwater and surface water chemistry data can be seen below in Table 9 and Table 10. It must be stated that only a statistical summary for Motswari groundwater has been provided, as there were insufficient surface water samples within this study area.

The water quality at Motswari is good to poor (Class I to Class III), with elevated dissolved minerals, that contribute to harder water and in most lodges, treatment is required. Elevated manganese and vanadium are observed at borehole M6, as well as low levels of chloride and total hardness. Elevated levels of arsenic are observed repeatedly at borehole M9, which is anomalous to this site only and not observed elsewhere in the study areas. In Balule, the fluoride levels at Motswari are much lower. The reasons for this may be due to the granitic intrusion of the Harmony Granite, as high fluoride concentrations have previously been noted in similar geological settings through the weathering of fluoride-bearing minerals such as apatite and biotite (Raju, 2017). The spatial distribution of fluoride can be seen in Figure 44.

Only one surface water sample was sampled for the Motswari study area, M_SW01 was sampled in a drainage line from the stakeholders, the actual location of this sample is unknown. With the exception of Class II Aluminium noted for this sample, all other parameters are ideal.

Within Balule, fluoride is elevated at several sites such as Ba06, Ba25 and the spring, which fall into class IV and make it unsuitable for use. These three sites historically show elevated fluoride levels, while other sites indicate it as a once-off anomaly. Elevated levels of sodium and chloride contribute to the higher EC and TDS generally across Balule. Total hardness is also high across a wide range of sites, within Classes II and III. Many of the lodges within the Balule study area have small treatment facilities to treat the water to better quality and make it more suitable.

Surface water samples were collected at Balule from drainage lines and the Olifants River, the drainage line samples were collected by landowners and provided to the author. The surface water samples collected are generally classed under Class 0 and rated as ideal water quality, suitable for lifetime use. One exception of surface water sample was collected from SW02 in March 2020, shown with high fluoride and EC, although this was a once-off anomalous value and was not repeated in subsequent sampling events.

The groundwater quality at both sites is typically high in nitrate concentrations as a result of either leaking French drains (discovered at Balule site Ba33) or the influence of connectivity between surface water and groundwater, such as at the Motswari study site.

At borehole M1, it was observed that nitrate concentrations varied between summer and winter conditions, this borehole is within 35 m of a water course. During the winter period, nearby watering

holes would be visited by large herds of roaming game such as buffaloes, wildebeest or plains game. Spending more time at the watering holes and excreting into the water, which would then cause the nitrate concentrations to increase. Alternatively, in summer when surface water is more available, the plains game would be more spread out and the fresher recharge water would dilute the nitrate concentrations throughout the groundwater.

The spatial distribution of nitrate for Balule is depicted in Figure 45, indicating that there is almost no distribution pattern of nitrate on a regional scale. Rather elevated levels of nitrate are localised to particular boreholes.

The spatial distribution of EC can be seen for Balule in Figure 46. The water quality worsens towards the middle of the study site and improves (lower EC) towards the west and the Olifants River. This transition may be comparative to the host rock lithology which transitions from the Makhutswi Gneiss to the Harmony Granite in the South-West of the Balule study zone. This may account for the slightly better water quality in this area. This would require further information and borehole geology logs.

Motswari was not analysed spatially for any chemistry parameters due to the low resolution of spatial distribution, only groundwater levels (mamsl) were contoured for Motswari, which is shown in Figure 37.

Table 9 – Statistical summary on all groundwater chemistry data for Motswari study area.

Statistics	pH	EC	Ca	Mg	Na	K	MAIk	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
Average	7.41	185.03	70.31	66.10	248.99	8.91	451.65	0.86	328.05	3.92	60.32	175.63	271.88	447.51	1351.07	0.02	0.04	0.24	0.04	0.01	0.02	0.10	0.02	0.02	31.34	0.70	0.03	0.10	0.04	0.02	0.02	II
Maximum	8.06	291.34	138.28	111.13	426.37	20.32	784.30	1.38	799.00	13.91	148.18	345.71	457.64	737.38	2126.80	0.02	0.16	0.37	0.08	0.07	0.06	1.32	0.05	0.02	44.97	1.57	0.03	1.32	0.28	0.06	0.02	III
Minimum	6.97	67.47	12.76	22.74	80.34	4.09	286.91	0.09	41.75	0.19	1.95	31.85	93.63	169.98	492.52	0.02	0.02	0.14	0.02	0.00	0.02	0.02	0.02	0.02	2.56	0.27	0.03	0.01	0.02	0.02	0.02	I
Standard Deviation	0.29	55.69	40.23	28.53	82.84	4.74	121.87	0.40	199.31	3.67	40.64	100.54	117.22	198.57	403.39	0.00	0.04	0.06	0.02	0.01	0.01	0.29	0.01	0.00	9.98	0.38	0.00	0.29	0.06	0.01	0.00	I
Median	7.33	191.52	46.82	69.30	254.43	7.48	411.10	0.93	334.49	3.07	49.64	116.90	285.37	372.87	1398.07	0.02	0.02	0.23	0.04	0.01	0.02	0.02	0.02	0.02	34.04	0.59	0.03	0.02	0.02	0.02	0.02	II

Table 10 – Statistical summary on all groundwater and surface water chemistry data for Balule study area.

Statistics	pH	EC	Ca	Mg	Na	K	MAIk	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
Average (Groundwater)	7.13	168.14	85.83	64.26	169.14	11.95	327.14	1.51	296.33	3.04	90.76	214.38	264.29	478.67	1051.12	0.02	0.02	0.11	0.14	0.02	0.03	0.06	0.02	0.02	29.93	0.78	0.03	0.01	0.05	0.03	0.02	III
Average (Surface Water)	7.69	45.09	29.27	19.66	41.24	5.45	137.28	0.70	51.45	0.99	36.43	73.10	80.93	154.02	345.59	0.07	0.02	0.05	0.04	0.01	0.09	0.02	0.02	0.02	7.82	0.19	0.03	0.01	0.02	0.02	0.02	0
Maximum (Groundwater)	8.09	495.03	269.39	173.50	568.44	41.29	634.64	8.70	1212.20	18.80	266.11	672.66	714.49	1355.09	2985.04	0.03	0.02	0.31	0.44	0.65	0.33	0.90	0.07	0.02	45.22	2.85	0.06	0.03	0.86	0.06	0.02	IV
Maximum (Surface Water)	8.35	182.61	70.59	113.32	316.03	19.86	469.58	6.65	417.45	6.07	125.60	176.26	466.66	642.91	1437.16	0.90	0.02	0.17	0.16	0.01	0.88	0.10	0.03	0.02	33.04	1.12	0.04	0.01	0.12	0.02	0.02	IV
Minimum (Groundwater)	6.61	43.38	32.47	5.60	27.19	2.34	95.27	0.03	28.82	0.08	6.21	81.07	23.08	133.16	302.32	0.02	0.02	0.04	0.02	0.00	0.02	0.02	0.02	0.02	5.67	0.14	0.03	0.01	0.02	0.02	0.02	0
Minimum (Surface Water)	6.82	2.87	1.86	0.55	2.57	0.95	8.89	0.04	2.00	0.10	1.91	4.64	2.26	6.91	18.17	0.02	0.02	0.04	0.01	0.01	0.02	0.02	0.02	0.02	0.44	0.02	0.03	0.01	0.02	0.02	0.02	0
Standard Deviation (Groundwater)	0.28	102.03	50.03	40.38	127.41	6.83	108.29	2.03	268.48	4.03	58.43	124.94	166.19	279.16	591.29	0.00	0.00	0.07	0.10	0.08	0.04	0.13	0.01	0.00	8.85	0.60	0.00	0.00	0.11	0.01	0.00	III
Standard Deviation (Surface Water)	0.52	41.94	14.68	22.64	65.68	5.36	85.44	1.46	93.53	1.74	30.31	36.64	93.21	122.86	333.57	0.19	0.00	0.03	0.03	0.00	0.21	0.02	0.00	0.00	6.28	0.23	0.00	0.00	0.02	0.00	0.00	II
Median (Groundwater)	7.15	140.73	74.02	51.01	118.34	11.69	338.97	0.70	205.41	1.35	76.03	184.82	209.51	409.99	905.72	0.02	0.02	0.09	0.13	0.01	0.02	0.02	0.02	0.02	31.58	0.60	0.03	0.01	0.02	0.02	0.02	II
Median (Surface Water)	7.90	38.64	28.74	18.15	26.41	2.73	134.84	0.35	24.39	0.35	36.32	71.82	74.76	150.03	293.17	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	5.93	0.13	0.03	0.01	0.02	0.02	0.02	0

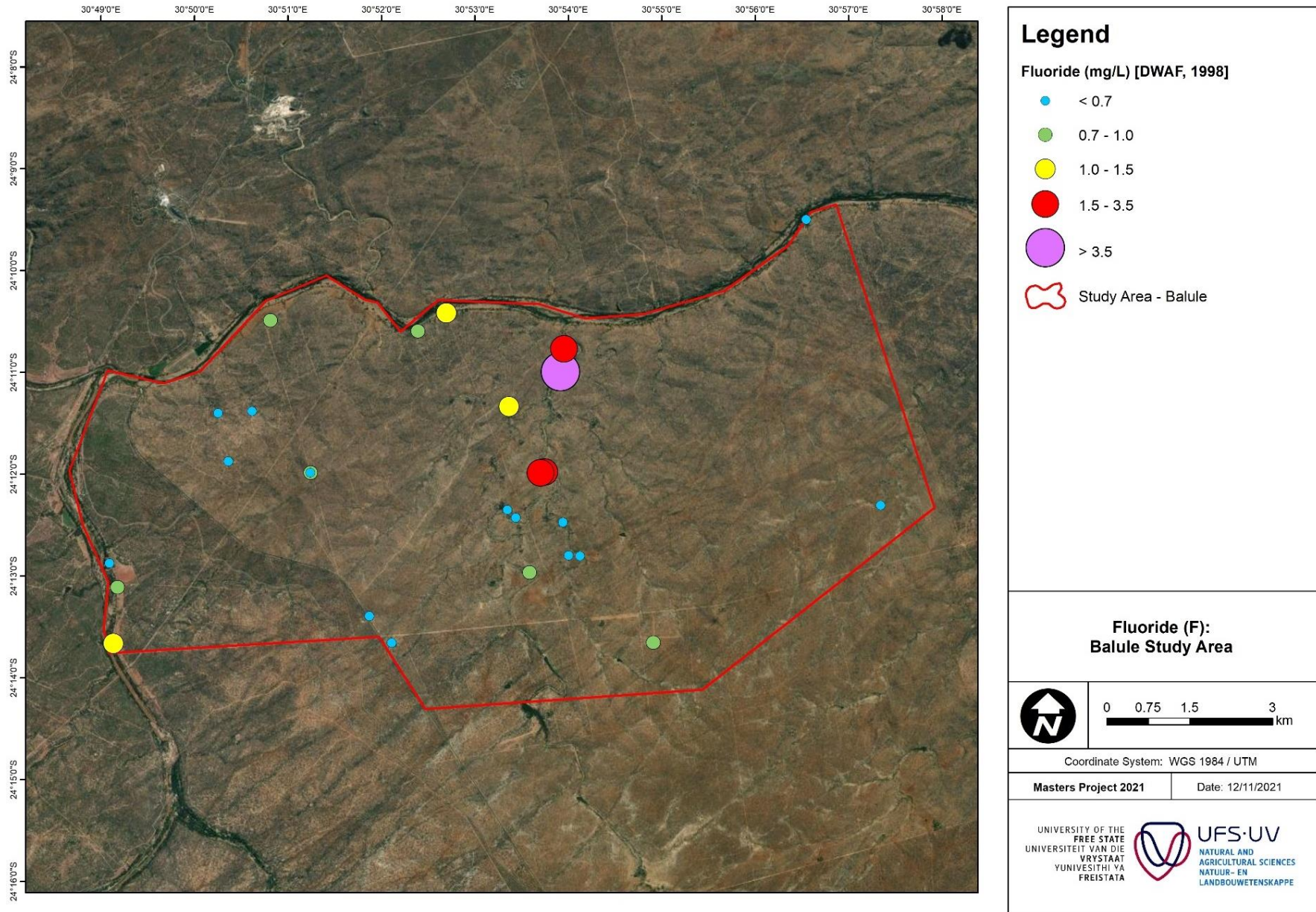


Figure 44 – Fluoride proportional map of Balule study area.

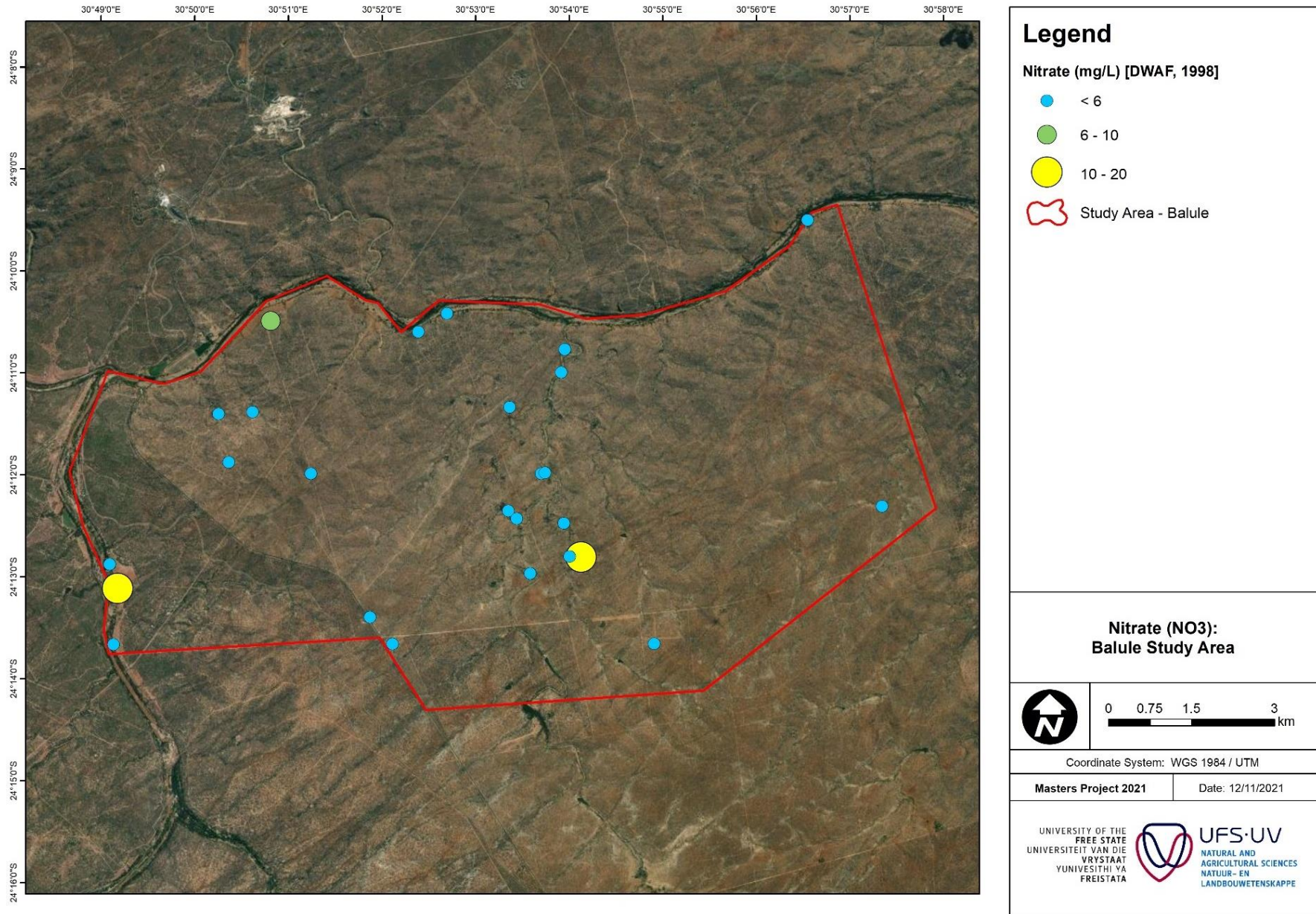


Figure 45 – Nitrate distribution of Balule, indicating no pattern of distribution.

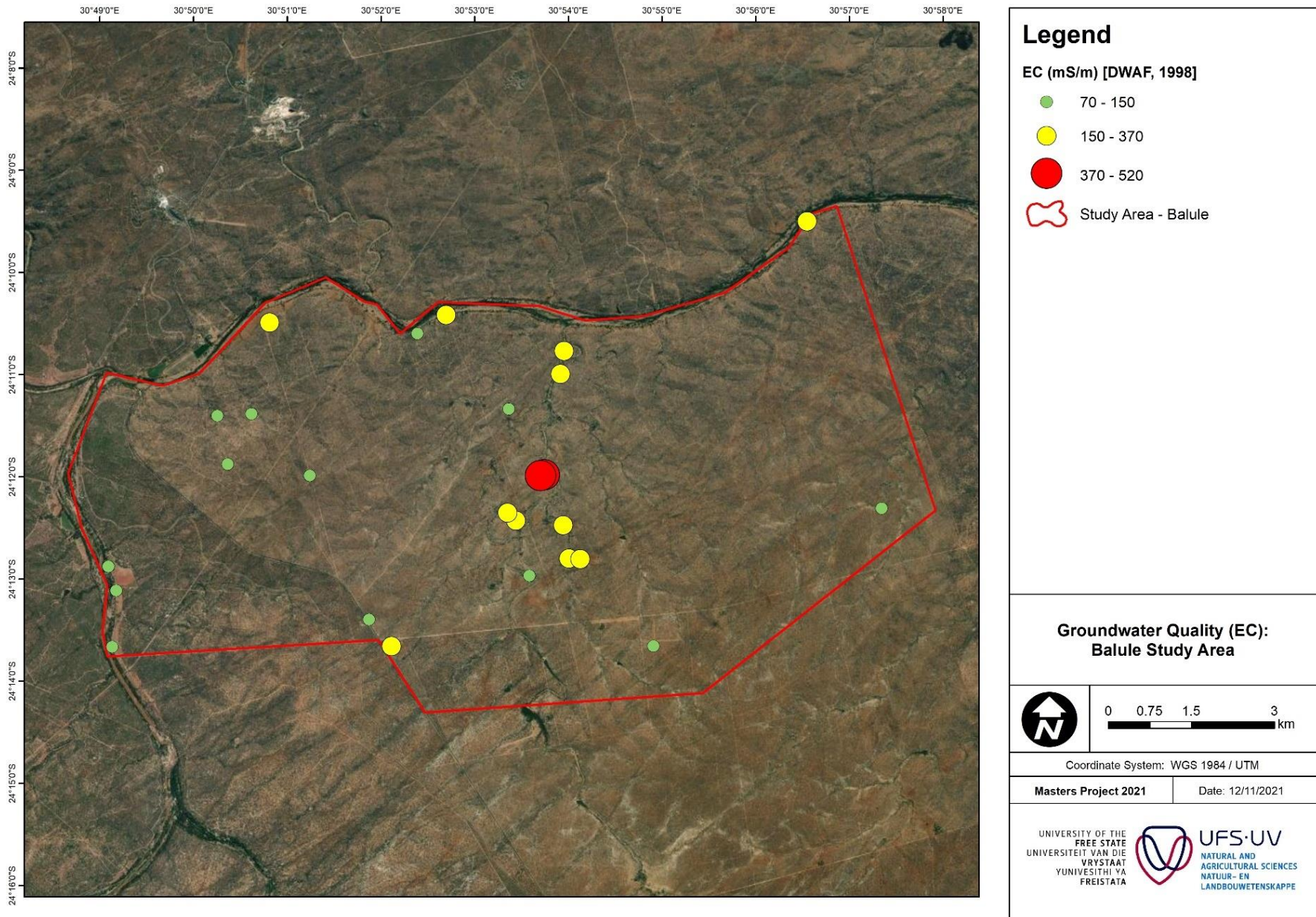


Figure 46 – EC map of Balule, better quality noted towards the west of study site, closer to the Olifants River.

Surface water quality samples were collected at four sample locations of the perennial Olifants River, shown in Figure 35. From interpreted surface water quality results, it was observed that during the month of March 2020 (end of seasonal rainfall period) the ionic concentration increased from the upstream sampling location to the downstream sampling location, as shown in Table 11. If ionic concentrations increase downstream of the river, it is then assumed that the surface water body is groundwater fed (Coluccio and Morgan, 2019). During the sampling period in March 2020, groundwater was then recharged through recharge zones migrating towards the perennial Olifants River as base flow. The hypothesis that the Olifants River is connected to the groundwater regime is supported by the hydraulic gradient flowing towards the river, based on field measurements and presented previously in the groundwater flow direction maps (Figure 38). However, upon observation of the sampling data, a small percentage increase and decrease are observed in the months of July 2019, October 2020 and April 2021, suggesting that the Olifants River is only partially receiving base flow, as some parameters indicate an increase and others indicate a decrease in ionic concentration. A seasonal variation of groundwater and surface water interaction may exist within the study area between the Olifants River and the groundwater. It is recommended that as part of the feasibility study, further investigation of the groundwater and surface water interactions be considered.

Table 11 – Change in major anion and cation concentrations (as a percentage) from upstream of the Olifants River to downstream.

Parameter (mg/L)	July 2019			March 2020			October 2020			April 2021		
	SW04	SW01	% Change	SW04	SW01	% Change	SW04	SW01	% Change	SW04	SW01	% Change
	Upstream	Downstream		Upstream	Downstream		Upstream	Downstream		Upstream	Downstream	
Ca	28.09	29.08	3.5%	32.32	70.59	118.4%	31.47	31.18	-0.9%	27.79	28.41	2.2%
Mg	20.55	20.76	1.0%	21.03	113.32	438.9%	21.53	20.98	-2.6%	18.18	18.13	-0.3%
Na	25.35	26.09	2.9%	29.64	94.77	219.8%	27.13	28.23	4.1%	19.83	21.31	7.4%
K	2.93	3.02	2.8%	3.51	13.00	270.5%	2.30	2.34	1.6%	2.14	2.53	18.5%
MAlk	141.43	141.90	0.3%	113.94	469.58	312.1%	142.29	142.82	0.4%	130.77	128.49	-1.7%
F	0.04	0.05	11.9%	0.34	0.67	97.1%	0.14	-0.10	N/A	0.59	0.48	-18.6%
Cl	24.89	23.84	-4.2%	33.57	204.83	510.2%	24.42	24.35	-0.3%	21.62	23.01	6.4%
NO3(N)	4.08	6.07	48.8%	0.37	4.97	1243.2%	0.12	0.12	0.0%	0.40	0.37	-7.5%
SO4	37.57	40.58	8.0%	54.74	95.07	73.7%	31.89	33.25	4.3%	38.00	38.71	1.9%

The general water quality across both sites is not ideal for drinking water purposes and should be treated to some degree before human consumption. High levels of hardness within the groundwater at both sites contribute to high maintenance costs within game lodges for anything that comes into contact with the groundwater. Lodges closer to the Olifants river prefer to use river water if available as it can be treated to better quality much simpler than groundwater. The river water in Balule from the Olifants river is suspected to have high microbiological concentrations throughout the entire river course. A limitation to this study was that Microbiological samples required analysis within 24 hours, this could not be done during the study period as field visits took two weeks at a time on some occasions.

5.3.3 Groundwater Recharge Estimation

The calculated rates per borehole are presented in Table 12, recharge within the Balule study area is 30% higher than recharge to Motswari. MAR is likely to increase recharge rates through the recharge methodology as described in the following chapter of this dissertation.

In comparison with DWAF (2006), the recharge calculations within this dissertation are consistent with regional Chloride Mass Balance calculations (DWAF, 2006).

Table 12 – Statistical summary of recharge calculations within both study areas.

Study area	Balule	Motswari
Study area extent (km ²)	93.8	30.54
Harmonic Mean (Chloride)	141.58	184.11
Average Annual Rainfall	421	
Recharge (mm/a)	6.31	3.75
Recharge (%)	1.24	0.89
Annual Recharge (m ³ /a)	592 020.22	148 222.35

5.4 Geophysics

The spatial distribution of all the geophysics profiles can be seen for each study area in Figure 47 and Figure 48. Magnetics results were used as an opportunity to identify whether magnetic anomalies could be used within the study areas to identify and delineate the location of dolerite dykes or the potential for lineaments. These lineaments are seen as the primary structures to target for injection and abstraction boreholes for a MAR scheme. The magnetics data was used to determine the presence and orientation of dykes and lineaments. The EM data was used later to confirm the presence and distribution of potential favourable groundwater targets, in correlation with the existing magnetics data which has been completed earlier in the dissertation. In total, only four EM profiles could be completed across both study areas due to time constraints. The EM method was used to verify the presence of magnetic anomalies and the correlating EM signature.

The presence of dolerite dyke structures is shown on the surface during a brief site walkover of both study areas in Figure 49. The dolerite dykes exhibit high degrees of weathering in narrow dykes as well as at the point of contact. Thicker/wider dykes are more competent and often were the impermeable controlling morphological feature of the landscape, seen with changes in drainage channel directions. The left-hand image (A) in Figure 49 shows how the dyke contact is not a uniform feature and can alter direction. The remaining images (B and C) both show fractures near to and within the point of contact indicated by yellow lines.

Within each study area, numerous magnetic profiles were conducted, longer profiles were then split into segmented sections to allow a closer inspection of magnetic anomalies to determine the dipping direction and trend of the dykes. The profiles for both magnetics and the EM profiles were conducted along straight sections of the road after the first magnetics profile proved problematic to walk in a straight orientation due to the vegetation growth and wildlife presence in the study area. As much as possible, all the profiles were conducted perpendicular to the lineaments mapped with aerial imagery.

The geophysics data was used as a tool to identify potential zones of MAR and abstraction sites. Through the use of the collected geophysical data, accurate drilling of injection boreholes would take place, within the drainage channels or adjacent. The seasonal flood water would then enter the subsurface through these injection or “recharge” boreholes.

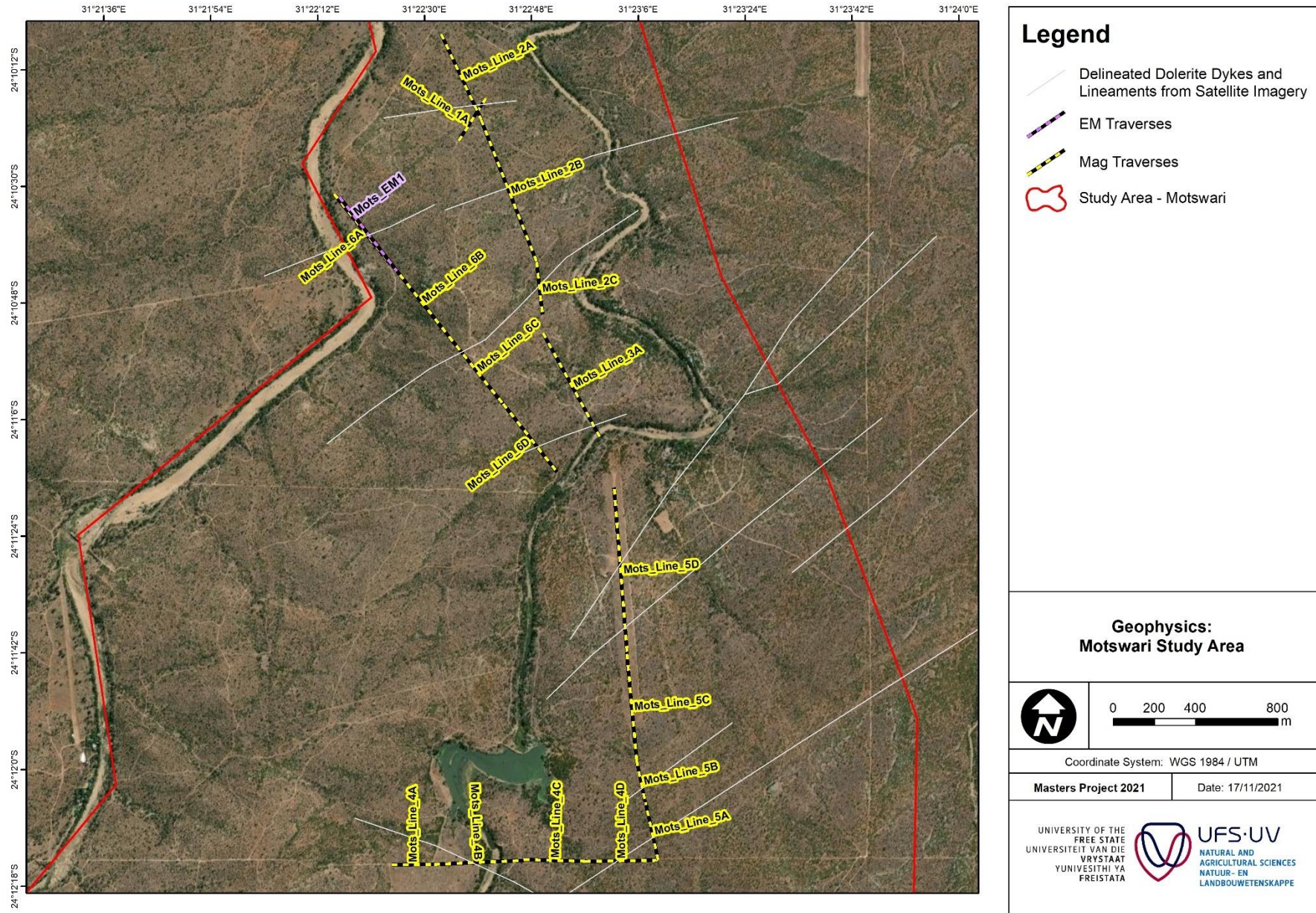


Figure 47 – Geophysical traverses conducted within the Motswari study area over dolerite dykes and lineaments.

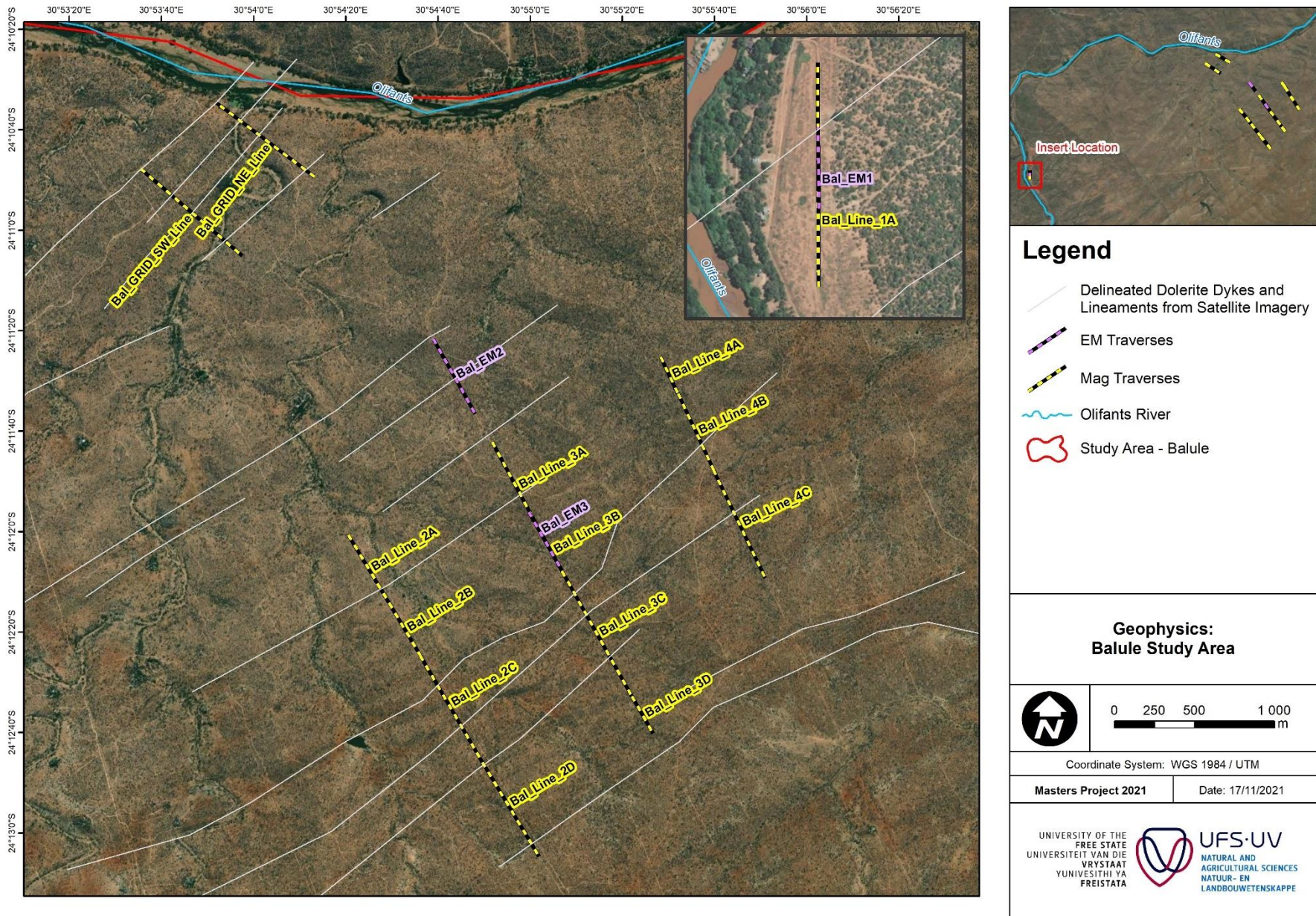


Figure 48 – Geophysical traverses conducted within the Balule study area over dolerite dykes and lineaments.



Figure 49 – Field examples of dolerite dyke intrusion into host rock and resulting fracturing (yellow lines), point of contacts shown as a dotted red line.

5.4.1.1 Motswari Magnetics Results

Mots_Line_1A (Figure 50) was walked from the South-West to the North-East, the profile was 240 meters long and used as a trial profile to identify whether the magnetics equipment was in appropriate working order. The profile recorded 416 stations, with a noticeable anomaly between stations 300 – 375, this may be due to the presence of an unmapped fault, as a decrease in magnetic susceptibility can be due to the reduction in magnetic minerals or a weathered zone. Weathered zones are zones whereby magnetic minerals have been broken down and result in a concentration that is lower than the baseline, as can be seen between stations 300 – 365 (see red square in Figure 50).

The magnetics data from the Mots_Line_2 profile had numerous gaps in it due to frequent stop-starts as a result of animals within the study area. The data resulting from the entire profile required sections of the dataset to be deleted and refined. The profile is shown in Figure 51 to Figure 53. In section Mots_Line_2A (Figure 51), there is an anomaly at station 800, whereby a sharp decline in magnetic susceptibility is followed by a gradual increase back to 29,000 nT, this was erroneous data as it did not follow the same trend of all other anomalies. Within the second section (Mots_Line_2B) of this traverse, a large anomaly was identified that may be an indicator of a dolerite dyke, between stations 1250 and 1350. The anomaly at station 650 (shown with a red square) in Mots_Line_2B (Figure 52) is an indicator of lower magnetic susceptibility at this point in the profile. The remaining data for Mots_Line_2C (Figure 53) indicated a gradual increase in magnetic susceptibility from station 100 to 250, which may be indicative of a dolerite dyke structure.

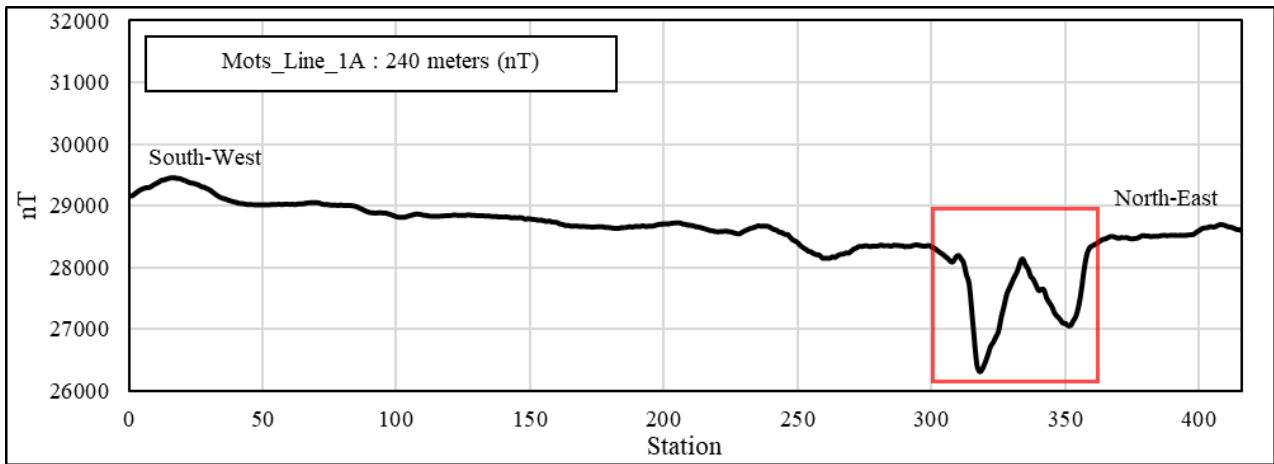


Figure 50 – Mots_Line_1A Magnetic Profile (240 m), downward trend anomalies marked with a red square.

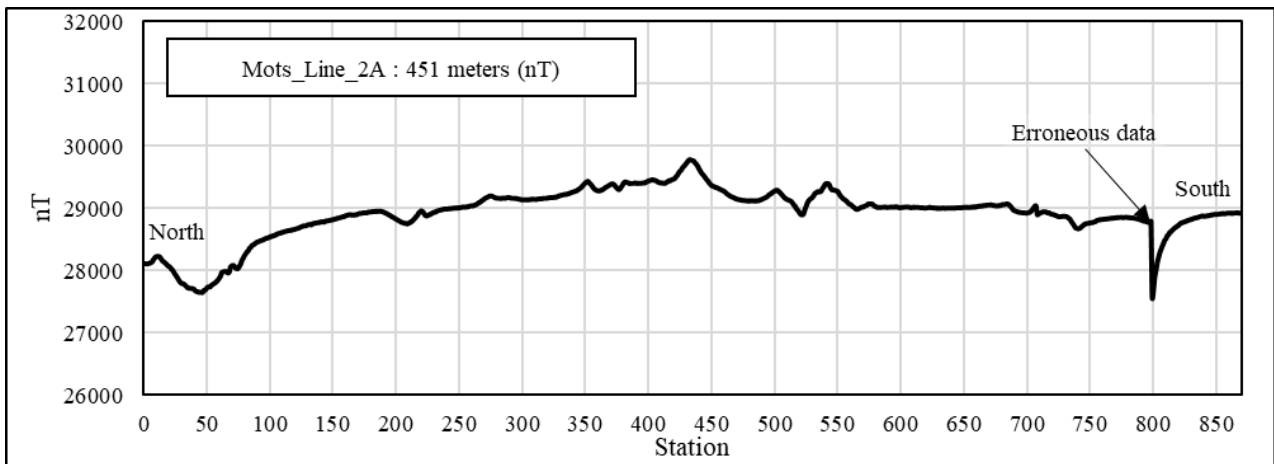


Figure 51 – Mots_Line_2A Magnetic Profile (451 m).

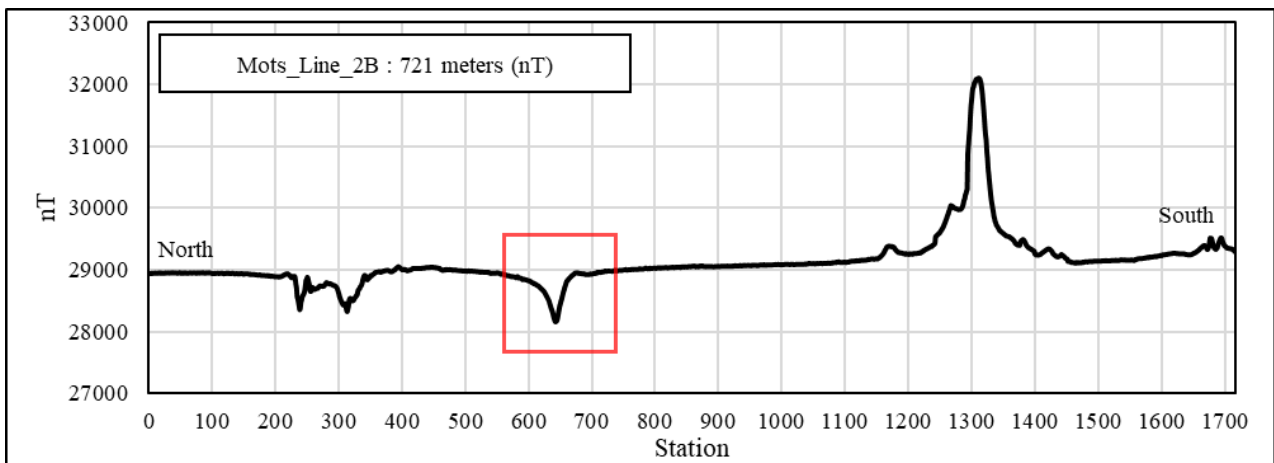


Figure 52 – Mots_Line_2B Magnetic Profile (721 m), downward trend anomalies marked with a red square.

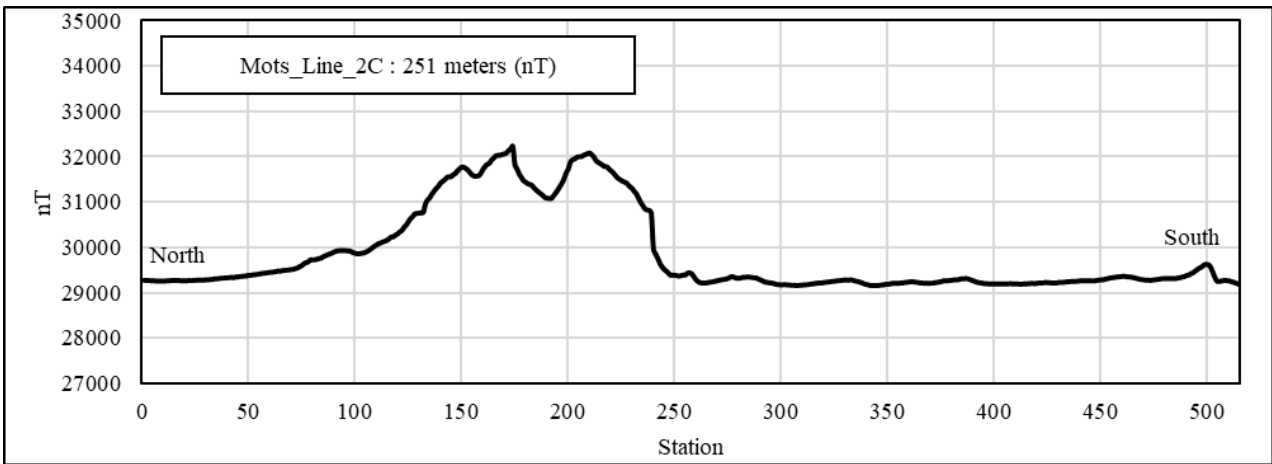


Figure 53 – Mots_Line_2C Magnetic Profile (251 m).

Mots_Line_3A (Figure 54) was walked downgradient from the North-West down across a drainage line to the South-East. The resulting profile is shown in Figure 54, the profile was walked perpendicular to the dyke outcrops and a dyke signature can be seen between stations 520 to 590. It was confirmed in the field to be a narrow dyke of approximately 4 m.

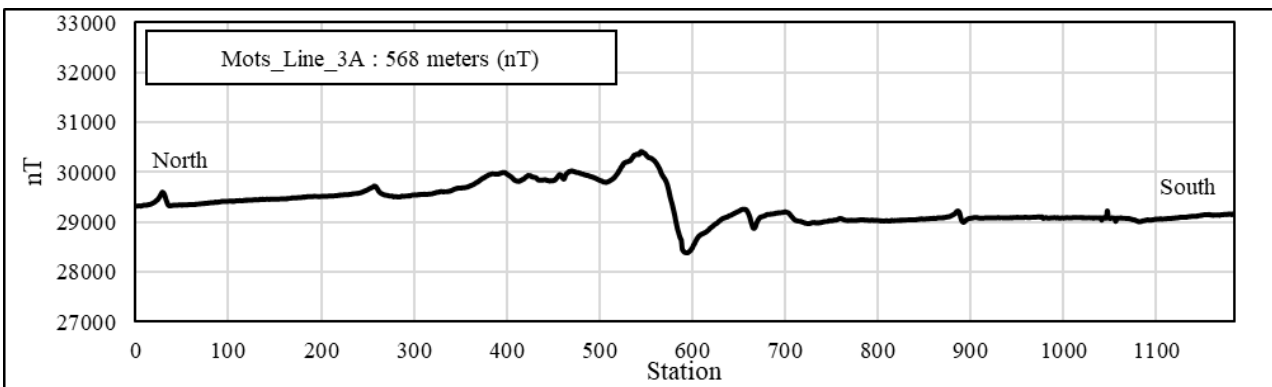


Figure 54 – Mots_Line_3A Magnetic Profile (568 m).

Mots_Line_4 was broken down into four separate sections, for a better view of the magnetics data. Profiles of all four sections are shown in Figure 55 to Figure 58, this profile was conducted from West to East. The first section (Mots_Line_4A) identified a gradual increase in magnetic susceptibility from station 165, to a maximum at station 180, then quickly returning to a baseline value at station 200, this may relate to a dolerite dyke intrusion which was intersected at this point in the profile. Similar signatures are identified between stations 120 – 150 in Figure 56, which shows a second lineament on Mots_Line_4B. A non-perennial drainage line was crossed at station 450 – 550 in Mots_Line_4B, which resulted in little changes to the base value of the profile (shown in the figure with a red square).

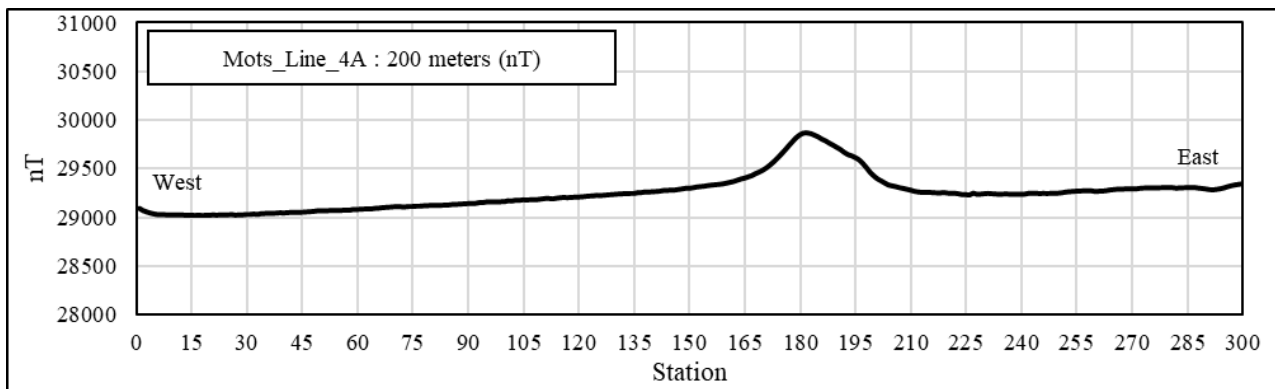


Figure 55 – Mots_Line_4A Magnetic Profile (200 m).

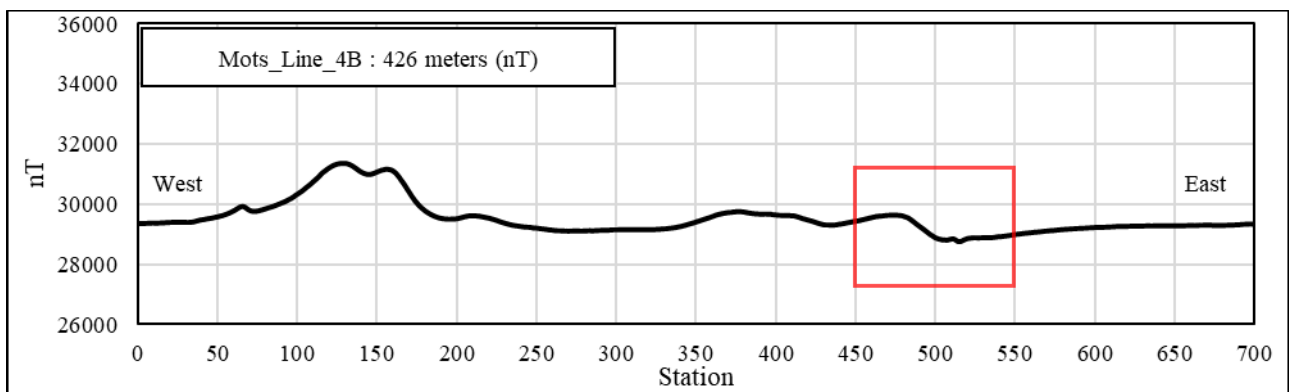


Figure 56 – Mots_Line_4B Magnetic Profile (426 m), drainage line marked with a red square.

Further along with the third section at Motswari of Mots_Line_4, between stations 150 – 340 of Mots_Line_4C (Figure 57), was an initially lower magnetic signature, followed immediately by a section of elevated magnetic susceptibility. This entire anomaly signature (station 150 to 350) is unknown, however, assumed to relate with a dolerite dyke structure that trends North-West to South-East.

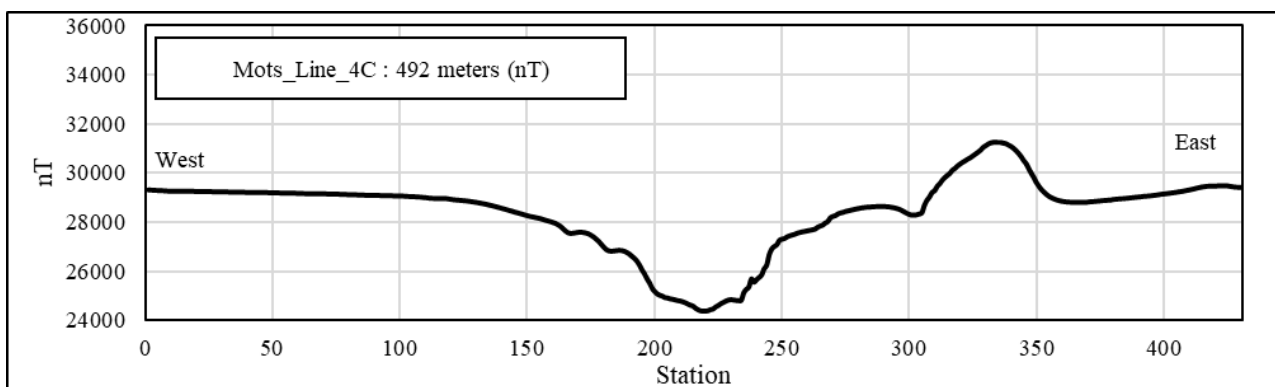


Figure 57 – Mots_Line_4C Magnetic Profile (492 m).

Mots_Line_4D (Figure 58) confirmed the presence of an additional two narrower dykes on this profile, shown at stations 100 and 465, with a wider dyke signature between stations 240 to 375. The narrower suspected dykes are shown with blue squares and the wider/thicker dyke is shown with a red square.

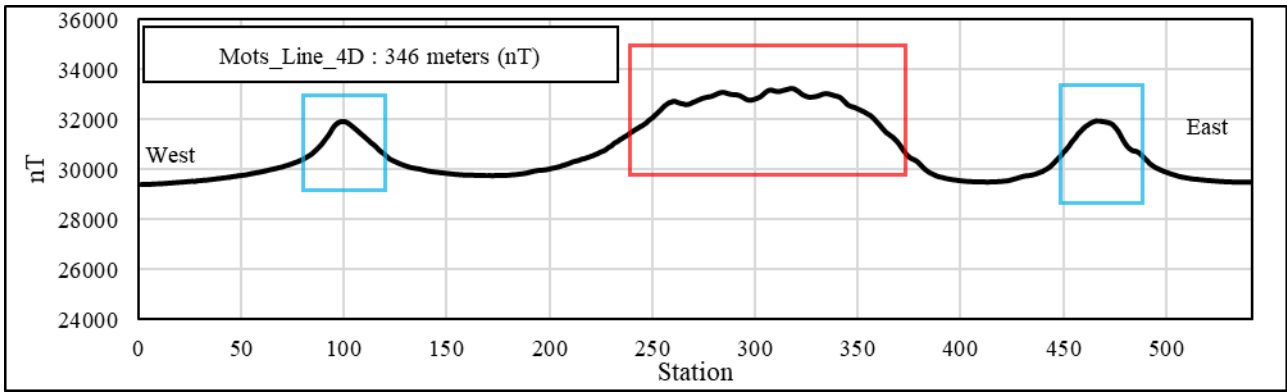


Figure 58 – Mots_Line_4D Magnetic Profile (346 m), anomalies marked with red and blue squares.

Mots_Line_5 was broken down into several separate sections, for a better view of the available data. Profiles for all four sections are shown in Figure 59 to Figure 62, this profile was conducted from south to north, along the length of a bush runway (or landing strip), perpendicular from Mots_Line_4 and is shown in Figure 47.

The profile is orientated at an angle to the mapped lineaments within the study area. The below base values noted between stations 90 to 120 in Mots_Line_5B correlate to the same signature in Figure 57 (Mots_Line_4C), these two can be closely linked and are likely the same lineament such as a weathered or fractured zone. The last section of Mots_Line_5 as shown in Figure 62, identifies a clear dyke structure, this is a North-East to South-West striking lineament. It is assumed the lodge has drilled their borehole to target this water supply, shown between stations 1000 to 1100, the profile is ended with electrical interference from the electric fence surrounding the Motswari lodge.

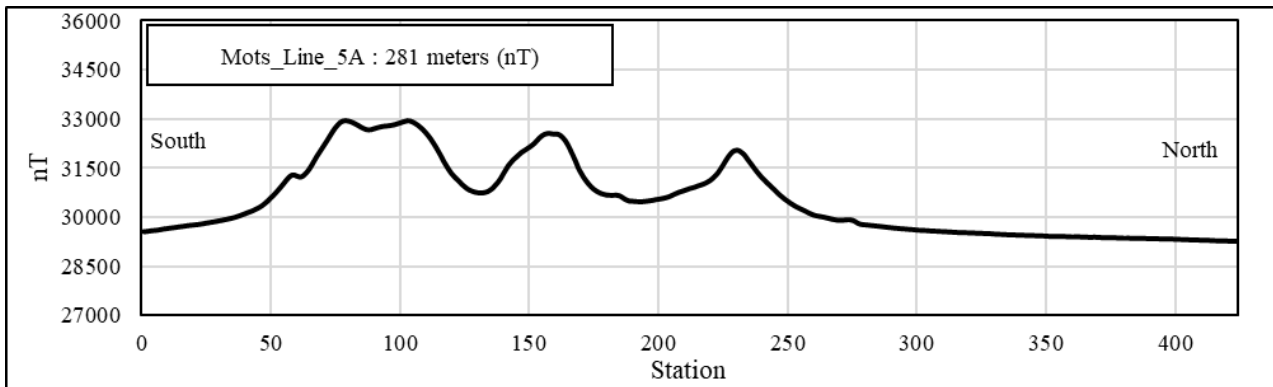


Figure 59 – Mots_Line_5A Magnetic Profile (281 m).

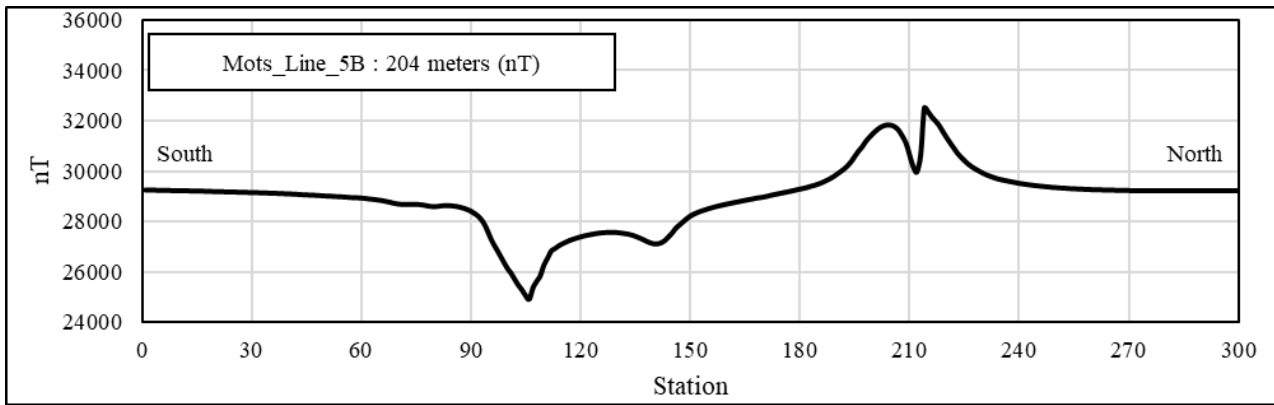


Figure 60 – Mots_Line_5B Magnetic Profile (204 m).

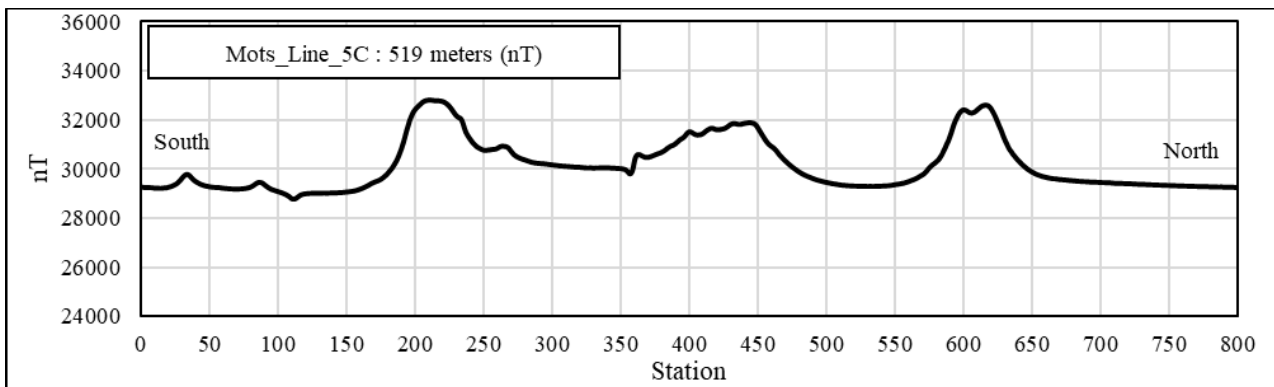


Figure 61 – Mots_Line_5C Magnetic Profile (519 m).

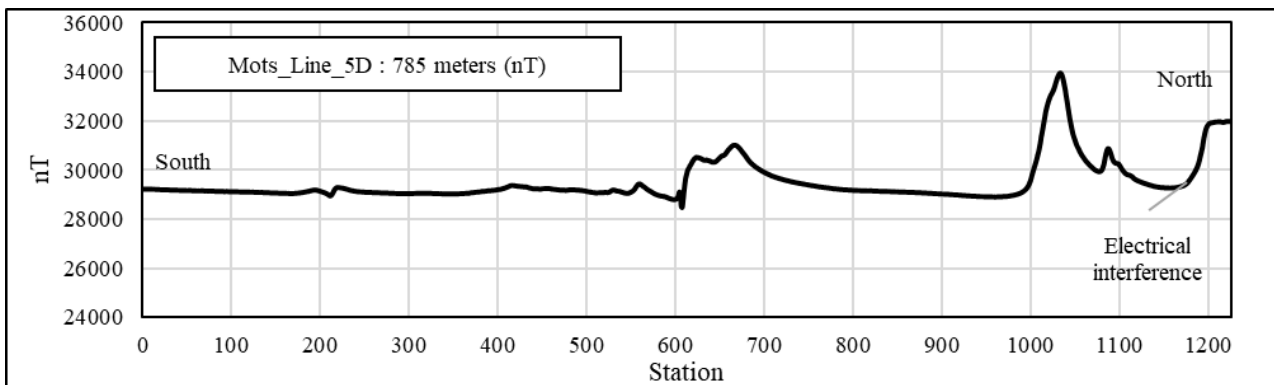


Figure 62 – Mots_Line_5D Magnetic Profile (785 m).

Mots_Line_6 was broken down into four separate sections, for a better view of the available data. Profiles for all four sections are shown in Figure 63 to Figure 66. This profile was conducted from North-West to South-East, along a boundary line. Mots_Line_6A (Figure 63) identifies two anomalies that can be seen at stations 265 and 375 (the anomalies are indicated with a red square on the graphs below). Section B shows no particular interest with a small variation in the magnetic values from start to end of the section. Section C identifies two strong above baseline anomalies at stations 175 and 525, these anomalies align with dykes on aerial imagery. Mots_Line_6D (Figure 66) identifies the presence of two possible dykes at stations 120 and 315, indicated by the increase of measurements above baseline for a short period and can be seen in aerial imagery.

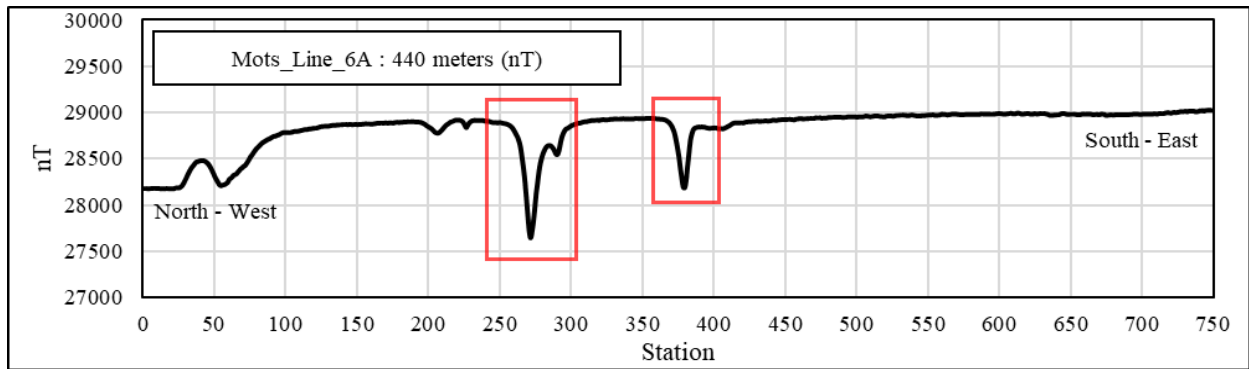


Figure 63 – Mots_Line_6A Magnetic Profile (440 m), anomalies marked with red squares.

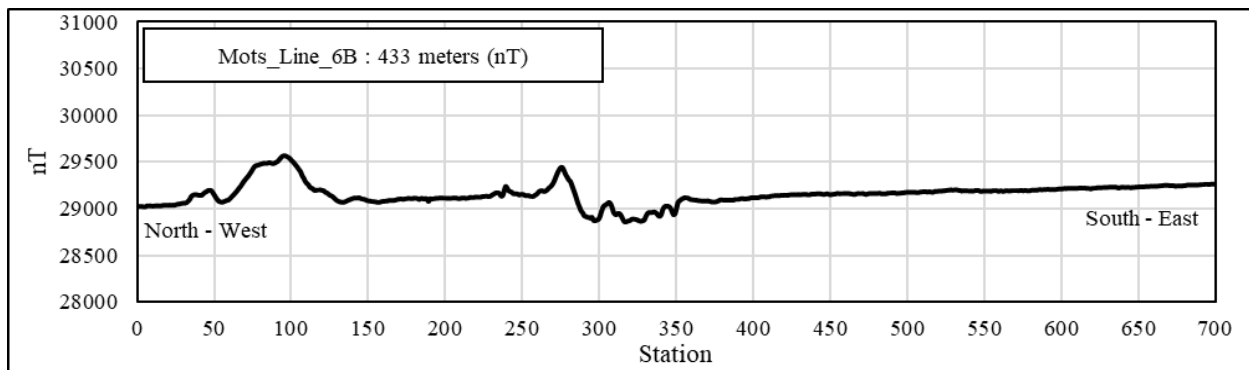


Figure 64 – Mots_Line_6B Magnetic Profile (433 m).

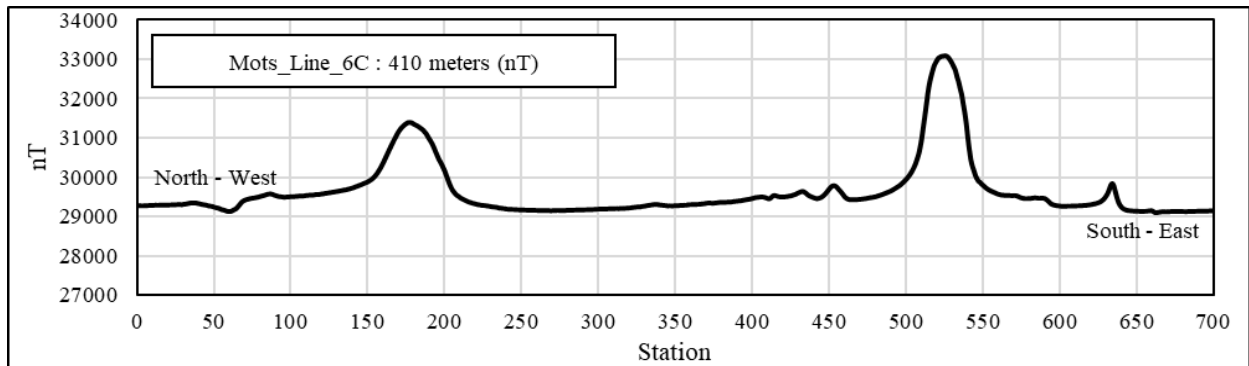


Figure 65 – Mots_Line_6C Magnetic Profile (410 m).

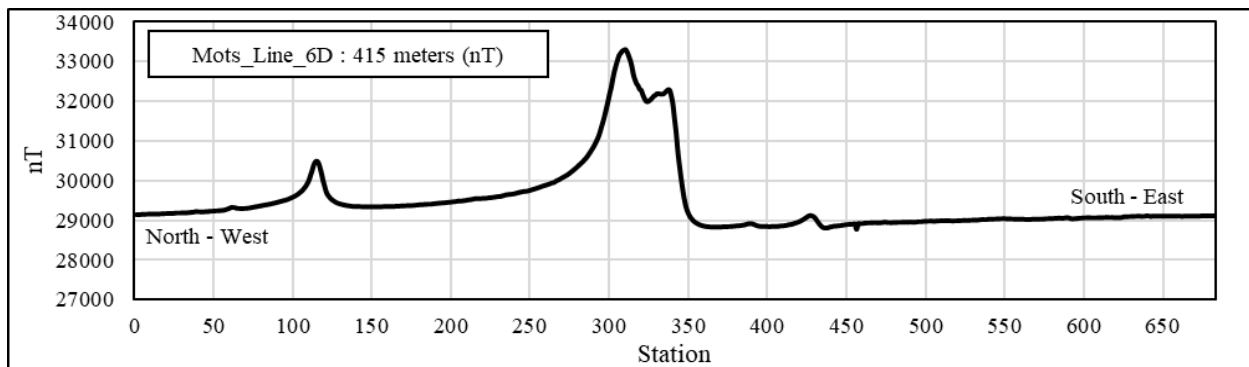


Figure 66 – Mots_Line_6D Magnetic Profile (415 m).

A total length of 6.75 km was walked to gather magnetics data at Motswari. Within this dataset, multiple anomalies were identified for potential groundwater targets to be used as either recharge boreholes or future drill sites and abstraction boreholes. These anomalies correlated to aerially identified dykes. In general, when these dykes were intersected, they would result in a large upward trend anomaly, unless a weathered or faulted zone (lineament) was intersected. In which case a downtrend trend anomaly was observed in the data.

5.4.1.2 Balule Magnetics Results

A total of five (5) magnetic profiles were conducted within the Balule study area, all the profiles were conducted perpendicular to the outcropping dykes that could be seen from aerial imagery. The first magnetics profile (Bal_Line_1A) was conducted along the edges of an old bush runway, crossing a dyke outcrop (observed from aerial imagery). This profile is shown in Figure 67, the profile was walked from South to North. An anomaly signature of a dyke (indicated with a red square) can be seen between stations 300 – 350.

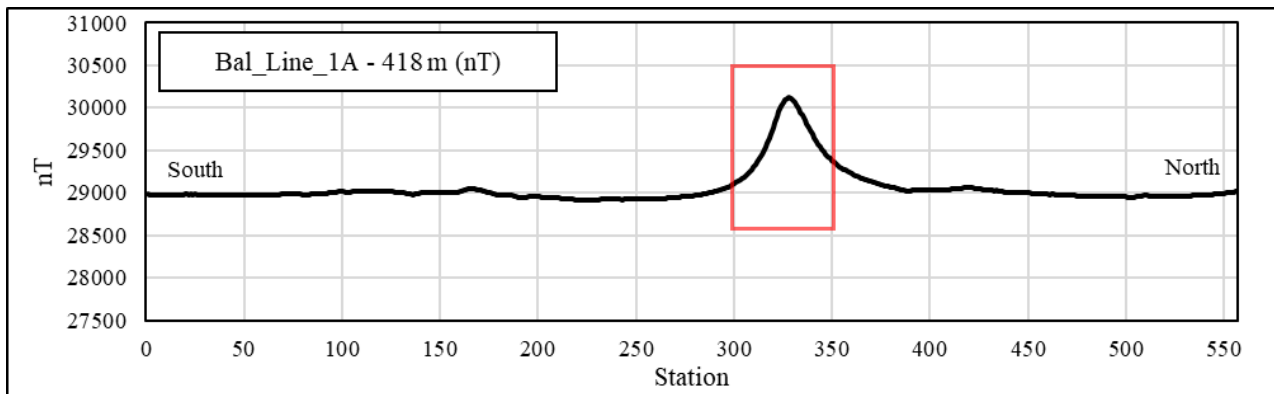


Figure 67 – Bal_Line_1A Magnetic Profile (418 m), anomaly marked with a red square.

The second profile of Balule was completed as two separate parallel lines at the bottom of a drainage line before the Olifants River (Figure 48), with the first section being a lower elevation to the north (closer to the Olifants River), traversed from East to West, shown in Figure 68 and the parallel traverse from West to East, slightly higher up to the south is shown in Figure 69. Shown in these two profiles are three dyke anomaly structures dipping at equal angles to one another, as shown on the aerial imagery of Figure 48, these two profiles were parallel to one another and show almost identical signatures, suggesting that the lineaments crossed are consistent across both sections of the profile.

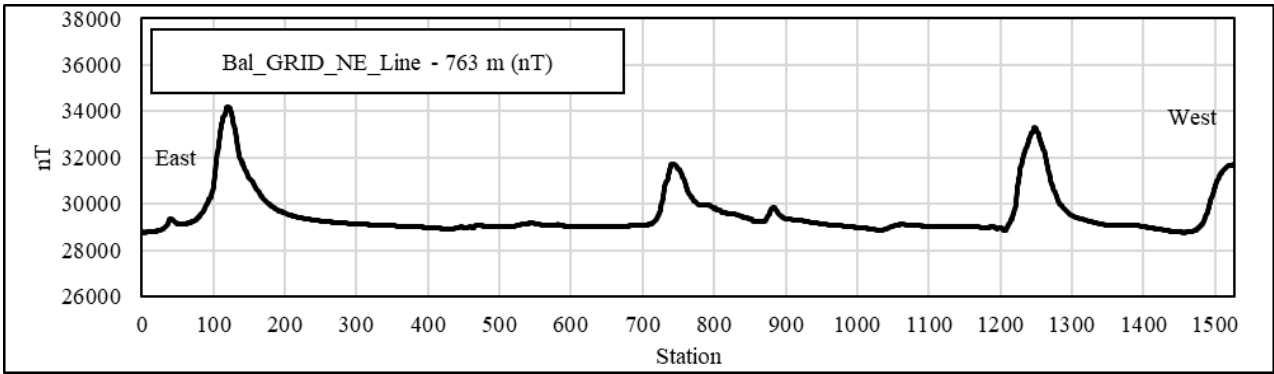


Figure 68 – Bal_GRID_NE_Line (763 m).

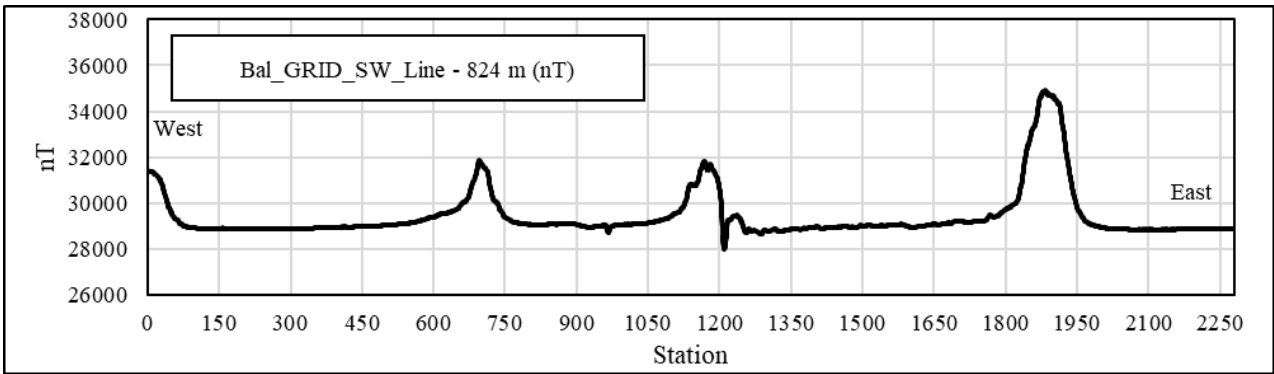


Figure 69 – Bal_GRID_SW_Line (824 m).

The remaining three traverses were all long and walked upgradient from North-West to the South-East along roads within the study area. Bal_Line_2 was a total length of 2.3 km and has been broken down into four separate sections. These can be viewed in Figure 70 to Figure 73. Dyke anomaly signatures were noted in Bal_Line_2A (Figure 70) at station 560, with an additional dyke structure on Bal_Line_2B (Figure 71) at station 200. Large magnetic signatures are noted within Bal_Line_2C (Figure 72) between stations 200 to 400, indicating a potential dyke swarm network of closely linked dykes that would have intruded into the host rock.

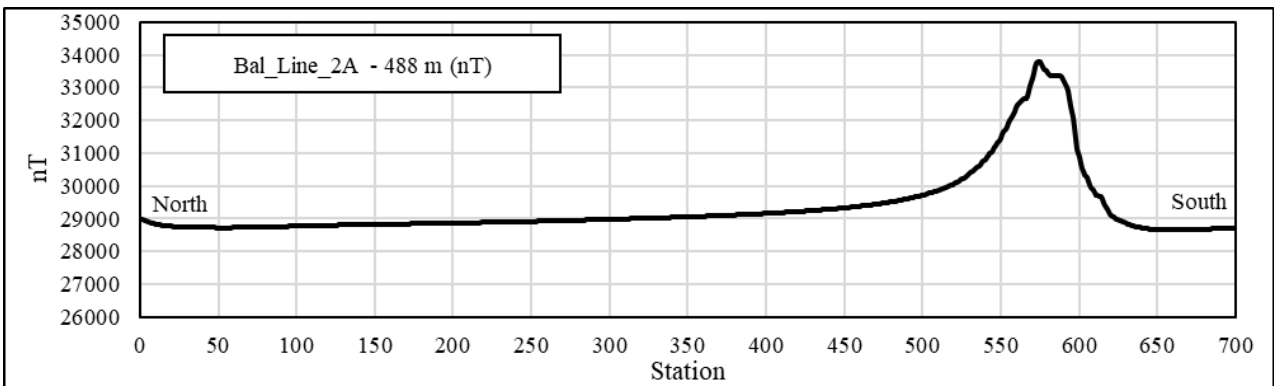


Figure 70 – Bal_Line_2A Magnetic Profile (488 m).

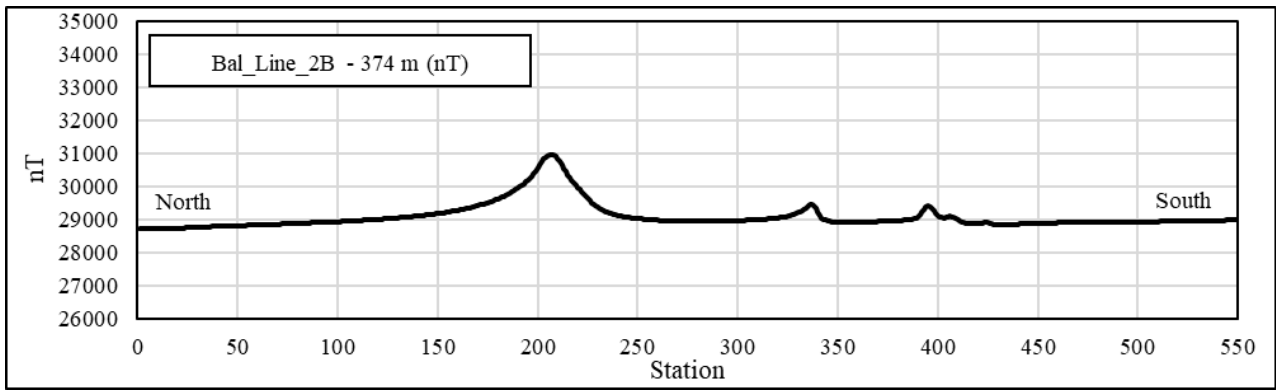


Figure 71 – Bal_Line_2B Magnetic Profile (374 m).

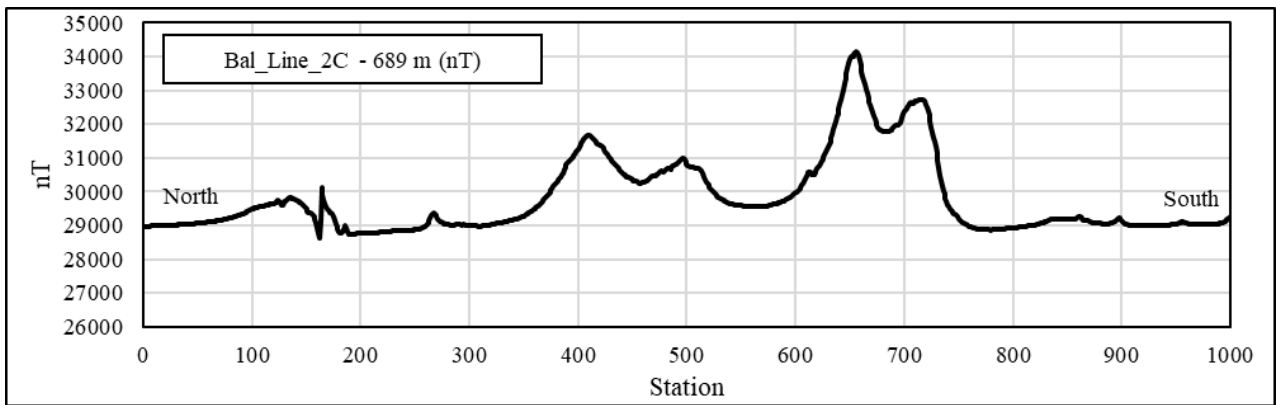


Figure 72 – Bal_Line_2C Magnetic Profile (689 m).

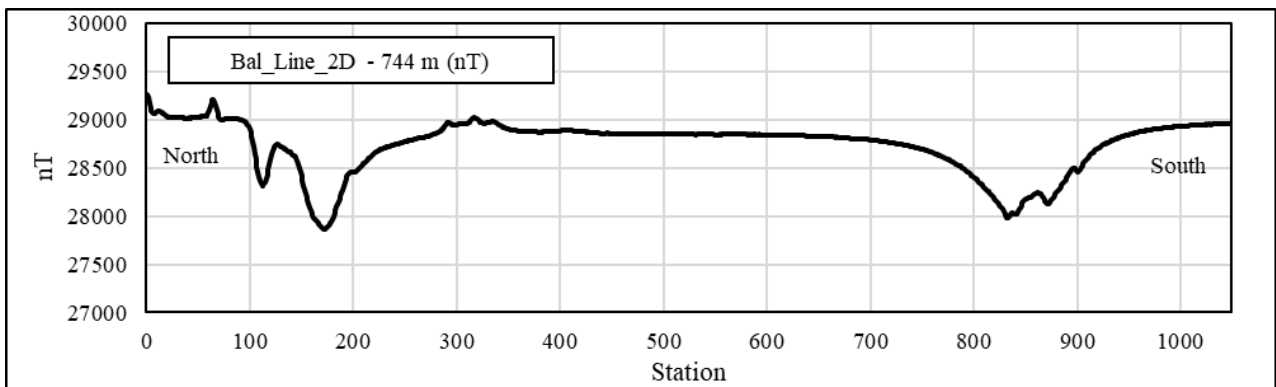


Figure 73 – Bal_Line_2D Magnetic Profile (744 m).

Bal_Line_3 was a total length of 2.0 km and has been broken down into four separate sections. These are shown in Figure 74 to Figure 77. The first section (Bal_Line_3A) shows a smaller and larger dyke anomaly signature (shown with red squares), between stations 200 to 250 and then again at station 450 in Figure 74. Bal_Line_3B (Figure 75) displays similarly to Bal_Line_3A, one dyke structure to the north. Bal_Line_3C (Figure 76) correlates to the third section on Bal_Line_2, exhibiting a swarm of potential dyke lineaments. Figure 77 is the final section of Bal_Line_3 and indicates two downward dipping anomalies within the profile, these two signatures align with similar signatures of Bal_Line_2D (Figure 73).

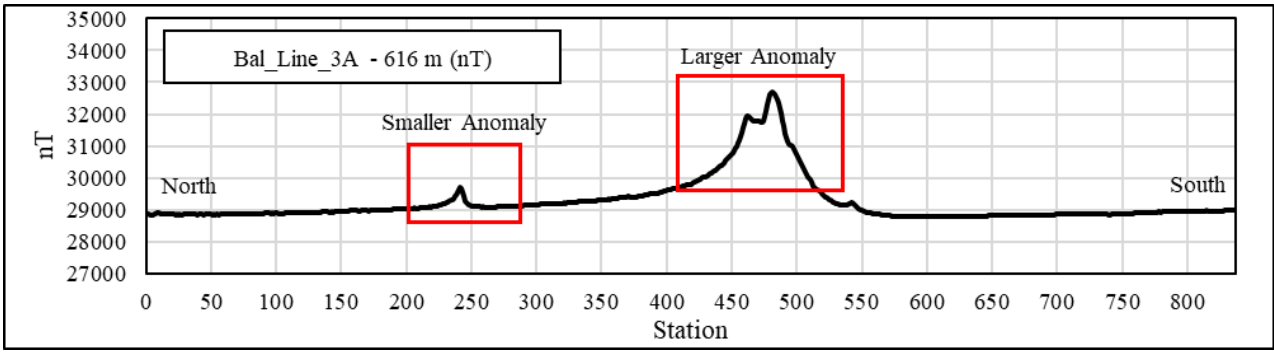


Figure 74 – Bal_Line_3A Magnetic Profile (616 m).

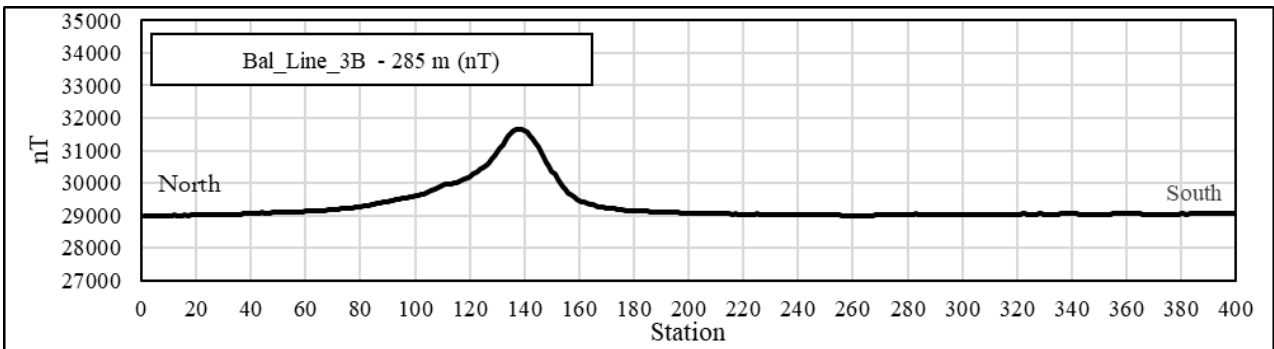


Figure 75 – Bal_Line_3B Magnetic Profile (285 m).

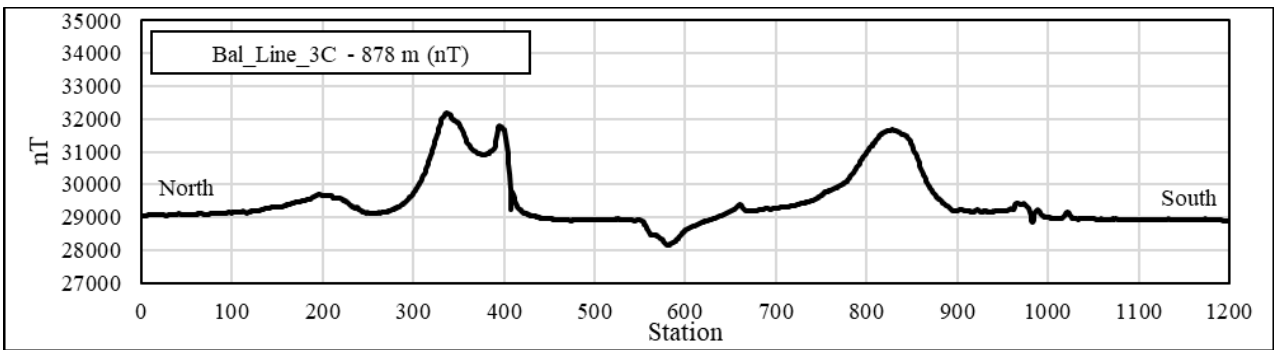


Figure 76 – Bal_Line_3C Magnetic Profile (878 m).

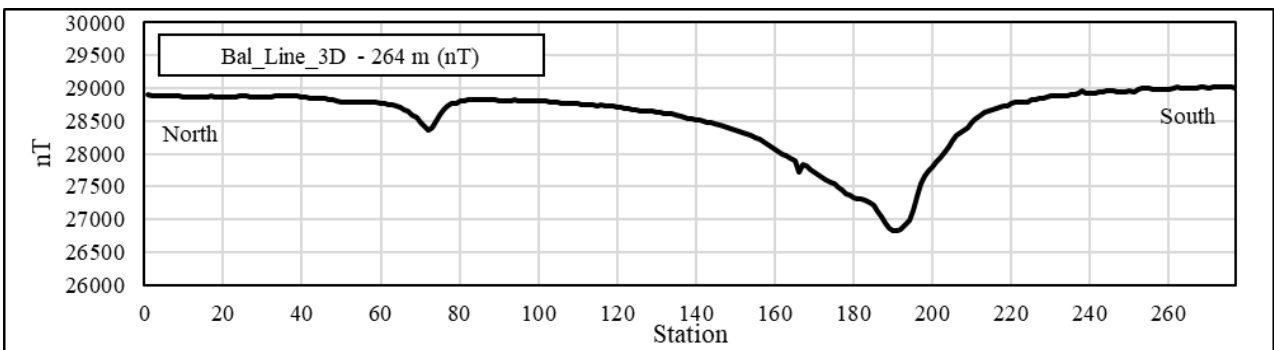


Figure 77 – Bal_Line_3D Magnetic Profile (264 m).

Bal_Line_4 was a shorter length profile of only 1.5 km and has been broken down into three separate sections. These are shown in Figure 78 to Figure 80. The final magnetic profile indicated two dyke structures, each being seen in Bal_Line_4A and Bal_Line_4B. The final section of this profile in Figure 80 relates to a continuity of the intruded and weathered zones already shown in Bal_Line_2C and Bal_Line_3C magnetic profiles of Balule (Figure 72 and Figure 76).

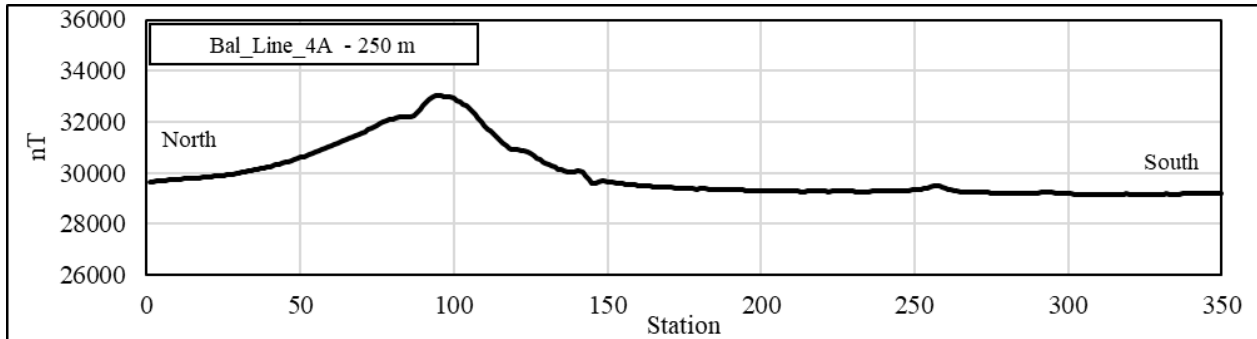


Figure 78 – Bal_Line_4A Magnetic Profile (250 m).

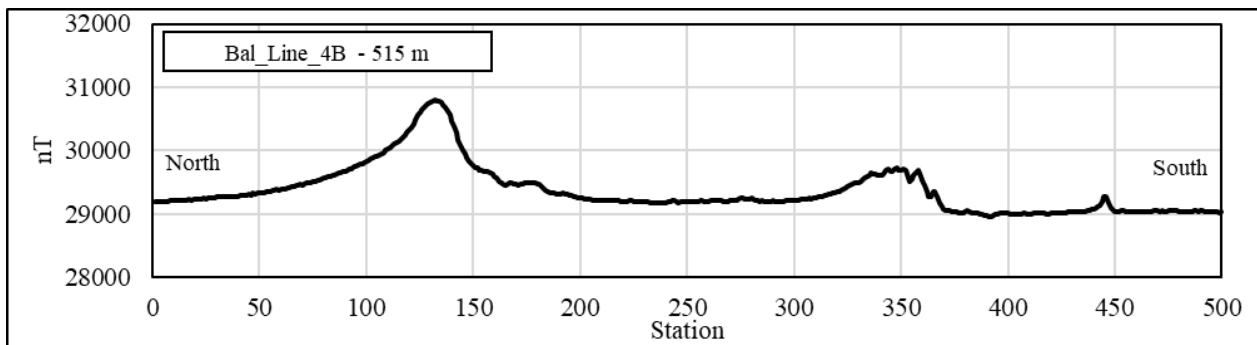


Figure 79 – Bal_Line_4B Magnetic Profile (515 m).

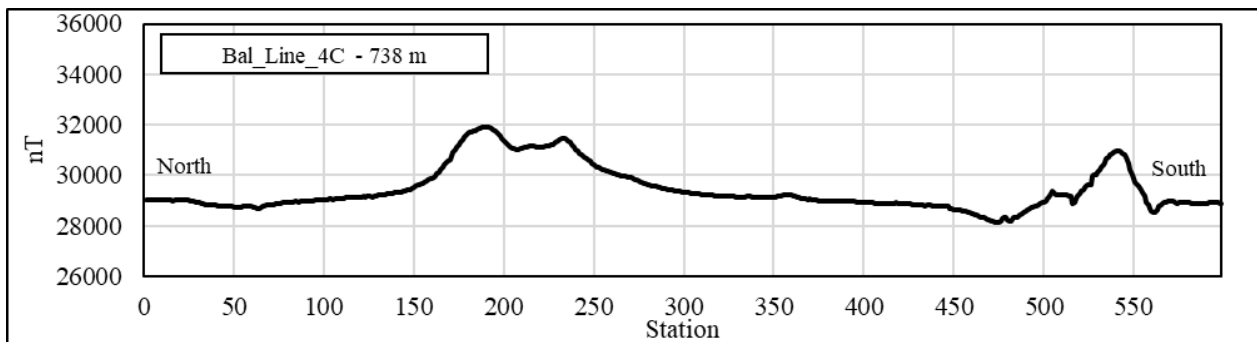


Figure 80 – Bal_Line_4C Magnetic Profile (738 m).

5.4.2 Electromagnetics

5.4.2.1 Motswari Electromagnetics Results

Only one profile was conducted in the Motswari study area, this profile was walked across the same length of profile as Mots_Line_6A, to identify anomaly signatures. The profile was 446 meters long

and recorded 53 stations. The profile is shown in Figure 81. The profile was stopped short before the electrical fencing surrounding the “Geiger Lodge Camp”, in order to ensure that there was no electrical interference from the lodge fencing.

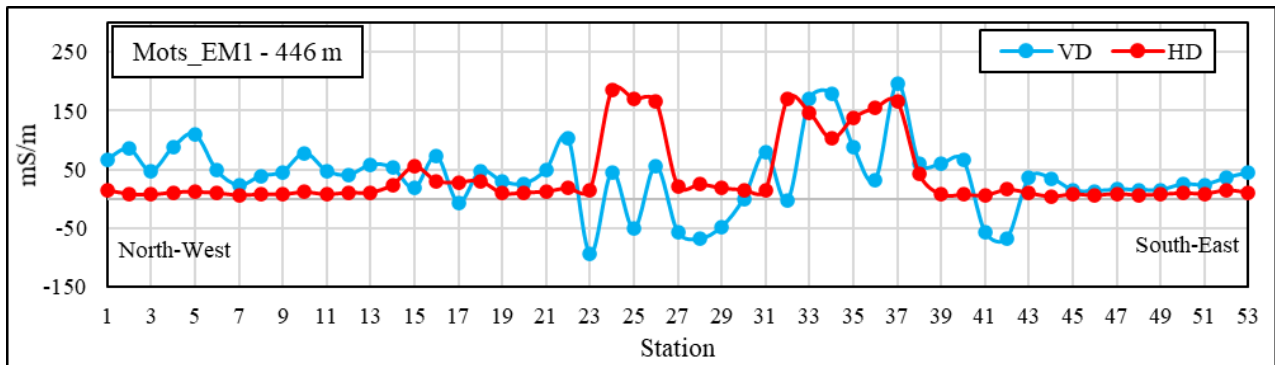


Figure 81 – Mots_EM1 Profile (446 m).

After investigating the EM data for Figure 81, the anomalies at stations 15, correlate to an observed lineament that is seen between stations 250 – 300 in Figure 63 and noted in the field from aerial imagery. Stations 23 – 27 appear to be aligned with a smaller magnetic anomaly and correlate to a mapped lineament. Interestingly enough, between stations 31 – 39, is a large anomaly noted which correlates to a mapped fault, suggesting that there is a North-East to South-West trending fault through the Mots_EM1 profile. This is shown on aerial imagery in Figure 82.

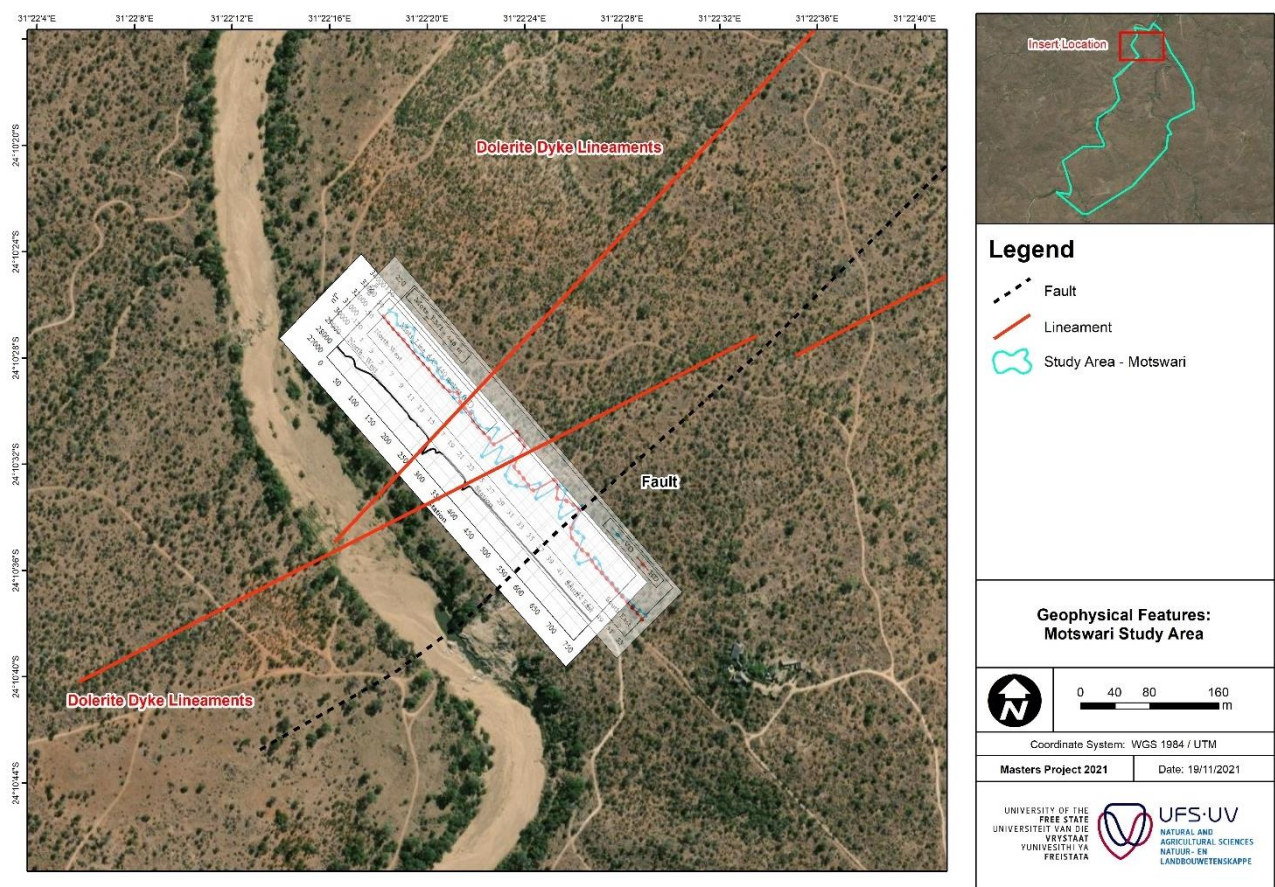


Figure 82 – Aerial imagery indicating the presence of fault and dyke anomalies.

5.4.2.2 Balule Electromagnetics Results

A total of 3 EM profiles were conducted within the Balule study area, similarly to Motswari, they were focused on similar profiles to the Magnetics profiles. A total of 1.1 km worth of EM data was obtained. The profiles are shown in Figure 83 to Figure 85.

Bal_EM1's Vertical Dipole measurement correlated with the mapped dyke in Bal_Line_1A (Figure 67) and may be indicative of a weathered zone after the deformation that occurred as the younger dyke intruded into the host rock of this particular location on the study area of Balule. Bal_EM2 (Figure 84) shows elevated Horizontal Dipole values between stations 33 to 37 over the Vertical Dipole and can suggest potential zones of weathering on either side of a dolerite dyke intrusion.

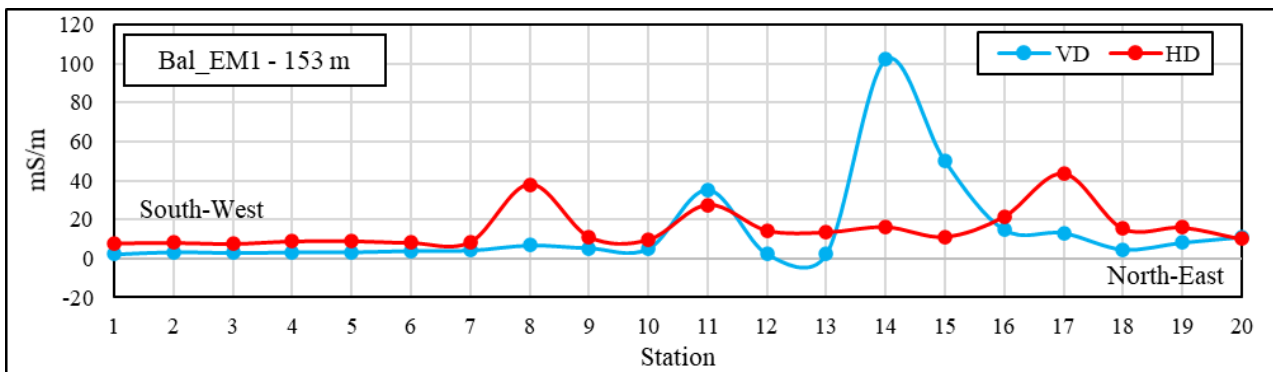


Figure 83 – Bal_EM1 Profile (153 m).

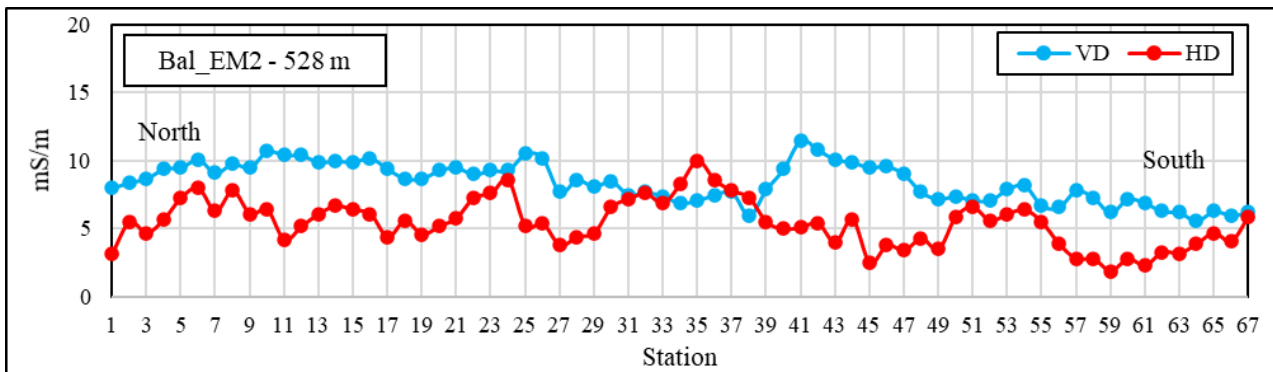


Figure 84 – Bal_EM2 Profile (528 m).

Bal_EM3 is a good example of a potential dyke anomaly structure. This is shown when the Horizontal Dipole measurements exceed the Vertical Dipole at station 29 in Figure 85. This observation correlates with the partnered Magnetics profile over the same stretch in Figure 75 (Bal_Line_3B), whereby a dyke signature is shown with elevated magnetic susceptibility between stations 120 to 140.

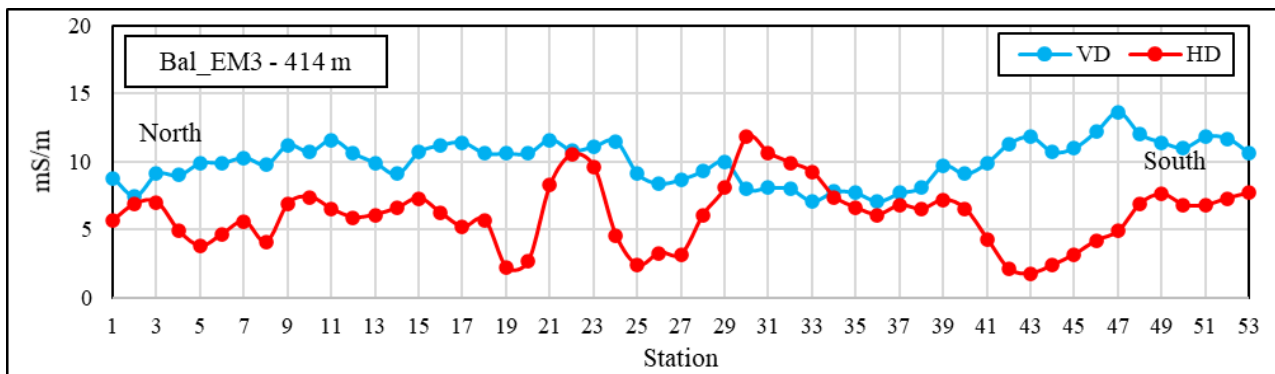


Figure 85 – Bal_EM3 Profile (414 m).

5.4.3 Summary of Geophysics

In summary, the Magnetics method was successful in confirming the presence of magnetic dolerite dykes within both study areas, anomalies noted in the profiles correlated well with aerial observed lineaments in both Figure 47 and Figure 48. The dolerite dykes shown on the magnetic traverses are assumed to be almost vertical within both study areas and range from a couple of meters thick to tens of meters wide. The profiles were additionally used to identify the trending direction of the profiles and this confirmed the trending direction of the dolerite dyke swarms, from North-East towards the South-West. The presence of groundwater flow was confirmed in the EM data through the identification of faults and fractured or baked zones between the dolerite intrusions and host rock. Dolerite dykes were discovered to be continuous lineaments, particularly seen in three Magnetics traverses in Balule, where anomaly signatures were identified across all three traverses that were continuous with one another. This is important as it delineates the likely preferential flow path of groundwater once it has recharged into the aquifer and will be discussed in the following chapter.

It is recommended that the geoelectric or resistivity method be used as part of the feasibility study to further accurately determine the specific dyke orientation and potential drill sites for both recharge boreholes and downgradient abstraction boreholes.

5.5 Hydrogeological Processes in the GKNP and Conceptual Model

Groundwater is a key component of water resource availability within the GKNP. Boreholes have an average blow yield of 4.04 L/s according to available NGA data. The sustainable yields of boreholes are likely much lower volumes and groundwater management is particularly lacking as groundwater users favour drilling new boreholes in place of sustainably managing what is available. Water levels have shown evidence of dropping since the start of monitoring in mid-2019 and only boreholes that are closely linked to surface water features show good seasonal response to rainfall. The surface water and groundwater are variably connected, shown with changes in the Olifants River water quality from upstream to downstream.

The controlling hydrogeological factor of the GKNP is geology and rainfall. Groundwater bearing features are dolerite dyke intrusions within host rock and secondary faulted fractures, faulting, weathered zones, as well as the contact of pluton intrusions (Harmony Granite) into the host rock of the study area. Cross-sections shown in Figure 86 and Figure 87 indicate the geological structures and role that the dolerite dyke intrusions and lineaments play in the groundwater network. Some boreholes have been sited based on dykes and lineaments, while others are drilled adjacent to drainage

lines for the downgradient flow of water. The water table has also been plotted and mirrors the topography by 85%.

Rainfall in the higher elevation areas falls during the hotter summer months, depending on rainfall intensity, the runoff will then infiltrate into the subsoil and then percolate to the groundwater table. Runoff also flows along the surface in drainage lines towards the North for both study sites and into non-perennial rivers as shown in Figure 23 for Motswari and into the Olifants river, shown in Figure 24. Infiltrated groundwater will be stored locally or flow along preferential flow paths such as the dolerite dykes and lineaments which have intruded into the host lithology. Secondary fractures and faults are also flow paths that groundwater can follow. Groundwater is then discharged to surface water, such as the Olifants River, and continues onwards in the hydrological cycle and away from the study area.

The conceptual model is shown in 2D through a variety of cross-sections in Figure 86 to Figure 88. The location of the cross-sections is displayed on the geology maps, Figure 25 and Figure 26. The first two figures include plotted water levels from boreholes that intersected through the profiles. Vertical to sub-vertical dykes and faulted zones are common throughout all three profiles and are often seen in close correlation to the boreholes, these are assumed to have been the original target for water supply at the time of drilling.

The conceptual models (Figure 86, Figure 87 and Figure 88) assist the reader and future feasibility studies in understanding and interpreting the hydrogeology of the study area. Groundwater flow direction is generally from higher to lower lying areas, supporting that any source water injected to the aquifer will be lost downgradient. The Makhutswi Gneiss aquifer units are the more favoured target units for groundwater exploitation and in particular, when these units are intersected by younger dolerite dykes. The conceptual model highlights the potential areas for MAR. These are whereby dolerite dykes intersect drainage lines (lowest topographical point), as this is where groundwater will accumulate and flow towards. The MAR scheme would need to take into account for groundwater flow away from the recharge site and this is discussed in the following chapter.

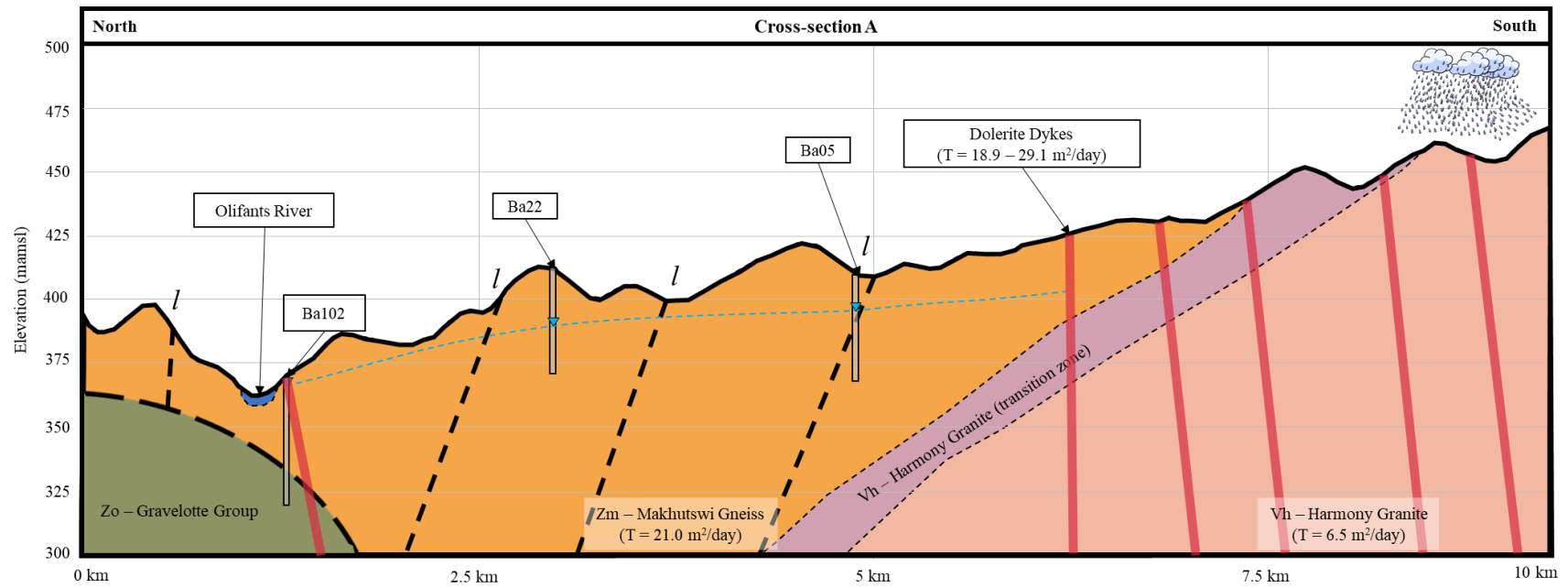


Figure 86 – Cross-section A showing North-South geological profile through Balule study area (Vertical Exaggeration – 1:50).

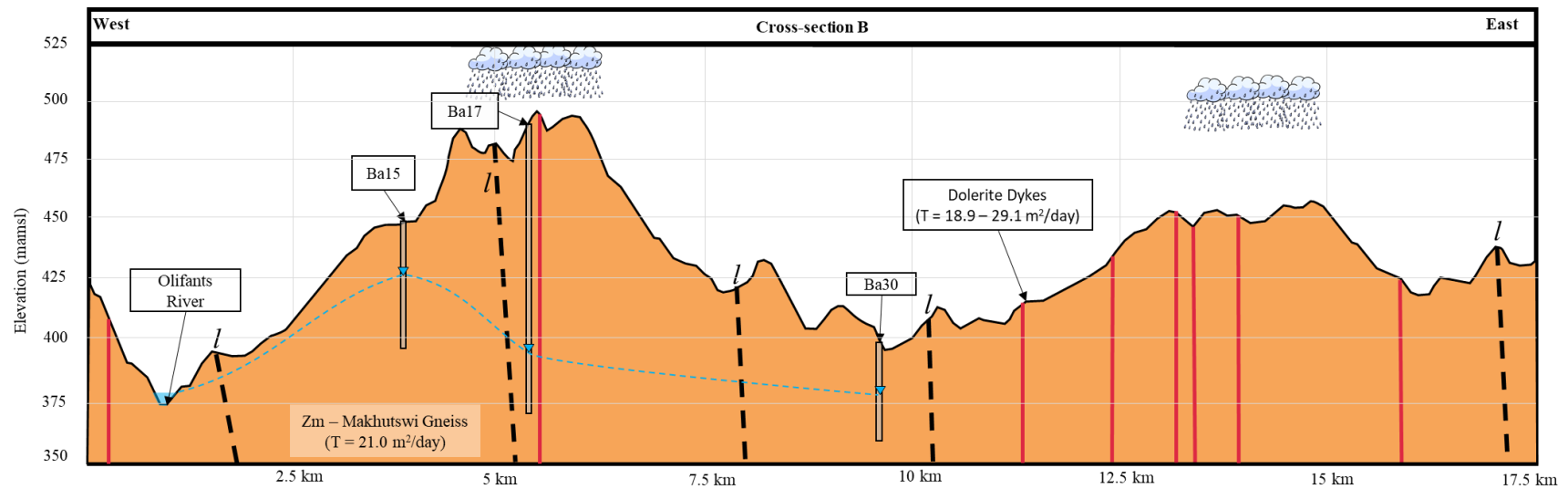


Figure 87 – Cross-section B showing West-East geological profile through Balule study area (Vertical Exaggeration – 1:100).

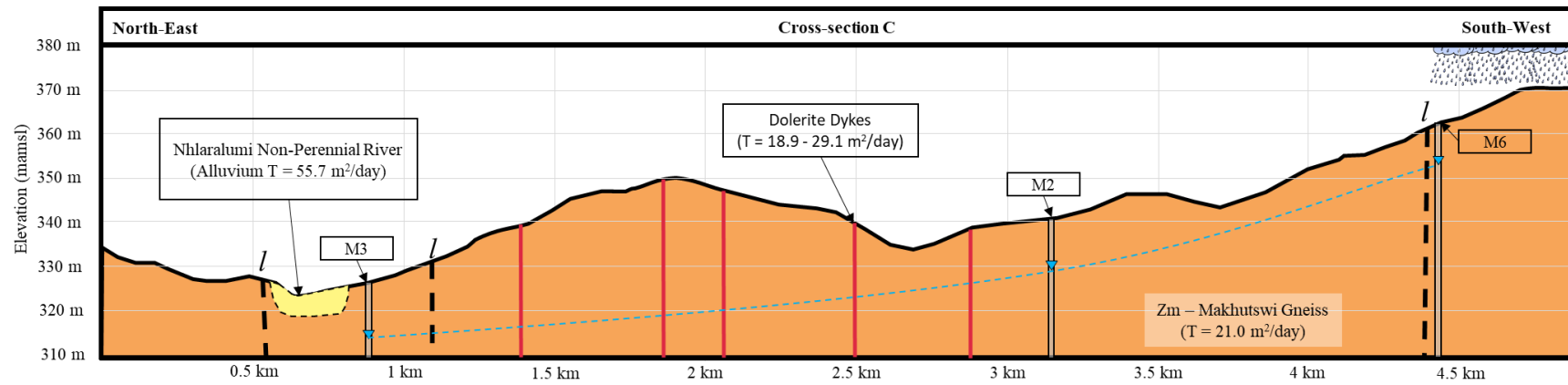


Figure 88 – Cross-section C showing North-East to South-West geological profile through Motswari study area (Vertical Exaggeration – 1:64).

CHAPTER 6: SUCCESS CRITERIA – KEY ACTIVITIES TO A PREFEASIBILITY STUDY FOR MAR

6.1 Introduction to Success Criteria

The project stage of a prefeasibility study requires four points; (1) the potential for MAR and a description of the information available, (2) feasibility of the study based on available data, (3) description of work required in the feasibility study and lastly to (4) establish whether there is an existing water use license condition or authorisation requirements (DWA, 2009). The success criteria for a prefeasibility study are listed in Table 1 and explained further in this section.

6.2 The Need for an Artificial Recharge Scheme

The needs and objectives for a MAR scheme within both study areas are listed below in order of need and importance and have been grouped as both study areas share the same objectives.

1. Increased water security, through increased recharge in the peak rainfall periods.
2. Increasing surface water infiltration for the dilution of the groundwater system and making the resultant water more desirable and reducing operational expenses.

While there are alternative forms of achieving these objectives, such as drilling more boreholes and developing a wellfield or building dams, even installing treatment plants, these are all more expensive and can take longer to implement. The construction of dams is not preferred within these study areas due to the high evaporation rates and wellfields will also not solve the water quality issue due to the poor natural groundwater quality. The operational ongoing costs of running treatment plants for example are high and a MAR scheme is also less invasive under the proposed methodology, discussed further in this chapter.

MAR will be a good solution to increasing water security, by refilling the aquifer during the rainy summer seasons and reducing loss from evaporation. Abstraction can take place in the dry winter period when the lodges and study areas see an influx of tourism. This in turn increases water demand and puts pressure on the aquifer system. The secondary objective can be achieved by introducing fresher source water, which will dilute the groundwater aquifer and overall provide better water quality at the abstraction (or collection) site downgradient of the recharge sites. MAR is likely to meet the primary objectives and secondary objectives.

6.3 The Source Waters

Every year, in the peak rainfall recharge season, an average of approximately 288 mm of rainfall is received in November through till February each year, during this time the non-perennial rivers are flowing for a period of time and large volumes of water are flushed through the drainage channel network. These periods of flow can last for a few hours, up until a week and is dependent on rainfall duration and intensity.

6.3.1 The Source Waters - Motswari

The MAR source water for Motswari will be in the form of floodwater after high-intensity rainfall events. An example of this floodwater is shown in the aerial imagery of Figure 89. Drainage channels will be used to guide the surface water to their respective recharge sites. The source water will vary and be inconsistent in regards to availability and quality. The MAR scheme will then be more opportunistic in its availability and only be able to recharge the groundwater system when source water is available. The closest approximation of this proposed MAR is the Kharkams MAR scheme (Braune and Israel, 2021). Due to the source water quality variation that is expected, it is recommended that as part of the feasibility study for MAR, that the surface water quality is monitored, both in seasonality variation and spatial distribution. The source water would enter the aquifers via appropriately selected recharge boreholes.



Figure 89 – Google Earth aerial imagery of floodwater through drainage channels in summer (left) and the same drainage channels void of any surface water in winter (right).

6.3.2 The Source Waters - Balule

The source water for Balule is similar to Motswari, floodwater runoff after high-intensity rainfall events. An example of this on a local scale is shown in Figure 90. This shows the variation between summer (high rainfall) and winter (low rainfall) within drainage lines and the impact that the source water has on the terrain. The images on the left are a good example of how the region experiences excess water runoff that can be used as source water to the MAR scheme. This water then makes its way into the larger rivers such as the Olifants, where it is lost downstream to neighbouring

communities and often becomes polluted due to poor hygienic practices. The source water would enter the aquifers via appropriately selected recharge boreholes.



Figure 90 – Variation in vegetation and seasonal drainage line flow between summer (left) and winter (right).

6.4 Aquifer Hydraulics

The aquifer hydraulics per study site is slightly variable, as Motswari is dominated by the Makhutswi Gneiss basement rocks, while Balule has an intrusion of the Harmony granite and transition zone, with a deeper underlying Gravelotte group in the north. Both study sites have mapped lineaments and the dolerite dyke swarm trending North-West to South-West. Each study site's aquifer hydraulics and potential for groundwater recharge is discussed separately below.

6.4.1 Aquifer Hydraulics - Motswari

Groundwater will be stored within the fractured dyke swarm network and mapped lineaments, as recharge boreholes would be targeted for these sites, shown visually in Figure 91. This image was taken of the Motswari study area. It is recommended that injection tests are completed as part of a feasibility study as only available literature could be sourced to give information on the transmissivity of the aquifer. Based on transmissivity values calculated from Holland (2012), the aquifer will receive the source water since the recharge method is opportunistic and whether the aquifer is partially full or empty, recharge can take place through the MAR method.

Due to the water table following the general topography, it's also suggested then that the source water will be lost downgradient of the source water injection sites. It will then be important to site these recharge boreholes upgradient of the abstraction boreholes, within the same lineaments or dykes, as shown in Figure 91. The narrow dolerite dykes are good preferential flow pathways if they are less than 10 m's thick. If they are thicker, then they will act as impermeable flow boundaries (Holland, 2012). The dolerite dyke lineament in Figure 91 is the same anomaly signature shown from Mots_Line_5D (Figure 62).

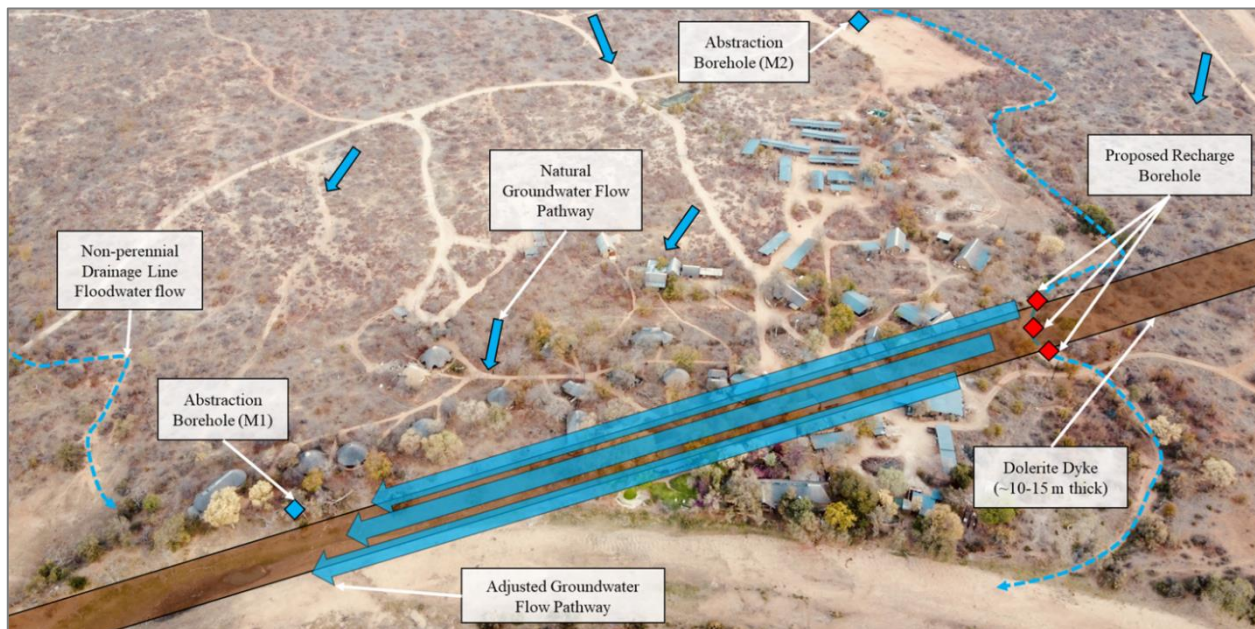


Figure 91 – Aerial imagery example of proposed recharge site is upgradient of abstraction sites (authors own).

Water strike depths within the Makhutswi Gneiss are commonly between 10-20 m from the surface and 80% of the water strikes identified within boreholes are between 10-60 m from the surface (Vegter, 2003). These strikes are likely the secondary fractures within the units or dolerite intrusions and are useful to help with borehole design to a MAR scheme.

An important aspect to a prefeasibility study that needs to be answered is whether the aquifer has sufficient storage to hold the recharged groundwater, for example, will the aquifer be able to store recharge water in summer before the onset of the winter season when there is almost no rainfall. In the instance of this study, the recharge rate is variable and cannot be guaranteed, as it is dependent on runoff after high-intensity rainfall events.

An additional aspect to consider as per a MAR prefeasibility study is whether the aquifer is permeable enough to receive the recharge water at a planned recharge rate. For the proposed opportunistic recharge method, it is certain that a predetermined desirable recharge rate will not be able to be guaranteed. For this reason, any recharged water, at any rate, is desirable. Aquifer transmissivity is an indication of whether groundwater can flow through an aquifer section of a unit under a hydraulic gradient (Goulburn-Murray WATER, 2015). The average transmissivity for units within the Motswari areas was calculated as 25.19 m²/day, with lineaments having a positive influence on borehole productivity (Holland, 2012). Injection testing is recommended as part of the feasibility testing within this site.

6.4.2 Aquifer Hydraulics - Balule

Boreholes located on the contact of the intrusive batholiths provided a higher potential for groundwater development (Holland, 2012), for this reason, boreholes closer to the Harmony Granite and transition zone can also be considered for groundwater development as MAR schemes, this is specific to only the Balule study area. A summary of aquifer transmissivities within the study area can be seen in Table 5. As stated in the previous section, source water will be opportunistic and therefore there will be no standardised or constant recharge rate to the recharge sites. Aquifer parameters, particularly transmissivity, are expected to be similar to the Motswari study site, due to the similar geology. The cross-sections of both study sites can be seen in Figure 86 to Figure 88.

Based on the above values, the aquifer will be able to receive the source water and if the recharge rate of the source water exceeds the borehole or aquifer's ability to receive, it will be excess runoff water and continue under natural conditions down the drainage lines, surpassing the recharge sites.

Figure 92 shows a potential location of seven MAR recharge boreholes that are upgradient of the proposed abstraction boreholes, using the magnetics data to delineate the continuation of the lineaments, shown as solid red lines in Figure 92. The recharge boreholes are located within drainage lines, where the lineaments and dykes intersect with these drainage lines, allowing source water to enter the fractured zone of the lineament within the host rock, through recharge boreholes. Injection testing is recommended as part of the feasibility testing.

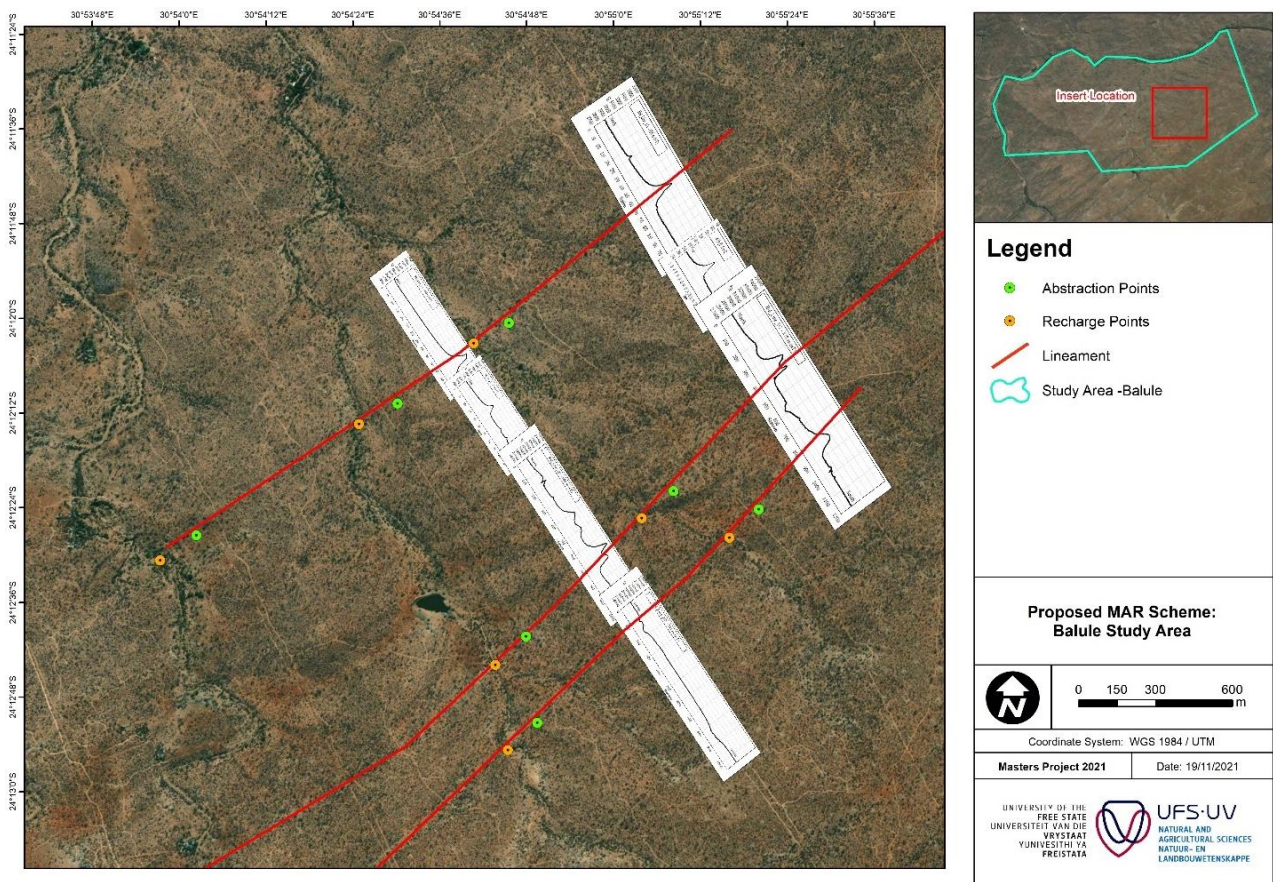


Figure 92 – Proposed MAR sites within Balule, upgradient boreholes sited at the highest point of lineaments, using geophysical methods, into the drainage line.

6.5 Water Quality

An important aspect of a prefeasibility study is to determine whether the source water quality is suitable for recharge, the potential for clogging concerns and whether blending will improve or deteriorate the groundwater quality. Understanding the natural groundwater quality is important and has been discussed in Chapter 5. The process of blending is discussed briefly below:

- Average groundwater quality is determined of both study sites, where results were below the detection limit, the detection limit was used as an estimate for calculation of averages.
- Similarly, the average surface water quality was determined for each site.
- Mixing was completed using the following ratios, then compared against DWAF (1996) drinking water quality guidelines.
 - 50% groundwater and 50% surface water
 - 25% groundwater and 75% surface water
 - 5% groundwater and 95% surface water

Source water quality results are shown in APPENDIX C – LABORATORY CHEMISTRY RESULTS (IGS). No geochemical modelling was completed in this dissertation and it has been recommended to include geochemical modelling into the feasibility study.

6.5.1 Water Quality - Motswari

The source water for Motswari is of good quality. It is rainfall-runoff and runs across pristine terrain that has been untouched by any anthropogenic activities. One noted potential of concern is small debris that gets transported across the runoff areas. Only one surface water sample could be collected within the Motswari study area and this was classed as ideal water quality (Class I) except for slightly elevated aluminium (Al) (Class II). It is not known whether this is a once-off occurrence and further surface water monitoring should be conducted as part of the feasibility study. The source water quality is much better than the groundwater. There will be a mixing of the two water qualities and thus making it overall better, the results of the different mixing ratios are shown in Table 13. All parameters indicate an improvement in water quality, except for aluminium (Al) and iron (Fe). The mixing of surface water with groundwater will cause an improvement of the natural groundwater quality and the final estimate of groundwater quality is shown in Table 13, particularly as more surface water is mixed with groundwater. The mixing of groundwater and surface water in the Motswari study site indicated an overall improved water quality from marginal (Class II) to good water quality (Class I).

As with most groundwater systems, the potential for clogging is prevalent, however, in these instances, the only concern will be the build-up of a calcium bicarbonate precipitate or to a smaller degree, iron biofouling. Both calcium and iron are naturally present in the groundwater system. Examples of precipitation shown on the current groundwater supply at Motswari are shown in Figure 93. It is recommended that geochemical modelling be completed for a full feasibility study, to determine the extent of precipitation and clogging within the MAR scheme.



Figure 93 – Image showing precipitate build-up on the borehole water supply, from parts of the submersible pump.

6.5.2 Water Quality - Balule

The source water of Balule is much more variable than Motswari, this is due to more surface water samples having been collected and as such more variation will be shown in the chemistry data. Drainage line samples were collected by landowners after intense rainfall events and if the drainage lines flooded. No locations were recorded by the landowners for these sites and as such, these locations are not provided in this dissertation.

Balule average source water is classed as ideal (Class O) for all parameters except for aluminium (Al). Mixing of surface water and groundwater results are summarised in Table 14. The mixing of more surface water with groundwater will result in an overall improvement of the final groundwater quality. Similar to Motswari, aluminium and iron displayed a worsening water quality when increased surface water was mixed with groundwater. The mixing of groundwater and surface water in the Balule study site indicated an overall improved water quality from poor (Class III) to good water quality (Class I).

Clogging is expected to be a concern, however, from the water quality observed in Table 14, it is assumed that the potential for clogging and mineralization will be worse than Motswari as the groundwater quality at Balule is worse. Should this prefeasibility study progress to a full feasibility study, it is recommended that geochemical modelling be completed and more source water samples are collected.

Table 13 – Results of mixing groundwater and surface water in comparison to DWAF (1996) – Motswari.

Description	pH	EC	Ca	Mg	Na	K	MAIc	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
Motswari : Average GW	7.41	185.03	70.31	66.10	248.99	8.91	451.65	0.86	328.05	3.92	60.32	175.63	271.88	447.51	1351.07	0.02	0.04	0.24	0.04	0.01	0.02	0.10	0.02	0.02	31.34	0.70	0.03	0.10	0.04	0.02	0.02	II
Motswari : Average SW	7.22	18.94	16.58	5.64	16.75	7.53	75.69	0.12	14.30	0.38	6.30	41.40	23.22	64.62	149.07	0.42	0.02	0.04	0.04	0.01	0.36	0.02	0.02	0.02	9.25	0.12	0.03	0.01	0.02	0.02	0.02	I
Motswari - 50% GW : 50 SW%	7.31	101.99	43.45	35.87	132.87	8.22	263.67	0.49	171.17	2.15	33.31	108.52	147.55	256.07	750.07	0.22	0.03	0.14	0.04	0.01	0.19	0.06	0.02	0.02	20.29	0.41	0.03	0.05	0.03	0.02	0.02	I
Motswari - 25 GW% : 75 SW%	7.26	60.46	30.01	20.75	74.81	7.87	169.68	0.30	92.74	1.26	19.81	74.96	85.38	160.34	449.57	0.32	0.02	0.09	0.04	0.01	0.27	0.04	0.02	0.02	14.77	0.27	0.03	0.03	0.03	0.02	0.02	I
Motswari - 05 GW% : 95 SW%	7.22	27.25	19.27	8.66	28.36	7.60	94.49	0.16	29.99	0.56	9.00	48.12	35.65	83.77	209.17	0.40	0.02	0.05	0.04	0.01	0.34	0.02	0.02	0.02	10.35	0.15	0.03	0.01	0.02	0.02	0.02	I

Table 14 – Results of mixing groundwater and surface water in comparison to DWAF (1996) – Balule.

Description	pH	EC	Ca	Mg	Na	K	MAIc	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
Balule : Average Groundwater	7.13	168.14	85.83	64.26	169.14	11.95	327.14	1.51	296.33	3.04	90.76	214.38	264.29	478.67	1051.12	0.02	0.02	0.11	0.14	0.02	0.03	0.06	0.02	0.02	29.93	0.78	0.03	0.01	0.05	0.03	0.02	III
Balule : Average Surface Water	6.99	23.02	18.13	6.26	24.47	6.44	98.37	0.45	23.42	0.34	5.87	45.27	25.78	71.05	145.70	0.28	0.02	0.05	0.04	0.01	0.37	0.04	0.02	0.02	7.90	0.15	0.03	0.01	0.02	0.02	0.02	I
Balule - 50% GW : 50% SW	7.06	95.58	51.98	35.26	96.80	9.20	212.76	0.98	159.87	1.69	48.31	129.83	145.03	274.86	598.41	0.15	0.02	0.08	0.09	0.02	0.20	0.05	0.02	0.02	18.91	0.47	0.03	0.01	0.03	0.02	0.02	I
Balule - 25% GW : 75% SW	7.03	59.30	35.05	20.76	60.63	7.82	155.57	0.72	91.64	1.01	27.09	87.55	85.40	172.95	372.06	0.22	0.02	0.06	0.07	0.01	0.28	0.04	0.02	0.02	13.41	0.31	0.03	0.01	0.03	0.02	0.02	I
Balule - 05% GW : 95% SW	7.00	30.27	21.51	9.16	31.70	6.72	109.81	0.50	37.06	0.47	10.11	53.72	37.70	91.43	190.97	0.27	0.02	0.05	0.05	0.01	0.35	0.04	0.02	0.02	9.00	0.18	0.03	0.01	0.02	0.02	0.02	I

6.6 The Recharge Method and Engineering Issues

The water will be recharged to the aquifer through recharge boreholes drilled into drainage lines that intersect with dolerite dykes or mapped lineaments, upgradient of the abstraction boreholes. The drilled boreholes will be cased within the shallow primary aquifer, to prevent recharge from base flow and allow recharge to the deeper secondary aquifer only, the surrounding riverbed sand will additionally act as a natural sand filter. The recharged water will then be abstracted by production boreholes, downgradient of the recharge site and within the same lineaments or dykes as the recharge borehole. This MAR method is termed Aquifer Storage Transfer and Recovery (ASTR), shown in Figure 91 and as a flow diagram in Figure 94.

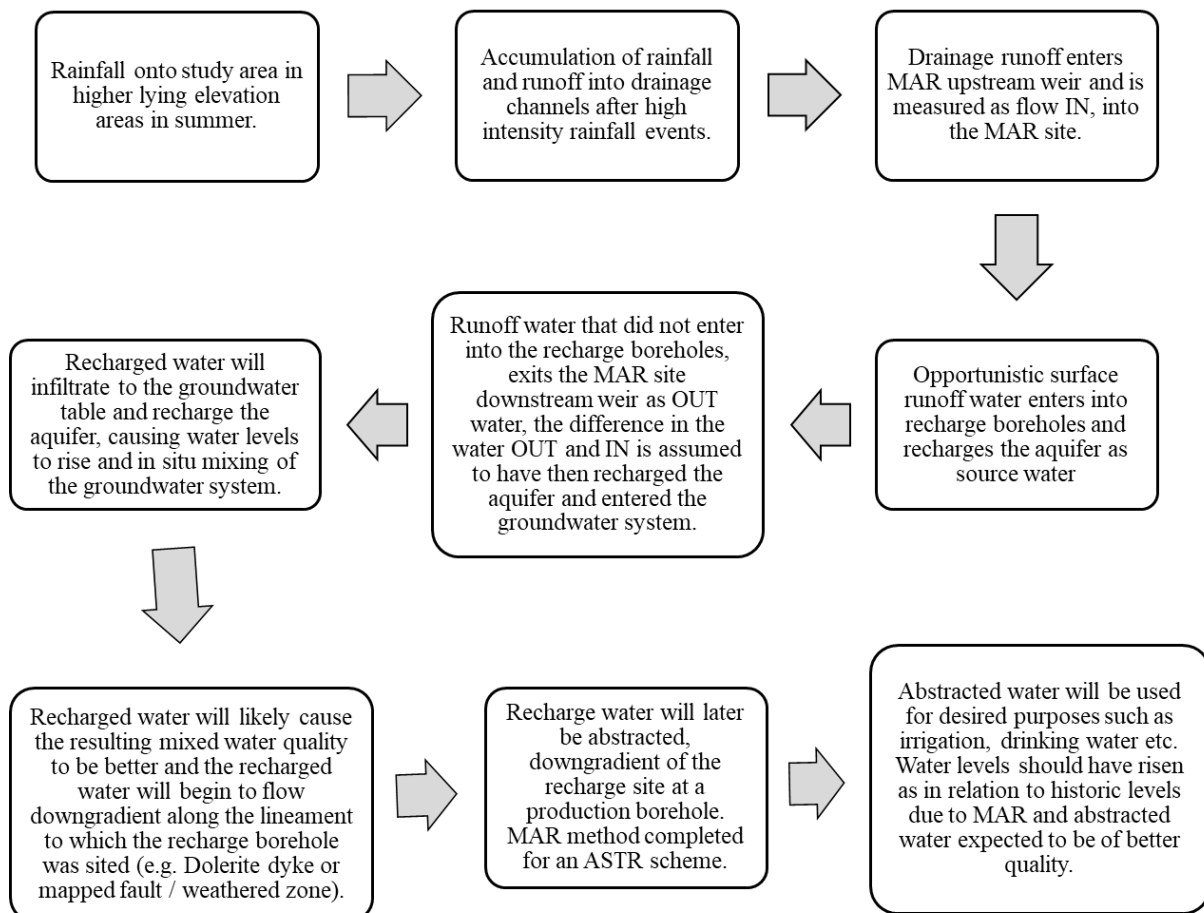


Figure 94 – Flow diagram illustration showing recharge process from rainfall to abstraction downgradient of recharge site.

The potential engineering issues will be the annual maintenance of the aquifer scheme, requiring a clean out of the rubble and washing through overburden/vegetation material that would have been deposited during floodwater events. This can be done through an overall general maintenance plan. No treatment processes will be required, just a filter mechanism to prevent larger rocks/boulders and even animals from making their way into the recharge boreholes. The proposed recharge borehole drilling construction is shown in Figure 95, although there is no set or standard depth to which the recharge borehole must be constructed, it will be dependent on geology and the depth of intersecting water strikes. Both the recharge borehole and abstraction borehole construction have been provided

in Figure 95. The recharge borehole differs slightly from the abstraction borehole, by having slotted PVC casing installed along the entire depth of the borehole, this is to increase structural integrity of the borehole and prevent collapse. The slotted stainless-steel grate is to prevent sand ingress and will need to be specified per site conditions.

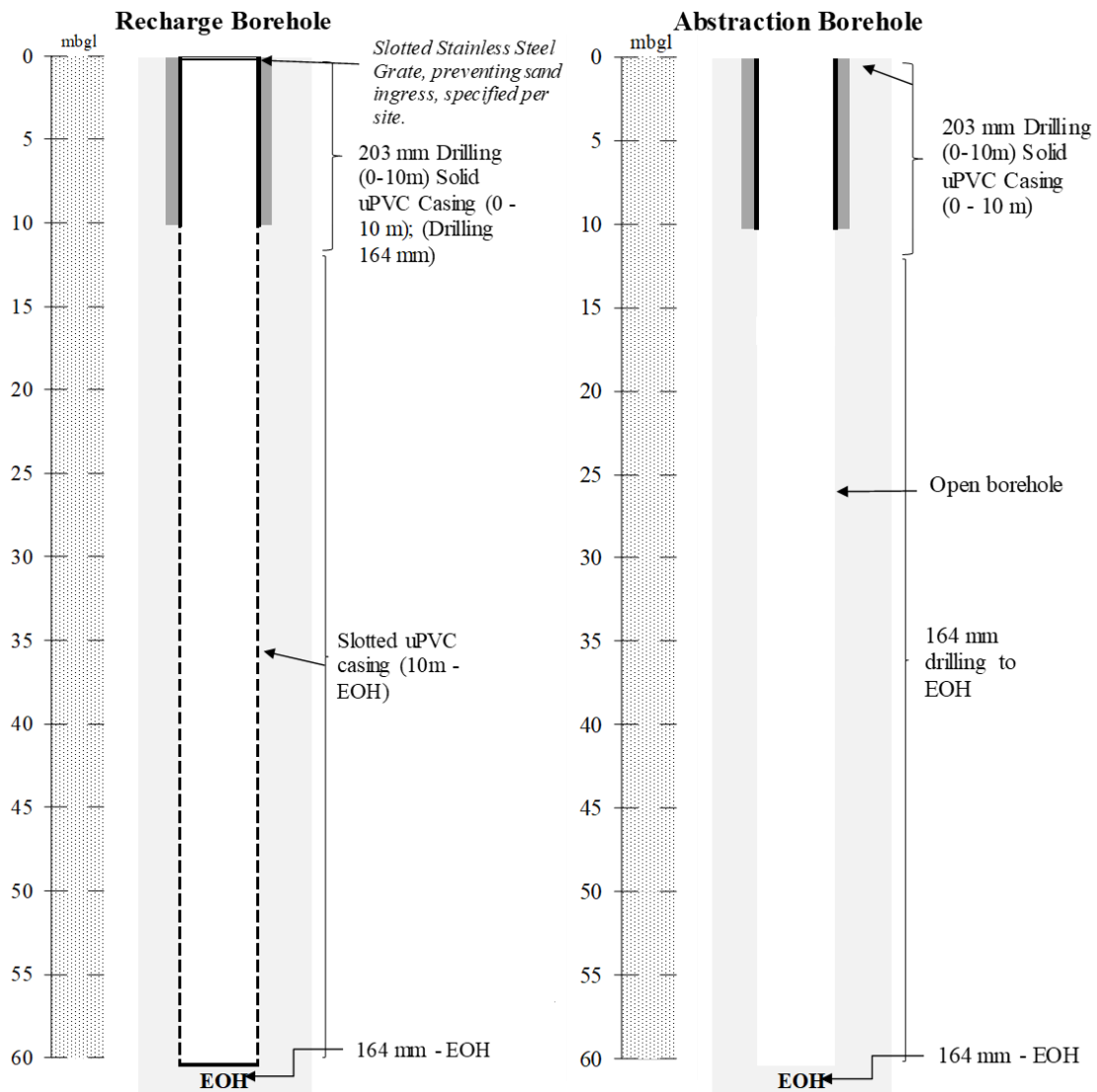


Figure 95 – Proposed Borehole Construction for recharge boreholes (left) and abstraction boreholes (right), downgradient of the recharge boreholes.

Due to the nature of groundwater recharge, no backfill will be required within the recharge borehole and additionally, the depth to which the borehole will need to be drilled will be dependent on lithology. Similarly, to MAR schemes designed in Sutherland (Fourie, 2021), the method can be designed to enhance the recharge to the aquifer when water is available. It has been termed a Nature-Based Solutions Approach (Fourie, 2021). Proposed methods were to use trenches, infiltration ponds and weirs. In the case of this study area within both Balule and Motswari, the trenches and infiltration ponds are suggested to be replaced with boreholes drilled into the drainage lines, where they coincide with the dolerite dykes or lineaments. Figure 96 is an example of how rock weirs within the drainage lines are to be constructed to slow the flow of water and increase recharge.

An important aspect to a MAR scheme is the extraction of injected MAR water, within the scheme. In some locations, there is a need to drill additional abstraction boreholes (as they do not exist), they will need to be drilled downgradient of the recharge sites. An example where no extraction points are required can be seen in Figure 91, as they currently already exist. The completed geophysical exploration work done can additionally be used further for both extraction borehole siting and recharge borehole sites. The MAR method is proposed to be the same for both study sites. To determine the volume of water being recharged to the groundwater table, it is suggested that with the MAR scheme, upstream weirs and downstream weirs be constructed to measure the continuous volume of water entering the recharge site and the volume exiting the recharge site. The difference will then be the volume of surface water recharged to the groundwater system with a flood event as well as some water will be lost to evaporation as there will be standing water between the measurement weirs.

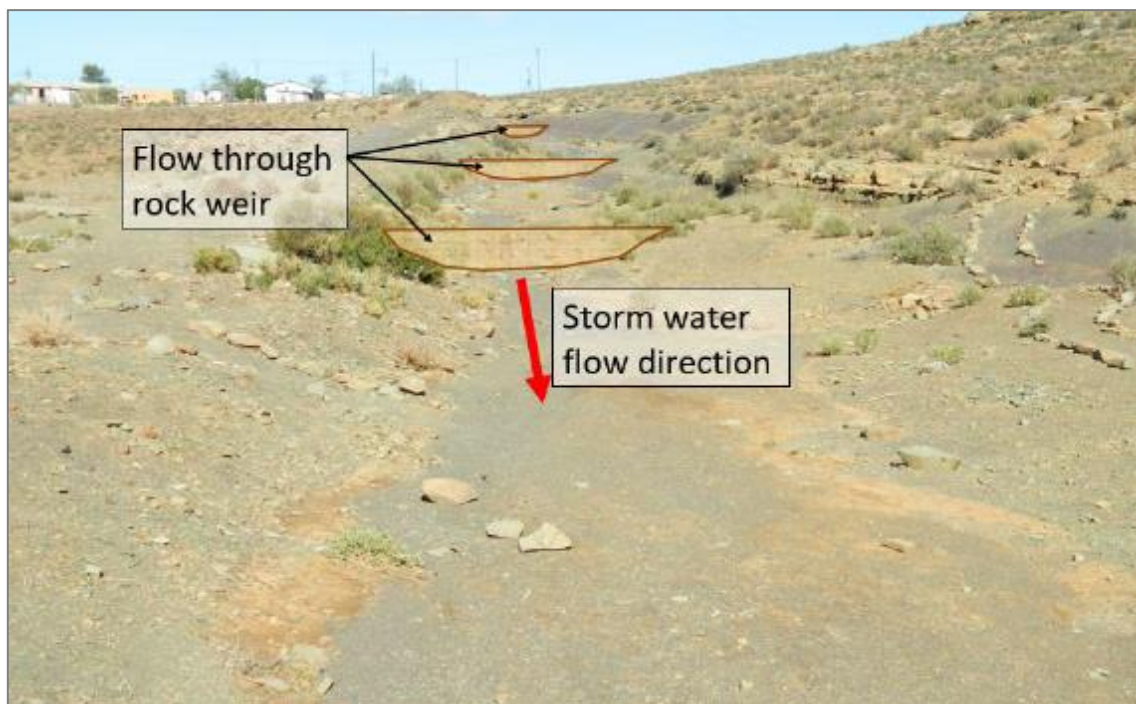


Figure 96 – Upstream view of canals in Sutherland where rock weirs are proposed to be constructed to slow the flow of water and increase recharge (Fourie, 2021).

It is recommended for the feasibility study to include a water balance calculation (including evapotranspiration) for each site. As well as the development of a numerical model to determine the range of potential recharge water volumes and radius of influence on water quality to determine if the groundwater users of the abstraction boreholes will benefit from the MAR scheme.

6.7 Environmental Issues

Some environmental issues were identified. As drilling would take place in river courses or drainage lines, further National Environmental Management Act (NEMA) practices will need to be followed and environmental impact assessments, potentially be completed. A major potential concern to drilling boreholes within a drainage line would be the reduction in base flow and this would need to be investigated further within the MAR feasibility study. The environmental issues are assumed to be the same for both study sites, due to similar settings. No further environmental issues were identified,

except for ensuring that animals and small rodents do not find their way into the borehole access chamber or that the construction of weirs may reduce the total flow to the confluence of downstream rivers.

6.8 Legal and Regulatory Issues

As with this particular study, should a full feasibility study commence, a Water Use License Application (WULA) would need to be filed, this can take anywhere from 90 to more than 300 days for full authorisation. Water rights would need to be identified as specific sections of the NWA would become relevant, such as the following:

- 21 (a) – taking water from a water resource
- 21 (c) – impeding or diverting the flow of water in a river course
- 21 (d) – engaging in a stream flow reduction activity contemplated in section 36
- 21 (e) – engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1)

No existing lawful use (ELU) could be found within either study area. Only one ELU was found within the request to DWS and this was outside both study areas, however in the same catchment. No further information was requested on this ELU as the distance rendered the ELU irrelevant to the study areas. At the Motswari study site, a WULA was in the process of being filed, however, it was never completed. To complete a feasibility study, a Water Use License will need to be acquired.

6.9 Economics

In order to develop a MAR scheme for either Balule or Motswari an estimation on costs for the scheme is required. The following costs will be required as shown in Table 15 and Table 16. The total cost of the entire scheme will be approximately R352,000 – R755,000 over 3 years to implement. An annual maintenance cost of approximately R20,000 will be required per artificial recharge site. As indicated on the previous page, the initial start-up costs of this scheme are the bulk of costs over a 10-to-50-year period, with the cost recovery likely to be received in the following few years. This should be compared against the cost of drilling additional boreholes for water supply or installing reverse osmosis/treatment facilities.

Table 15 – Estimated costs to complete a feasibility study.

Feasibility study Items	Contractor Fees	Professional Fees
Geophysical exploration and siting of recharge and abstraction borehole sites.	0	R40,000 – R60,000
Environmental Impact Assessment (Including Geochemical Modelling)	0	R100,000 – R350,000
Design of MAR Scheme	0	R40,000 – R80,000
Water Use License Application	0	R25,000 – R30,000
Injection testing per borehole	R10,000 – R15,000	R5,000 – R10,000
Total	R10,000 – R15,000	R210,000 – R530,000

Table 16 – Estimated costs to develop a MAR scheme within the study area (single site with multiple recharge boreholes/abstraction boreholes).

Scheme development items	Contractor Fees	Professional Fees
Drilling per borehole with mud rotary followed by percussion to an approximate depth of 60 m's	R50,000 – R100,000	R10,000 – R15,000
Installation and construction of two measuring weirs	R40,000 – R50,000	0
Implementation and Maintenance of MAR scheme annually	R5,000	R15,000
Equipping of dedicated monitoring borehole	R10,000 – R15,000	R2,000 – R10,000
Total	R105,000 – R175,000	R27,000 – R40,000

Both options can be particularly expensive and neither do they achieve the objective of water security or providing better water quality at an affordable price. To complete a prefeasibility study economics check-list, the cost of MAR needs to be compared in Rands per Cubic Meters (or kilolitre (kL)) to other water source options. In the case of this prefeasibility study, the investment cost of a MAR scheme (for one site) was compared to the water treatment costs of treating the existing water to drinking water standards. The majority of groundwater users are already using some form of treatment system on the water supply and these can become very expensive to continually maintain and keep in a working condition, particularly in remote locations. The construction of dams has been excluded for consideration from this study, as the GKNP has resorted to the removal of artificial dams, particularly for water supply to allow the area to return to a more natural state (Spies et al., 2018). Building more dams to substitute water supply from groundwater is not ideal for the study area.

Two separate water treatment companies were approached for the capital expense (CAPEX) and operational expenses (OPEX) for a treatment system to treat the current groundwater to drinking standards. Both treatment companies were provided with the same groundwater quality samples. This was compared in R/kL for each treatment company against the costs of developing a MAR scheme. The costs in Table 17 are all best estimates per scheme and water source. For comparative purposes, the costs of treating and supplying 30 kL per day were used and OPEX costs were extended to costs per annum (10,950 kL/annum).

Table 17 – Comparative costs for CAPEX and OPEX to implement either a MAR scheme or treatment of existing groundwater quality to drinking standards.

	Managed Aquifer Recharge (feasibility study and implementation)	Treatment Company #1	Treatment Company #2
CAPEX	R352,000.00 – R775,000.00	R300,000.00	R450,000.00
OPEX (per annum)	R20,000.00	R156,000.00	R150,000.00
Capex R/kL	R32.14 – R70.78	R27.50	R41.10
OPEX R/kL (per annum)	R1.83	R14.23	R13.70

From the costs observed in Table 17, the CAPEX expense for a MAR scheme is higher. After investigating the comparative costs from the most expensive to the most affordable, a MAR scheme is relatively similar to a treatment system. However, where the OPEX costs of a treatment system can be as high as R156,000 per annum, the operational costs of a MAR scheme are noticeably less. It must be noted that should a MAR scheme require extensive WUL compliance conditions, the OPEX

can likely increase through license compliance conditions. Based on the costs of a MAR scheme and benefits of added water security and opportunistic water treatment through mixing, the costs for CAPEX and OPEX are worth investing for the progression to a feasibility study.

6.10 Management and Technical Capacity

The scheme will be maintained by local groundwater users who would benefit from the implementation of the MAR scheme. Ultimately in the future, the scheme will be larger and maintained by the water user's association. However, for the MAR scheme to become self-sufficient and managed correctly, the following skills will need to be transferred from a hydrogeologist to local management authorities:

- Accurately measuring water levels with a dip-meter and tape measure, for the tracking and recording of water levels.
- Collecting representative water samples and measuring *in situ* water quality from monitoring boreholes to monitor whether the MAR scheme is optimised and performing as intended.
- Clearly and legibly recording the above measurements on the provided field sheets for the later processing of a project hydrogeologist.
- Ability to clean out weirs, shallow recharge boreholes and reliable infrastructure to the MAR scheme.

The data that is recorded and used in this MAR scheme at a later stage is intended to serve as a case study for similar exercises in related settings and regions that are facing the same problems for groundwater security and water quality. An appointed hydrogeologist is important to oversee the MAR scheme and ensure it is best managed and cared for, scientifically.

6.11 Institutional Arrangements

The source water will be supplied through annual rainfall during the summer season. The source water is free and thus will not have any additional costs, although there is a large investment of the MAR scheme to use the source water, as shown in Table 17. It is suggested that the water quality from the injection sites, source water and abstraction water be tested quarterly to monitor the changes in water quality per season. The scheme will be monitored and managed by private individuals under their WUL conditions and the guidance of an appointed hydrogeologist.

6.12 Pre-feasibility Study Checklist Summary

After the successful completion of the Prefeasibility study checklist, both study areas of Motswari and Balule are appropriate for progression to a full feasibility study. By introducing fresh runoff source water to the groundwater system through the ASTR methodology, an MAR scheme can be developed at these two study sites. The Motswari study area's objectives are more aligned towards improving the overall water quality of the groundwater system and this can be achieved through an MAR scheme. The Balule study area's objective are more focused towards reducing the observed impact of a dropping water level trend, shown at monitoring boreholes. The reversal of this unsustainable groundwater use can be achieved through an MAR scheme. Both study sites should be considered as potential future MAR schemes and feasibility studies should be conducted on both sites in the next 4 to 5 years.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The main findings of the study can be summarised as follows, in conjunction with the aims and objectives of the study:

The study area's hydrogeology is controlled by the dominant geology of the area, being the metamorphic Makhutswi Gneiss or Harmony Granite pluton and much younger intrusive dolerite dyke swarms. This geology controls the flow pathways, residence time and extent to groundwater recharge under natural conditions. A small portion of alluvium adjacent to the perennial Olifants River and flood plains in the study areas is estimated to have the highest transmissivity, followed by the dolerite dyke structures and Archaean gneiss which dominates both study areas.

Monitoring water level data indicates that the average water level drop is approximately 2.14 meters since mid-2019 from the Balule study area. This water level drop may be a result of the aquifer being dewatered as a result of reduced rainfall recharge or over-abstraction of the groundwater resource from groundwater users.

The natural water quality of the groundwater within the study areas is classified according to DWAF (1996) as marginal to poor water quality (Class II to Class III) and many groundwater users are reliant on treating the water before consumption. In areas where the groundwater system is connected to the surface water system (such as a river or shallow dam), seasonal variations of water quality have been observed. The source water quality was a more preferable water quality, except for two dissolved metals, aluminium and iron. Mixing calculations between the source water and groundwater indicated an overall improvement of the water quality, particularly when a larger concentration of source water was mixed with a smaller concentration of groundwater. In both study areas, the water quality indicated an improvement to a DWAF (1996) classification of Class I, according to mixing ratio calculations.

The surface water and groundwater interactions are variable within the study areas. Indications of increased chemical trace concentrations are observed along the course and downstream of the perennial Olifants River in the month of March 2020 indicated that the surface water system is groundwater fed through recharge zones migrating towards the Olifants River as base flow. The hypothesis that the Olifants River is connected to the groundwater regime is supported by the hydraulic gradient flowing towards the river, based on field measurements and presented in groundwater flow direction maps. However, in the sampling periods of July 2019, October 2020 and April 2021 a small percentage increase and decrease are observed suggesting that the Olifants River is only partially receiving base flow, as some parameters indicate an increase and others indicate a decrease in ionic concentration. A seasonal variation of groundwater and surface water interaction may exist within the study area between the Olifants River and the groundwater. This hypothesis will require proof through aquifer testing and groundwater monitoring as part of a feasibility study.

Field visits and the collection of hydrogeological data contributed towards the development of a conceptual site model, the interpreted data and information has been used further for identifying potential drill targets (recharge boreholes and abstraction boreholes) for a MAR scheme. The recharge boreholes can be constructed in such a manner as to become direct recharge flow paths for flooding surface water and increase the recharge rate and infiltration. The surface water will infiltrate into these recharge sites to the groundwater, where increased recharge and recovering water levels are expected. A dilution effect is expected to improve water quality and make it more potable or less

harsh on the maintenance required with infrastructure in the existing water supply schemes. In addition to identifying recharge boreholes, abstraction boreholes have been identified to complete the MAR scheme.

Precipitation and clogging through MAR is a potential concern as already seen from groundwater users within the water supply schemes. It is recommended that geochemical modelling be completed as part of the feasibility study to predict the impacts of introducing source water to the groundwater through MAR.

Recharge calculations were consistent with DWAF (2006) calculated recharge values of the study area. However, it is assumed that future MAR will artificially increase this recharge rate through the proposed MAR methodology.

The hydraulic gradient of the groundwater levels followed the topographic gradient with an 85% correlation for both study sites. For this reason, the Aquifer Storage Transfer and Recovery MAR method was selected, whereby the recharge site of the MAR scheme is upgradient to the abstraction site. Opportunistic recharge water will then flow towards the abstraction site and away from the recharge zone. Aquifer testing is strongly recommended for the development of a numerical model to determine the range of potential recharge water volumes and radius of influence on water quality to determine if the groundwater users of the abstraction boreholes will benefit from the MAR scheme.

To implement and complete a feasibility study for a MAR scheme, the estimated CAPEX costs are expected to be much higher in comparison to more conventional methods of water supply such as a treatment plant for treating water to the required water quality. However, a MAR scheme's OPEX costs are considerably more affordable. The proposed MAR scheme method is also less invasive than treatment plants. The MAR method will require few adaptations for the current groundwater users and will allow for increased water security and improved water quality through mixing between the source water and natural groundwater.

A prefeasibility study has been concluded and indicates the way forward to the next step of a MAR scheme, a full feasibility study. The prefeasibility study concluded that the both study areas are ideal locations for MAR. The primary and secondary objectives of the MAR scheme can be achieved through the methodology as set out in this dissertation.

7.2 Recommendations

As the current study area is experiencing a period of lower-than-average rainfall, high expenditure on water supply maintenance and the need for better groundwater management to increase water security for groundwater users is needed. It is recommended that this dissertation be used as a prefeasibility study towards a full feasibility study for MAR. The feasibility study should follow the guidelines as set by DWA (2009) – A complete check-list for implementing a successful artificial recharge project. Further recommendations for a MAR scheme are listed below:

- Installation of water metering devices onto all current production boreholes within the study areas to record annual, monthly and weekly abstraction volumes for improved management of the overall groundwater resource.
- Dedicated dataloggers should be installed into monitoring boreholes for hourly monitoring of water levels. Monitoring data along with an appropriate groundwater management plan should be implemented in order to ensure sustainable management of the current groundwater system.

- Biannual site visits by a hydrogeologist should take place for the continuation of building a database on available hydrogeological data.
- Injection tests at dedicated boreholes should be completed to determine aquifer parameters and whether the aquifer will safely receive source water of variable volumes and rates for extended periods.
- Geochemical modelling should be completed to determine the extent of clogging that can be generated within the recharge boreholes, this will assist with maintenance planning.
- A numerical model should be developed to determine the range of potential recharge water volumes and radius of influence on water quality to determine if the users of the abstraction boreholes will benefit from the MAR scheme.
- A managed aquifer recharge scheme be designed and implemented over the following 3-5 years of a feasibility study; this can be achieved through the following tasks:
 - Drilling of recharge boreholes and confirmation of borehole locations by employing the Geoelectric (resistivity) method.
 - Drilling of dedicated monitoring boreholes and new abstraction boreholes downgradient of the recharge boreholes. Monitoring boreholes can be constructed similarly to abstraction boreholes, without any pumping infrastructure.
 - Construction of weirs above and below recharge site, to determine the volumes of water recharged per rainfall event and the annual source water availability.
- Continued groundwater education to groundwater users on the correct use and sustainable management of a resource, applying the reduce, reuse, recycle concepts before taking more than what is available.
- Due to the inability to measure microbiological parameters within surface water and groundwater because of the short turnaround time from sample collection to laboratory submission, it is recommended that this be considered for future studies. This should be considered a priority if the water is going to be used for human consumption.

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APPENDIX A – DESKTOP STUDY SITES

Site Name	Latitude	Longitude	Catchment	Study Area	Source	Construction Completion	Depth (mbgl)	Discharge (l/s) (blow yield)	Water Levels (mbgl)	Water Strike (mbgl)	Casing Depth (mbgl)
2431AB00051	-24.195860°	31.393209°	B73D	Motswari	NGA	1991/09/06	45.00	0.25	-	-	-
2431AB00052	-24.195860°	31.393219°	B73D	Motswari	NGA	1991/09/09	40.00	0.25	11.59	-	-
2431AB00053	-24.185670°	31.388719°	B73D	Motswari	NGA	1991/09/09	45.00	0.63	12.87	-	-
2431AB00054	-24.182250°	31.387429°	B73D	Motswari	NGA	1991/09/09	42.00	2.50	9.76	-	-
2431AB00055	-24.181370°	31.388969°	B73D	Motswari	NGA	1991/09/09	32.00	3.80	8.00	-	-
2431AB00056	-24.176760°	31.384109°	B73D	Motswari	NGA	1991/09/10	30.00	3.80	9.95	-	-
2431AB00057	-24.174490°	31.381339°	B73D	Motswari	NGA	1991/09/10	30.00	0.38	-	-	-
2431AB00058	-24.180220°	31.387339°	B73D	Motswari	NGA	1991/09/09	20.00	0.63	9.12	-	-
2431AB00062	-24.177370°	31.386589°	B73D	Motswari	NGA	1991/09/09	60.00	1.26	-	-	-
2431AB00091	-24.165730°	31.379839°	B73D	Motswari	NGA	1991/09/18	45.00	0.76	19.56	-	-
2431AB00096	-24.222720°	31.356739°	B73D	Motswari	NGA	1991/09/11	42.00	1.90	-	-	-
2431AB00098	-24.215990°	31.353889°	B73D	Motswari	NGA	1991/09/11	20.00	0.60	5.60	-	-
2431AB00100	-24.218240°	31.387469°	B73D	Motswari	NGA	1991/09/11	30.00	3.80	14.34	-	-
2431AB00104	-24.246240°	31.348359°	B73D	Motswari	NGA	1991/09/11	40.00	2.50	9.28	-	-
2431AB00105	-24.247740°	31.349359°	B73D	Motswari	NGA	1991/09/11	15.00	0.19	-	-	-
2431AB00107	-24.215980°	31.353889°	B73D	Motswari	NGA	1991/09/11	43.00	1.90	-	-	-
2430BB00005	-24.206240°	30.891511°	B72D	Balule	NGA	1986/08/05	42.00	20.00	8.00	34.00	8.00
2430BB00013	-24.195130°	30.833181°	B72D	Balule	NGA	1974/01/21	33.00	6.40	24.00	31.00	-
2430BB00014	-24.195130°	30.883181°	B72D	Balule	NGA	1986/10/16	62.00	10.00	50.00	54.00	10.00

Site Name	Latitude	Longitude	Catchment	Study Area	Source	Construction Completion	Depth (mbgl)	Discharge (l/s) (blow yield)	Water Levels (mbgl)	Water Strike (mbgl)	Casing Depth (mbgl)
2430BB00015	-24.195130°	30.833191°	B72D	Balule	NGA	1986/10/13	72.00	2.00	9.00	40.00	6.00
2430BB00016	-24.195140°	30.833181°	B72D	Balule	NGA	1973/04/25	61.26	4.26	10.06	32.30	
2430BB00017	-24.195130°	30.833201°	B72D	Balule	NGA	1975/09/17	68.00	0.02	32.40	48.00	-
2430BB00018	-24.195150°	30.833181°	B72D	Balule	NGA	1975/09/25	77.00	0.18	44.40	70.00	-
2430BB00019	-24.195130°	30.833211°	B72D	Balule	NGA	1975/10/01	64.00	1.96	27.50	50.00	-
2430BB00020	-24.195160°	30.833181°	B72D	Balule	NGA	1974/01/25	65.00	0.71	30.00	40.00	-
2430BB00021	-24.195130°	30.833221°	B72D	Balule	NGA	1967/12/11	51.81	-	-	18.30	-
2430BB00022	-24.195170°	30.833181°	B72D	Balule	NGA	1968/07/24	46.00	4.26	13.41	19.80	-
2430BB00023	-24.193740°	30.936791°	B72D	Balule	NGA	1986/09/08	106.00	-	-	-	-
2430BB00024	-24.193740°	30.936801°	B72D	Balule	NGA	1986/08/22	90.00	-	-	-	-
2430BB00025	-24.193750°	30.936791°	B72D	Balule	NGA	1986/08/23	60.00	40.00	28.00	40.00	6.00
2430BB00026	-24.236240°	30.912911°	B72D	Balule	NGA	1985/10/29	65.00	0.05	40.00	60.00	1.00
2430BB00027	-24.236240°	30.912921°	B72D	Balule	NGA	1982/07/29	31.00	1.00	17.00	23.00	2.00
2430BB00028	-24.236250°	30.912911°	B72D	Balule	NGA	1982/07/23	74.00	-	-	-	-
2430BB00029	-24.234240°	30.912911°	B72D	Balule	NGA	1986/08/13	75.00	1.00	48.00	68.00	3.00
2430BB00033	-24.206520°	30.886511°	B72D	Balule	NGA	1984/08/24	55.00	-	-	-	7.50
2430BB00034	-24.206520°	30.886521°	B72D	Balule	NGA	1987/07/26	28.00	1.33	10.00	25.00	3.60
2430BB00052	-24.175890°	30.869551°	B72D	Balule	NGA	1991/12/09	85.00	1.38	-	-	-
2430BB00053	-24.173570°	30.875801°	B72D	Balule	NGA	1991/12/09	42.00	10.13	-	-	-
2430BB00054	-24.172600°	30.880061°	B72D	Balule	NGA	1991/12/09	42.00	12.50	-	-	-

Site Name	Latitude	Longitude	Catchment	Study Area	Source	Construction Completion	Depth (mbgl)	Discharge (l/s) (blow yield)	Water Levels (mbgl)	Water Strike (mbgl)	Casing Depth (mbgl)
2430BB00055	-24.185890°	30.883741°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00056	-24.189070°	30.896321°	B72D	Balule	NGA	1991/12/11	18.10	-	8.10	-	-
2430BB00057	-24.190690°	30.896911°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00058	-24.192410°	30.887981°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00059	-24.190740°	30.896891°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00060	-24.195640°	30.889431°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00061	-24.200020°	30.887021°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00062	-24.201890°	30.887721°	B72D	Balule	NGA	1991/12/11	21.54	-	11.54	-	-
2430BB00063	-24.199200°	30.895461°	B72D	Balule	NGA	1991/12/10	-	3.80	-	-	-
2430BB00064	-24.200640°	30.896171°	B72D	Balule	NGA	1991/12/10	22.00	3.80	-	-	-
2430BB00065	-24.202440°	30.892021°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00066	-24.205300°	30.889041°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00067	-24.206620°	30.889091°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00068	-24.204270°	30.894381°	B72D	Balule	NGA	1991/12/10	27.03	17.03	-	-	-
2430BB00069	-24.209440°	30.889511°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00070	-24.212230°	30.889071°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00071	-24.209390°	30.899731°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00072	-24.215460°	30.898501°	B72D	Balule	NGA	1991/12/10	60.00	0.57	-	-	-
2430BB00073	-24.217210°	30.899401°	B72D	Balule	NGA	1991/12/10	60.00	1.10	13.93	-	-
2430BB00074	-24.219190°	30.899541°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-

Site Name	Latitude	Longitude	Catchment	Study Area	Source	Construction Completion	Depth (mbgl)	Discharge (l/s) (blow yield)	Water Levels (mbgl)	Water Strike (mbgl)	Casing Depth (mbgl)
2430BB00075	-24.222900°	30.901231°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00076	-24.221350°	30.895221°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00077	-24.221100°	30.888301°	B72D	Balule	NGA	1991/12/10	-	-	-	-	-
2430BB00078	-24.205520°	30.880701°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00079	-24.219090°	30.860221°	B72C	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00080	-24.173410°	30.865551°	B72D	Balule	NGA	1991/12/11	-	-	-	-	-
2430BB00082	-24.236240°	30.908181°	B72D	Balule	NGA	1945/12/13	32.30	2.52	4.57	16.70	-
2430BB00083	-24.236250°	30.908191°	B72D	Balule	NGA	1945/11/15	32.30	0.00	11.88	-	-
2430BB00084	-24.236260°	30.908201°	B72D	Balule	NGA	1945/11/12	12.80	0.00	-	-	-
2430BB00085	-24.236270°	30.908201°	B72D	Balule	NGA	1950/08/10	31.40	2.50	9.14	16.20	-

APPENDIX B – WATER LEVEL MONITORING DATA

Study Area	Site	Date	WL (mbgl)
Motswari	M1	2019/06/27	14.37
		2020/03/11	4.95
		2020/09/19	6.4
		2021/04/15	4.4
	M2	2019/06/27	11.44
		2020/03/11	8.31
		2020/09/19	11.1
		2021/04/15	11.25
	M3	2019/06/27	44.54
		2020/03/11	18.18
		2020/09/21	17.38
		2021/04/16	14.06
	M4	2019/06/27	15
		2020/03/11	16.04
	M6	2019/06/27	17.29
		2020/03/11	12.02
		2020/09/20	11.76
		2021/04/15	8.94
	M7	2021/04/16	20
	M8	2019/06/27	8.43
		2020/03/11	7.7
		2020/09/20	8.51
		2021/04/16	7.87
	M9	2019/06/27	9.37
2020/03/11		7.4	
2020/09/20		10.72	
Balule	Ba01	2019/06/27	8.95
		2020/03/11	5.81
		2020/09/24	6.54
		2021/04/10	5.49

Study Area	Site	Date	WL (mbgl)
Balule	Ba03	2019/06/27	8.12
		2020/03/11	13.49
		2020/09/23	16.28
		2021/04/10	6.79
	Ba04	2019/06/27	5.63
		2020/03/11	6.05
		2020/09/23	6.32
		2021/04/10	4.3
	Ba05	2019/06/27	18
	Ba06	2019/06/27	7.6
		2020/03/11	7.76
		2020/09/23	7.81
		2021/04/10	6.48
	Ba07	2019/06/27	5.97
		2020/03/11	6.91
		2020/09/23	7.15
		2021/04/10	4.04
		2021/08/10	6.99
		2021/08/20	7
		2021/08/24	7.05
		2021/08/31	7.07
		2021/09/07	7.11
		2021/09/14	7.11
	Ba07	2021/09/21	7.15
		2021/09/29	7.2
		2021/10/05	7.34
	Ba09	2019/06/27	37
		2020/03/11	37.77
		2020/09/22	38.2
		2021/04/11	37.75
		2021/08/10	38.88

Study Area	Site	Date	WL (mbgl)
Balule	Ba09	2021/08/20	38.92
		2021/08/24	38.92
		2021/08/31	38.97
		2021/09/07	38.98
		2021/09/14	38.95
		2021/09/21	39.2
		2021/09/29	39
		2021/10/05	39.06
	Ba11	2019/06/27	17.64
		2020/03/11	9.05
		2020/09/22	19.74
		2021/04/11	18.05
	Ba12	2019/06/27	32.22
		2020/03/11	32.4
		2020/09/22	32.55
		2021/04/11	32.36
		2021/08/10	33.23
		2021/08/20	33.27
		2021/08/24	33.22
		2021/08/31	33.79
		2021/09/07	33.98
		2021/09/14	33.28
		2021/09/21	33.26
		2021/09/29	33.25
		2021/10/05	33.24
	Ba13	2019/06/27	7.56
	Ba14	2019/06/27	14.76
		2020/03/11	15.06
		2020/09/22	15.39
		2021/04/11	15.48
	Ba15	2019/06/27	25.91

Study Area	Site	Date	WL (mbgl)
Balule	Ba15	2020/03/11	26.31
		2020/09/22	26.57
		2021/04/11	26.64
		2021/08/10	27.67
		2021/08/20	27.16
		2021/08/24	27.63
		2021/08/31	27.62
		2021/09/07	27.68
		2021/09/14	27.64
		2021/09/21	27.71
		2021/09/29	27.73
		2021/10/05	27.75
		Ba16	2019/06/27
	2020/03/11		40.43
	2020/09/22		40.75
	2021/04/11		40.86
	2021/08/10		42.82
	2021/08/20		41.8
	2021/08/24		41.81
	2021/08/31		42.82
	2021/09/07		41.83
	2021/09/14		41.82
	2021/09/21		41.85
	2021/09/29		41.86
	2021/10/05		41.88
	Ba17	2019/06/27	89.18
	Ba18	2019/06/27	25.96
		2020/03/11	19.07
		2020/09/24	22.18
		2021/04/10	16.9
	Ba19	2019/06/27	11.98

Study Area	Site	Date	WL (mbgl)	
Balule	Ba19	2020/03/11	12.24	
		2020/09/24	12.75	
		2021/04/10	12.19	
		2021/08/12	13.2	
		2021/08/25	13.26	
		2021/09/07	13.31	
		2021/09/29	13.32	
		2021/10/08	13.32	
		Ba21	2019/06/27	8.03
			2020/03/11	6.78
	2020/09/23		6.73	
	2021/04/10		5.51	
	Ba22	2019/06/27	26.73	
	Ba23	2019/06/27	12.64	
		2020/03/11	12.87	
		2020/09/23	14.36	
	Ba24	2021/04/11	13.9	
		2019/06/27	6.43	
		2020/03/11	12.46	
	Ba25	2020/09/23	14.54	
		2021/04/11	6.7	
		2019/06/27	20.24	
		2020/03/11	21.19	
	Ba27	2020/09/23	20.76	
		2021/04/11	19.39	
		2019/06/27	48	
	Ba28	2019/06/27	27.7	
		2021/04/11	29.47	
	Ba29	2019/06/27	7.98	
		2020/03/11	13.57	
			2020/09/23	9.11

Study Area	Site	Date	WL (mbgl)
Balule	Ba29	2021/04/10	7.88
	Ba30	2019/06/27	13.27
		2020/03/11	11.67
		2020/09/23	14.27
		2021/04/10	13.2
	Ba31	2019/06/27	23.5
	Ba101	2020/08/03	5.75
		2020/09/23	5.35
		2021/04/10	4.02
		2021/08/10	6.34
		2021/08/20	5.2
		2021/08/24	5.27
		2021/08/31	5.51
		2021/09/07	5.34
		2021/09/14	5.24
		2021/09/21	5.34
	2021/09/29	5.6	
	2021/10/05	5.68	
	Ba201	2021/04/11	9.49
	Ba202	2020/09/23	10.14
2021/04/11		9.14	

APPENDIX C – LABORATORY CHEMISTRY RESULTS (IGS)

Site ID	Sample Date	Lab Number	pH	EC	Ca	Mg	Na	K	MAIc	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
M1	2019/07/11	514-25	7.68	238.00	138.28	91.51	285.49	10.12	443.68	0.09	573.81	13.91	121.82	345.71	375.18	720.89	1726.43	0.02	0.02	0.33	0.08	0.01	0.02	0.02	0.02	0.02	35.02	1.43	0.03	0.04	0.02	-	-	III
M1	2020/03/26	244-11	7.15	67.47	37.62	25.99	80.34	5.13	286.91	1.21	41.75	2.11	14.73	93.93	107.05	200.97	492.52	0.02	0.02	0.15	0.02	0.02	0.02	0.02	0.02	35.51	0.35	0.03	0.01	0.02	0.02	0.02	II	
M1	2020/10/06	637-22	7.46	224.75	121.05	89.15	244.01	4.78	451.79	0.56	380.29	8.54	79.99	302.26	367.10	669.36	1640.65	0.02	0.02	0.28	0.06	0.01	0.02	0.02	0.02	40.11	0.86	0.03	0.05	0.02	0.06	0.02	III	
M1	2021/05/23	292-25	7.09	97.64	61.74	39.55	96.71	4.73	373.85	0.93	101.24	0.40	30.14	154.15	162.85	317.00	712.74	0.02	0.02	0.20	0.03	0.01	0.02	0.02	0.02	32.80	0.45	0.03	0.05	0.12	0.02	0.02	II	
M2	2019/07/11	514-26	7.70	200.00	117.61	91.30	228.40	8.25	527.30	0.21	384.08	0.94	78.62	294.03	374.33	668.36	1440.01	0.02	0.02	0.22	0.08	0.01	0.02	0.03	0.02	37.70	1.03	0.03	0.05	0.02	-	-	III	
M2	2020/03/26	244-19	7.27	104.34	63.62	45.70	114.76	4.78	356.01	1.10	117.31	3.28	30.20	158.86	188.19	347.05	761.67	0.02	0.02	0.19	0.04	0.01	0.02	0.02	0.02	37.18	0.59	0.03	0.01	0.02	0.02	0.02	II	
M2	2021/05/23	292-26	6.97	233.84	130.60	96.42	232.88	6.07	479.95	1.22	461.05	9.50	96.32	326.10	397.06	723.16	1707.00	0.02	0.02	0.28	0.07	0.01	0.02	0.02	0.05	44.97	0.90	0.03	0.01	0.02	0.02	0.02	III	
M3	2021/05/23	292-27	7.23	165.86	42.34	57.35	225.35	6.67	377.51	1.29	316.29	3.68	61.67	105.72	236.18	341.90	1210.75	0.02	0.02	0.21	0.07	0.01	0.02	0.02	0.02	32.22	0.40	0.03	0.08	0.02	0.02	0.02	II	
M5	2020/03/26	244-13	7.47	191.52	46.82	69.50	278.79	11.35	393.30	0.90	334.49	4.65	61.89	116.90	286.21	403.11	1398.07	0.02	0.02	0.23	0.08	0.01	0.02	0.07	0.02	31.47	0.62	0.03	0.01	0.02	0.02	0.02	II	
M6	2020/03/26	244-14	7.33	135.03	30.58	22.74	266.29	13.34	605.24	1.38	78.99	0.19	31.99	76.35	93.63	169.98	985.73	0.02	0.02	0.30	0.02	0.01	0.04	1.32	0.02	23.27	0.29	0.03	1.32	0.02	0.02	0.02	II	
M6	2020/10/06	637-23	7.58	210.34	39.60	40.00	426.37	13.35	784.30	1.27	181.12	2.86	49.64	98.88	164.73	263.61	1535.51	0.02	0.02	0.37	0.04	0.01	0.06	0.20	0.02	35.85	0.45	0.03	0.07	0.02	0.02	0.02	II	
M7	2019/07/11	514-27	7.88	151.00	36.40	37.83	275.78	5.96	579.05	0.54	178.63	2.28	34.52	91.00	155.10	246.10	1158.93	0.02	0.02	0.23	0.02	0.01	0.02	0.03	0.02	33.17	0.40	0.03	0.03	0.02	-	-	II	
M7	2020/03/26	244-15	7.23	165.14	41.33	40.78	290.25	9.73	543.94	0.96	188.98	3.89	31.27	103.21	167.93	271.14	1205.54	0.02	0.02	0.27	0.02	0.01	0.02	0.02	0.02	35.28	0.44	0.03	0.02	0.02	0.02	0.02	II	
M7	2021/05/23	292-28	7.42	163.47	40.16	37.94	275.38	4.09	578.55	1.28	187.28	4.40	34.47	100.29	156.25	256.54	1193.34	0.02	0.02	0.29	0.02	0.01	0.02	0.02	0.02	36.76	0.32	0.03	0.01	0.02	0.02	0.02	II	
M8	2020/03/26	244-16	8.06	214.80	12.76	82.81	319.41	19.87	346.98	0.67	479.76	0.22	1.95	31.85	341.02	372.87	1568.04	0.02	0.02	0.27	0.02	0.01	0.02	0.02	0.02	2.56	0.27	0.03	0.01	0.02	0.02	0.02	II	
M8	2020/10/06	637-24	7.16	291.34	41.85	111.13	376.23	20.32	297.85	0.61	799.00	-	23.45	104.51	457.64	562.16	2126.80	0.02	0.02	0.30	0.02	0.00	0.02	0.05	0.02	7.99	0.74	0.03	0.01	0.02	0.02	0.02	III	
M9	2019/07/11	514-28	7.80	227.00	120.93	106.11	254.43	8.05	359.05	0.15	605.73	7.85	148.18	302.33	435.05	737.38	1637.52	0.02	0.07	0.14	0.06	0.01	0.02	0.02	0.02	31.13	1.57	0.03	0.03	0.28	-	-	III	
M9	2020/03/26	244-17	7.22	182.38	90.98	69.30	214.76	7.48	384.90	0.86	334.74	0.94	79.21	227.19	285.37	512.55	1331.40	0.02	0.12	0.19	0.04	0.02	0.02	0.02	0.02	28.45	1.14	0.03	0.01	0.02	0.02	0.02	III	
M9	2021/05/23	292-29	7.14	251.75	121.63	100.75	245.19	5.16	411.10	1.03	488.40	0.90	136.06	303.70	414.89	718.59	1837.74	0.02	0.16	0.19	0.05	0.07	0.02	0.02	0.02	34.04	1.06	0.03	0.01	0.06	0.02	0.02	III	
M_SW01	2020/03/26	244-12	7.22	18.94	16.58	5.64	16.75	7.53	75.69	0.12	14.30	0.38	6.30	41.40	23.22	64.62	149.07	0.42	0.02	0.04	0.04	0.01	0.36	0.02	0.02	9.25	0.12	0.03	0.01	0.02	0.02	0.02	I	

Site ID	Sample Date	Lab Number	pH	EC	Ca	Mg	Na	K	MAIc	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class	
Ba01	2019/07/11	514-1	7.06	145.03	61.11	102.05	88.12	12.32	390.12	0.11	168.18	10.64	81.48	152.78	418.41	571.19	950.62	0.02	0.02	0.04	0.16	0.01	0.02	0.02	0.02	0.02	30.89	0.40	0.03	0.01	0.02	-	-	II	
Ba01	2020/03/26	244-1	6.73	43.48	32.47	21.41	27.19	4.21	113.06	0.26	28.87	0.38	62.63	81.07	88.16	169.23	304.36	0.02	0.02	0.04	0.04	0.01	0.02	0.02	0.02	0.02	5.67	0.14	0.03	0.01	0.02	0.02	0.02	0	
Ba01	2020/10/06	637-1	6.87	139.81	61.65	96.48	92.11	14.94	403.95	0.48	171.52	4.28	84.03	153.93	397.29	551.22	978.70	0.02	0.02	0.08	0.14	0.01	0.02	0.02	0.02	0.02	33.02	0.34	0.03	0.01	0.02	0.03	0.02	II	
Ba01	2021/05/23	292-1	7.17	154.09	74.49	113.09	97.28	11.52	409.00	0.63	201.89	3.23	130.99	185.99	465.68	651.68	1078.65	0.02	0.02	0.04	0.16	0.02	0.02	0.02	0.02	0.02	35.48	0.39	0.03	0.01	0.05	0.02	0.02	III	
Ba02	2019/07/11	514-2	7.14	161.02	68.82	46.29	187.82	11.76	302.66	0.03	283.87	10.69	75.91	172.05	189.77	361.82	1024.51	0.02	0.02	0.09	0.08	0.01	0.02	0.02	0.02	0.02	29.80	0.71	0.03	0.01	0.03	-	-	II	
Ba03	2019/07/11	514-3	7.19	199.36	95.02	70.18	135.00	9.81	279.22	0.11	380.85	0.18	95.58	237.55	287.73	525.28	1066.61	0.02	0.02	0.05	0.07	0.01	0.02	0.02	0.02	0.02	39.12	0.80	0.03	0.02	0.02	-	-	II	
Ba03	2021/05/23	292-2	7.33	204.69	84.10	74.30	213.86	12.18	316.09	3.20	486.17	0.27	99.90	210.00	305.95	515.95	1023.43	0.02	0.02	0.15	0.12	0.01	0.02	0.02	0.02	0.02	37.28	0.74	0.03	0.01	0.02	0.02	0.02	III	
Ba04	2019/07/11	514-4	7.06	256.34	86.97	56.03	361.29	12.17	402.67	0.47	534.44	5.62	104.41	217.41	229.74	447.15	1583.36	0.02	0.02	0.17	0.14	0.01	0.02	0.06	0.02	0.02	29.75	1.32	0.03	0.01	0.02	-	-	II	
Ba04	2021/05/23	292-3	7.01	199.29	73.83	44.01	286.19	9.40	347.17	3.72	438.05	0.25	86.22	184.35	181.23	365.58	1195.76	0.02	0.02	0.18	0.11	0.01	0.03	0.03	0.02	0.02	33.60	1.02	0.03	0.01	0.02	0.02	0.02	IV	
Ba05	2019/07/11	514-5	7.18	189.77	90.72	51.21	213.55	11.62	245.08	0.67	416.82	0.66	78.97	226.79	209.95	436.74	1111.59	0.02	0.02	0.09	0.35	0.01	0.02	0.03	0.17	0.02	0.02	24.85	1.28	0.03	0.03	0.02	-	-	II
Ba06	2019/07/11	514-6	7.32	179.10	50.00	19.85	270.11	12.48	154.85	7.13	407.75	1.30	122.96	125.01	81.39	206.39	1050.93	0.02	0.02	0.09	0.06	0.02	0.02	0.02	0.02	0.02	23.12	0.71	0.03	0.01	0.03	-	-	IV	
Ba06	2020/10/06	637-2	7.04	162.73	43.82	16.10	261.60	17.18	143.43	6.30	329.34	0.11	114.77	109.42	66.28	175.71	955.20	0.02	0.02	0.16	0.04	0.00	0.02	0.02	0.02	0.02	23.07	0.51	0.03	0.01	0.04	0.02	0.02	IV	
Ba06	2021/05/23	292-4	7.68	164.27	46.82	17.17	240.75	10.09	147.93	8.70	403.30	0.19	111.75	116.91	70.72	187.63	964.28	0.02	0.02	0.12	0.04	0.01	0.04	0.02	0.03	0.02	24.49	0.55	0.03	0.01	0.02	0.02	0.02	IV	
Ba06	2020/03/26	244-2	6.86	165.91	50.78	18.96	266.83	10.81	148.19	6.95	371.24	0.28	117.53	126.79	78.09	204.89	973.90	0.02	0.02	0.15	0.05	0.01	0.02	0.02	0.02	0.02	24.12	0.71	0.03	0.01	0.02	0.02	0.02	IV	
Ba09	2019/07/11	514-7	7.32	105.38	69.33	30.91	130.05	9.10	404.25	0.13	82.22	0.38	24.30	173.33	126.72	300.05	752.01	0.02	0.02	0.06	0.12	0.01	0.03	0.90	0.02	0.02	24.69	0.70	0.03	0.01	0.02	-	-	II	
Ba09	2020/10/06	637-3	6.94	102.38	63.01	26.04	127.50	4.48	401.42	0.54	88.90	0.30	23.84	157.34	107.22	264.56	731.01	0.02	0.02	0.14	0.09	0.00	0.02	0.18	0.02	0.02	23.96	0.50	0.03	0.01	0.03	0.03	0.02	I	
Ba10	2019/07/11	514-8	7.63	75.70	54.89	36.87	56.28	2.96	289.62	0.05	46.71	0.99	35.81	137.24	151.18	288.42	527.63	0.02	0.02	0.04	0.14	0.01	0.02	0.02	0.02	0.02	29.65	0.59	0.03	0.02	0.02	-	-	I	
Ba10	2020/03/26	244-3	7.47	43.38	32.94	21.44	28.80	4.39	121.54	0.23	28.82	0.36	56.85	82.26	88.29	170.55	302.32	0.02	0.02	0.04	0.04	0.01	0.02	0.02	0.02	0.02	5.78	0.14	0.03	0.01	0.02	0.02	0.02	0	
Ba10	2020/10/06	637-4	6.97	128.36	70.81	46.74	135.41	2.88	261.80	0.70	166.94	2.51	95.47	176.81	192.47	369.28	894.66	0.02	0.02	0.11	0.16	0.03	0.02	0.02	0.02	0.02	33.05	0.58	0.03	0.01	0.12	0.03	0.02	II	
Ba10	2021/05/23	292-5	7.23	92.31	72.94	44.29	66.81	2.72	336.90	0.55	70.12	1.06	55.52	182.12	182.39	364.50	643.41	0.02	0.02	0.04	0.14	0.01	0.02	0.02	0.02	0.02	33.94	0.63	0.03	0.01	0.02	0.02	0.02	II	
Ba11	2019/07/11	514-9	7.40	161.28	47.48	45.11	246.74	14.04	450.46	0.05	236.81	0.22	53.90	118.71	184.97	303.68	1095.60	0.02	0.02	0.07	0.04	0.01	0.33	0.51	0.02	0.02	7.63	0.46	0.03	0.01	0.02	-	-	II	
Ba13	2019/07/11	514-10	7.53	89.28	45.84	37.74	90.69	12.80	319.73	0.20	71.38	0.27	21.98	114.60	154.72	269.32	601.60	0.02	0.02	0.04	0.19	0.01	0.02	0.08	0.02	0.02	31.56	0.43	0.03	0.01	0.02	-	-	I	
Ba14	2019/07/11	514-11	6.72	79.09	47.38	44.74	68.90	9.74	294.62	0.09	69.05	0.08	29.14	118.46	183.43	301.89	564.06	0.02	0.02	0.04	0.23	0.01	0.17	0.03	0.02	0.02	31.44	0.41	0.03	0.01	0.03	-	-	II	
Ba14	2020/10/06	637-5	7.03	78.71	44.66	40.09	67.48	5.75	316.34	0.44	72.30	1.77	16.41	111.53	165.10	276.62	561.23	0.02	0.02	0.07	0.22	0.00	0.02	0.03	0.02	0.02	36.06	0.33	0.03	0.01	0.02	0.02	0.02	I	
Ba14	2021/05/23	292-6	6.61	77.76	45.09	39.58	60.38	7.34	312.35	0.57	73.67	1.61	18.61	112.58	162.99	275.58	554.42	0.02	0.02	0.04	0.23	0.01	0.02	0.02	0.02	0.02	41.07	0.32	0.03	0.01	0.02	0.02	0.02	I	
Ba15	2020/10/06	637-6	6.65	89.72	69.45	41.51	58.60	6.07	374.59	0.37	66.07	0.19	6.21	173.42	170.95	344.37	639.67	0.02	0.02	0.07	0.21	0.01	0.02	0.09	0.03	0.02	34.22	0.47	0.03	0.01	0.02	0.03	0.02	II	
Ba17	2019/07/11	514-12	6.98	94.45	75.92	42.48	67.15	12.09	341.03	0.11	80.49	0.40	27.42	189.80	174.18	363.97	648.49	0.02	0.02	0.04	0.07	0.01	0.02	0.02	0.02	0.02	28.11	0.55	0.03	0.01	0.02	-	-	II	
Ba17	2020/10/06	637-7	7.32	95.02	76.28	43.26	68.56	10.92	359.48	0.49	76.15	4.13	25.10	190.47	178.16	368.63	652.79	0.02	0.02	0.09	0.06	0.02	0.02	0.02	0.02	0.02	29.83	0.47	0.03	0.01	0.02	0.04	0.02	II	
Ba17	2021/05/23	292-7	7.28	94.74	76.78	42.34	61.55	11.35	385.85	0.48	85.09	4.72	28.48	191.72	174.37	366.09	650.85	0.02	0.02	0.04	0.06	0.06	0.02	0.02	0.02	0.02	33.63	0.49	0.03	0.01	0.03	0.02	0.02	II	
Ba18	2019/07/11	514-13	7.23	77.76	34.84	42.47	56.59	12.01	227.84	0.16	64.88	0.19	62.49	87.11	174.11	261.21	502.15	0.02	0.02	0.04	0.13	0.01	0.02	0.02	0.02	0.02	18.32	0.24	0.03	0.02	0.02	-	-	I	
Ba18	2020/03/26	244-4	7.16	80.23	39.23	47.02	58.63	12.13	235.83	0.45	70.31	0.69	72.07	97.96	193.62	291.57	518.29	0.02	0.02	0.07	0.13	0.01	0.02	0.02	0.02	0.02	19.31	0.24	0.06	0.01	0.02	0.02	0.02	I	
Ba18	2020/10/06	637-8	7.06	122.34	58.77	72.84	86.87	15.09	341.28	0.56	137.09	1.61	112.61	146.74	299.95	446.69	790.33	0.02	0.02	0.18	0.18	0.01	0.02	0.02	0.02	0.02	18.96	0.31	0.03	0.01	0.02	0.03	0.02	II	
Ba18	2021/05/23	292-8	7.16	115.99	54.89	66.05	88.94	14.81	365.50	0.84	131.32	1.39	109.34	137.07	271.98	409.04	749.30	0.02	0.02	0.13	0.17	0.01	0.02	0.02	0.02	0.02	24.67	0.31	0.03	0.01	0.02	0.02	0.02	II	
Ba19	2019/07/11	514-14	6.86	142.87	103.45	63.50	126.47	11.24	366.96	0.12	233.55	0.44	50.58	258.63	260.37	519.00	957.95	0.02	0.02	0.05	0.16	0.01	0.02	0.02	0.02	0.02	35.66	0.78	0.03	0.01	0.07	-	-	II	
Ba21	2019/07/11	514-15	7.03	141.39	73.23	50.81	147.17	8.16	344.36	0.55	208.92	5.16	50.97	183.08	208.30	391.38	907.06	0.02	0.02	0.09	0.10	0.01	0.02	0.02	0.02	0.02	36.78	0.72	0.03	0.02	0.02	-	-	II	
Ba21	2020/03/26	244-5	6.81	140.87	80.25	53.60	145.02	8.54	324.21	0.91	214.79	5.83	45.80	200.38	220.71	421.08	904.37	0.02	0.																

Site ID	Sample Date	Lab Number	pH	EC	Ca	Mg	Na	K	MAI _k	F	Cl	NO3(N)	SO4	CA Hard.	Mg Hard.	Tot. Hard.	TDS (sum)	Al	As	B	Ba	Cu	Fe	Mn	Mo	Pb	Si	Sr	U	V	Zn	Ni	Sb	DWAF Class
Ba27	2019/07/11	514-19	7.25	138.11	84.69	71.15	90.48	11.35	304.47	0.62	229.90	0.38	61.67	211.73	291.70	503.43	856.05	0.02	0.02	0.04	0.12	0.01	0.02	0.02	0.02	0.02	32.99	0.57	0.03	0.02	0.02	-	-	II
Ba27	2020/03/26	244-8	6.63	138.35	92.57	74.30	87.05	12.32	272.61	0.79	241.82	3.74	59.15	231.13	305.98	537.11	857.79	0.02	0.02	0.08	0.11	0.02	0.02	0.02	0.02	0.02	35.37	0.58	0.03	0.01	0.05	0.02	0.02	II
Ba28	2019/07/11	514-20	6.90	190.72	100.87	123.34	97.33	12.92	410.58	0.76	327.99	0.16	76.15	252.17	505.71	757.88	1150.71	0.02	0.02	0.05	0.38	0.01	0.02	0.02	0.02	0.02	35.79	0.74	0.03	0.01	0.86	-	-	III
Ba28	2020/10/06	637-12	6.95	192.93	112.14	127.95	105.38	21.25	443.01	0.48	304.39	10.29	71.58	280.02	526.92	806.93	1163.39	0.02	0.02	0.13	0.36	0.02	0.02	0.02	0.02	0.02	36.54	0.68	0.03	0.01	0.03	0.04	0.02	III
Ba28	2021/05/23	292-12	6.78	185.84	105.71	118.92	96.32	17.73	431.20	0.83	360.18	9.69	79.62	263.97	489.70	753.67	1120.60	0.02	0.02	0.09	0.37	0.01	0.02	0.02	0.02	0.02	41.80	0.67	0.03	0.01	0.35	0.02	0.02	III
Ba29	2020/10/06	637-13	6.97	494.14	190.41	165.25	515.14	41.29	634.64	2.00	860.30	0.10	266.11	475.44	680.50	1155.94	2979.63	0.02	0.02	0.29	0.15	0.65	0.02	0.30	0.02	0.02	35.59	2.61	0.03	0.01	0.02	0.06	0.02	III
Ba29	2021/05/23	292-13	6.99	495.03	212.47	173.50	568.44	24.77	487.55	3.40	1212.20	0.12	250.41	530.53	714.49	1245.02	2985.04	0.02	0.02	0.29	0.16	0.10	0.03	0.02	0.02	0.02	41.75	2.85	0.03	0.01	0.02	0.02	0.02	IV
Ba30	2019/07/11	514-21	6.77	376.76	217.26	146.44	359.00	12.42	452.61	0.98	871.10	3.83	168.96	543.14	600.42	1143.56	2245.79	0.02	0.02	0.18	0.38	0.01	0.02	0.09	0.02	0.02	34.71	1.81	0.03	0.01	0.02	-	-	III
Ba30	2020/03/26	244-9	6.84	465.60	198.18	168.84	562.18	29.89	628.35	3.10	1003.70	0.19	248.31	494.86	695.27	1190.13	2775.00	0.02	0.02	0.31	0.15	0.04	0.04	0.02	0.02	0.02	39.19	2.52	0.03	0.01	0.02	0.03	0.02	III
Ba30	2020/10/06	637-14	6.97	424.18	246.70	151.24	407.10	29.42	482.01	1.21	979.60	0.13	188.15	616.02	622.82	1238.84	2528.11	0.02	0.02	0.25	0.39	0.01	0.02	0.09	0.02	0.02	35.68	1.96	0.03	0.01	0.02	0.04	0.02	III
Ba30	2021/05/23	292-14	6.94	442.41	269.39	165.72	397.06	20.14	484.05	1.96	1065.50	0.45	199.74	672.66	682.43	1355.09	2636.78	0.02	0.02	0.25	0.44	0.01	0.02	0.09	0.02	0.02	41.02	2.30	0.03	0.01	0.02	0.02	0.02	III
Ba33	2019/07/11	514-22	7.32	108.87	51.14	31.07	118.50	11.60	226.86	0.11	155.72	13.19	35.27	127.84	127.40	255.25	688.75	0.02	0.02	0.04	0.05	0.01	0.02	0.02	0.02	0.02	34.90	0.63	0.03	0.01	0.03	-	-	II
Ba33	2020/10/06	637-15	7.22	126.45	81.26	43.57	122.03	4.69	303.87	0.50	175.08	3.47	47.13	202.90	179.44	382.33	800.43	0.02	0.02	0.12	0.02	0.00	0.02	0.02	0.02	0.02	28.82	0.49	0.03	0.01	0.04	0.04	0.02	II
Ba33	2021/05/23	292-15	7.37	126.19	81.06	49.21	105.22	5.57	344.25	0.83	201.47	5.06	56.73	202.40	202.63	405.03	798.79	0.02	0.02	0.07	0.02	0.08	0.02	0.02	0.02	0.02	38.94	0.51	0.03	0.01	0.03	0.02	0.02	II
Ba201	2020/10/06	637-16	7.20	164.12	132.17	80.69	109.76	2.34	367.87	0.37	174.94	18.80	134.13	330.03	332.28	662.31	1038.89	0.02	0.02	0.24	0.18	0.01	0.02	0.02	0.02	0.02	39.43	0.81	0.03	0.01	0.02	0.04	0.02	III
Ba201	2021/05/23	292-16	7.07	127.38	99.64	60.46	87.34	2.42	368.95	0.78	116.62	17.12	105.17	248.80	248.98	497.78	806.32	0.02	0.02	0.13	0.15	0.01	0.02	0.02	0.02	0.02	45.22	0.65	0.03	0.01	0.02	0.02	0.02	II
Ba202	2020/10/06	637-17	7.62	132.66	74.21	63.08	118.17	4.74	321.75	0.99	156.69	2.50	101.32	185.30	259.76	445.06	839.76	0.02	0.02	0.08	0.08	0.01	0.02	0.02	0.02	0.02	31.60	0.55	0.03	0.01	0.02	0.04	0.02	II
Ba202	2021/05/23	292-17	7.38	133.33	77.08	65.69	108.47	6.33	373.00	1.39	180.20	3.15	125.89	192.47	270.50	462.97	843.98	0.02	0.02	0.04	0.10	0.01	0.02	0.02	0.02	0.02	33.73	0.59	0.03	0.01	0.02	0.02	0.02	II
Spring	2020/10/06	637-25	8.09	164.63	44.09	5.60	292.15	16.72	95.27	5.95	426.86	0.10	134.23	110.08	23.08	133.16	1042.13	0.02	0.02	0.17	0.03	0.01	0.02	0.02	0.02	0.02	11.58	0.81	0.03	0.01	0.02	0.03	0.02	IV
Spring	2021/05/23	292-32	7.18	177.45	53.81	7.77	287.52	15.98	126.44	7.68	443.20	0.14	133.01	134.36	31.99	166.34	1123.25	0.03	0.02	0.15	0.10	0.01	0.04	0.02	0.02	0.02	16.15	0.80	0.03	0.01	0.02	0.02	0.02	IV
Ekuthuleni Dam	2020/03/26	244-10	7.14	23.70	24.05	6.61	10.65	17.90	123.41	0.11	6.95	0.18	2.52	60.05	27.21	87.26	150.02	0.02	0.02	0.04	0.07	0.01	0.10	0.02	0.02	0.02	7.93	0.19	0.04	0.01	0.02	0.02	0.02	0
Rainfall	2020/10/06	637-26	7.83	2.87	1.86	0.55	2.57	0.95	8.89	0.10	2.00	0.20	3.75	4.64	2.26	6.91	18.17	0.02	0.02	0.04	0.01	0.01	0.02	0.02	0.02	0.02	0.44	0.02	0.03	0.01	0.12	0.02	0.02	0
Drainage 1	2021/05/23	292-18	6.82	6.04	7.27	1.88	6.75	2.44	41.53	0.31	3.92	0.10	1.91	18.16	7.72	25.88	38.25	0.16	0.02	0.04	0.02	0.01	0.88	0.10	0.02	0.02	6.50	0.06	0.03	0.01	0.02	0.02	0.02	I
Drainage 2	2021/05/23	292-19	7.10	45.40	32.40	11.87	47.89	10.01	166.74	0.78	53.81	0.45	9.91	80.89	48.86	129.75	287.38	0.05	0.02	0.06	0.06	0.01	0.07	0.02	0.02	0.02	7.39	0.26	0.03	0.01	0.02	0.02	0.02	I
Drainage 3	2021/05/23	292-20	7.06	31.01	24.23	8.35	32.63	7.74	134.99	0.52	28.34	0.51	6.26	60.49	34.37	94.86	196.27	0.03	0.02	0.05	0.06	0.01	0.04	0.02	0.02	0.02	5.57	0.19	0.03	0.01	0.02	0.02	0.02	0
Drainage 5	2021/05/23	292-21	7.01	9.62	8.62	2.95	10.60	5.58	50.23	0.19	7.59	0.29	5.40	21.53	12.16	33.69	60.90	0.90	0.02	0.04	0.03	0.01	0.48	0.02	0.02	0.02	12.13	0.07	0.03	0.01	0.02	0.02	0.02	0
SW01	2019/07/11	514-30	8.09	38.00	28.09	20.55	25.35	2.93	141.43	0.04	24.89	4.08	37.57	70.23	84.24	154.46	298.95	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	5.32	0.13	0.03	0.01	0.02	-	-	0
SW01	2020/03/26	244-20	7.21	146.48	70.59	113.32	94.77	13.00	469.58	0.67	204.83	4.97	95.07	176.26	466.66	642.91	1152.81	0.02	0.02	0.06	0.16	0.01	0.02	0.02	0.02	0.02	33.04	0.44	0.03	0.01	0.02	0.02	0.02	III
SW01	2020/10/06	637-18	8.27	40.52	31.18	20.98	28.23	2.34	142.82	-	24.35	0.12	33.25	77.84	86.38	164.22	318.91	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	5.69	0.13	0.03	0.01	0.02	0.02	0.02	0
SW01	2021/05/23	292-34	8.12	33.74	28.41	18.13	21.31	2.53	128.49	0.48	23.01	0.37	38.71	70.93	74.66	145.59	265.53	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	6.12	0.09	0.03	0.01	0.02	0.02	0.02	0
SW02	2020/03/26	244-22	7.39	182.61	58.19	8.19	316.03	19.86	143.14	6.65	417.45	0.19	125.60	145.31	33.73	179.03	1437.16	0.02	0.02	0.17	0.04	0.01	0.02	0.02	0.02	0.02	13.01	1.12	0.03	0.01	0.02	0.02	0.02	IV
SW02	2020/10/06	637-19	8.26	39.39	29.90	20.12	26.74	2.10	141.00	0.15	24.32	0.11	35.67	74.66	82.85	157.50	309.97	0.02	0.02	0.05	0.03	0.01	0.02	0.02	0.03	0.02	5.77	0.12	0.03	0.01	0.02	0.02	0.02	0
SW02	2021/05/23	292-35	8.00	33.74	28.11	18.02	20.60	2.22	130.46	0.54	24.43	0.40	38.15	70.19	74.21	144.41	265.53	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	6.30	0.09	0.03	0.01	0.02	0.02	0.02	0
SW03	2019/07/11	514-29	8.35	40.00	29.08	20.76	26.09	3.02	141.90	0.05	23.84	6.07	40.58	72.70	85.10	157.80	312.22	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.02	5.66	0.14	0.03	0.01	0.02	-	-	I
SW03	2020/03/26	244-18	7.97	42.66	32.55	21.18	30.05	4.03	117.04	0.35	31.95	0.34	60.50	81.27	87.21	168.48	335.72	0.02	0.02	0.04	0.04	0.01	0.02	0.02	0.02	0.02	5.86	0.15	0.03	0.01	0.02	0.02	0.02	0
SW03	2020/10/06	637-20	8.24	39.29	31.23	21.02	27.53	2.34	142.29	-	24.90	0.13	32.16	77.98	86.54	164.5																		