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Site suitability assessment for managed aquifer recharge: a case study of the City of Johannesburg Metropolitan Area, South Africa

by

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An MSc research report submitted to the School of Geosciences, Faculty of Science in partial fulfilment for the requirements of the Master of Science Degree in Hydrogeology by research and coursework



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August 2025

Declaration of original work

I, Tholoana Matsie Mabula, hereby declare that this research report titled ‘Site Suitability Assessment for Managed Aquifer Recharge: A Case Study of the City of Johannesburg Metropolitan Area, South Africa’ is my own, unaided work. This research is to be submitted to the Degree of Master of Science in Hydrogeology at the University of the Witwatersrand, Johannesburg and has not been submitted previously for any degree or examination to any other university. Information which has been obtained from sources has been indicated and acknowledged by detailed and complete referencing.

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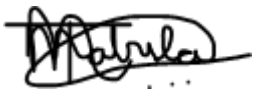

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Tholoana Matsie Mabula

27 August 2025

Abstract

Water issues relating to infrastructure and water quality are experienced by the City of Johannesburg (CoJ). Managed aquifer recharge (MAR) is known as the intentional procedure of storing water underground in an aquifer, either by injection or infiltration methods, for later recovery. This water management tool is particularly crucial in water-scarce regions to augment water supply. The study aims to explore the suitability of MAR schemes implementation in the City of Johannesburg (CoJ) for augmenting domestic water supply in Randburg, CoJ, through the assessment of their hydrogeological environments. The importance of this research is related to the expanding population which puts pressure on the existing infrastructure and surface water resources. Acknowledging the potential water insecurity of the area, the study provides an alternate solution to reduce the pressure on surface water supplies. To achieve the study's objectives, geological and hydrogeological mapping were carried out, meteorological data was assessed, GIS software determined potential sites for the proposed scheme. In addition to this, the potential source water for the scheme was identified. The methodology employed in this study included extensive literature review and desktop study, fieldwork inclusive of geological mapping, electrical resistivity tomography, and double ring infiltration test, as well as suitability mapping with GIS-MCDA. Ambiguity and subjectivity of outcomes were limitations encountered as a result of the employed methodology. The major findings of this study show that crystalline rock and sandy clay loam soil dominate the area of study. Deeper groundwater levels were located closer to the Johannesburg Botanical Gardens and at the base of the Melville Koppies resulting in suitable to high suitability areas for the proposed MAR scheme being located at those locations. The land cover at those locations consisted predominantly of urban sports or recreational grounds with gentle slopes near the Emmarentia Dam. As a result of high urbanisation, only a small percentage of the study area is suitable for MAR schemes.

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List of Abbreviations

AHP: Analytical Hierarchy Processes

ASR: Aquifer Storage and Recovery

ASTR: Aquifer Storage Transfer and Recovery

BIT: Bhungroo Irrigation Technology

CoJ: City of Johannesburg

DRI: Double Ring Infiltration

ERT: Electrical Resistivity Tomography

FIS: Fuzzy Interference System

GIS-MCDA: Geographical Information Systems Multi-Criteria Decision Analysis

OWA: Ordered Weighted Averaging

MAR: Managed Aquifer Recharge

Mbgl: Meters below ground level

MIF: Multi-Influence Factor

NGA: National Groundwater Archive of the Department of Water and Sanitation

SAT: Soil Aquifer Transfer

SAWS: South African Weather Services

SOTERSAF: Soil and Terrain Database for South Africa

WLC: Weighted Linear Combination

Chapter One: Introduction

1.1 General introduction

Climate change and variability effects such as changes in rainfall occurrence and intensity result in the straining of water resources (Ebrahim *et al*., 2020; Magombeyi and Matambo, 2023). The occurrence of natural disasters such as droughts, both meteorological and hydrological, and floods is a result of decreasing or increasing rainfall intensity, respectively (Wendt, 2023). These natural disasters result in the halting of economic activity due to the disturbance experienced in the agricultural, industrial, manufacturing and other industries and due to the damage to infrastructure. An important water management objective is the reduction of water insecurity during times of drought (Dillon *et al.*, 2020). According to the African Ministers' Council on Water, frequent droughts in sub-Saharan Africa are a serious climatic risk which jeopardises lives, the supply of food and water, and have an enormous detrimental effect on the gross domestic product (GDP) growth in one-third of the continent's countries (African Ministers Council on Water, 2012; Ebrahim *et al*., 2020). In addition to providing water to Africa's growing population, groundwater is a resource with huge prospects for growth in the future for a variety of uses. One of these uses includes the prevention of famine in various regions of the continent. Groundwater is essential for maximizing the resilience of water supply (Dillon, 2005; Dillon *et al.*, 2019).

Johannesburg resembles a semi-arid environment whereby groundwater is crucial for socio-economic development (Leketa *et al.*, 2018; Leketa and Abiye, 2021) and provides a significant supply of water. The area consists of four types of aquifers namely: intergranular, fractured, karst and fractured intergranular aquifers (Barnard, 2000). The shallow Malmani dolomite aquifer and the area's surface water bodies have become extremely contaminated, seen as an increase in silica content which results from silica dissolution. The silica dissolution occurs as a result of acid mine drainage from abandoned gold mines (Abiye, 2011; Leketa *et al.*, 2018). The contamination is also from the release of partially remediated urban water outflow from metropolitan regions (Leketa *et al.*, 2019). This has restricted the utilisation of surface water resources to mostly leisure and agricultural purposes. The restriction is seen especially for water in the Crocodile River and Hartbeespoort Dam, which are downstream of Johannesburg (Leketa *et al.*, 2018). According to Van Rooyen (2014),

groundwater quality is directly impacted by a city's land use, which is frequently overlooked. The poor construction of infrastructure and bad management of wastewater and purification systems have a significant impact on the quality of groundwater in large cities, particularly when an urbanised area depends on groundwater for its water supply (Assefa and Dinka, 2023). Once groundwater is contaminated, it is difficult to remediate due to its complexity therefore making the monitoring of groundwater vulnerability to pollution pivotal (Assefa and Dinka, 2023). The number of people living in urban areas increases exponentially annually and as a result, cities are compelled to grow beyond their current boundaries, which leads to more residential developments and businesses in industrial areas (van Rooyen, 2014). This expansion puts additional strain on the urban environment, including the stormwater systems, water supply, and service delivery (van Rooyen, 2014; Ebrahim *et al*., 2020; Kumar *et al.*, 2020; Sheridan, 2024). Various land use types affect the quality of groundwater. This may be seen at the University of Johannesburg and the surrounding industries disposing wastes, both from human and industrial activity, which enters the groundwater system eventually and elevates the nitrate levels of the groundwater (Assefa and Dinka, 2023).

Surface water (dams, rivers etc.) provides majority of the water supply for metropolitan cities and economic hubs like Johannesburg and Pretoria. As a result, there is increased water usage which slowly exhausts the resource (Todes, 2012; van Rooyen, 2014). The main supply of Johannesburg surface water is from the Vaal Dam which is part of the Lesotho Highlands Transfer Scheme. The Vaal Dam receives water from the Katse Dam via a transfer and delivery tunnel (Wendt, 2023; Sheridan, 2024). Due to the delay in additional dam construction, the availability of water supply remains constant whilst population grows rapidly by about 25% resulting in the growing water insecurity (Sheridan, 2024). Despite surface water being the main source of supply to Johannesburg and Pretoria, the surrounding rural communities rely on groundwater for household purposes. The water comes from a shallow aquifer primarily composed of alluvials and fragmented crystalline rocks (Abiye *et al.*, 2011). The Department of Water and Sanitation (DWS) is responsible for ensuring water security in South Africa by distributing water based on the population in the area. In Johannesburg, Rand Water allocates the water on behalf of DWS and ensures that the quality is compliant with South African Drinking Water Standards. Rand Water sells this water to Joburg

Water to distribute to its residents. Intermittent water supply (IWS) in Johannesburg is a water management strategy employed to reduce water insecurity. Recently, the occurrence of IWS has become more frequent, indicating the issue of strained water supply (Sheridan, 2024). The frequent IWS results in the growing need for additional water supply for households such as JoJo tanks which compromise the water distribution network (Sheridan, 2024).

The increasing strain on the stormwater systems and surface water infrastructure necessitates the sustainable management and utilisation of groundwater resources. The presence or absence of water in void spaces of rocks, either primary and/or secondary porosity features which allow for storage and movement of groundwater, is defined as groundwater potential zones (Netsianda and Abiye, 2017). The unintentional replenishment of an aquifer is known as indirect recharge whereas targeted aquifer replenishment and storage of water for future extraction and favourable use is known as managed aquifer recharge (MAR). MAR is a water management tool that has the potential reduce the strain experienced by the stormwater systems. Artificial recharge is a type of MAR which has strong human influence (Dillon, 2005; Ebrahim *et al*., 2020).

MAR operates as a significant buffer against the effects of climate variability and change, particularly when more water is replenished during times of floods or rain for recovery, during times of drought. The benefits of water stored in the sub-surface include that the water is not affected by evaporation losses, and it provides a viable alternative for water supply (Ebrahim *et al*., 2020). Water resources of an area can be significantly and sustainably managed through the application of MAR using various sources of surface water. These sources include wastewater reuse and stormwater collection (Page *et al.*, 2018). For towns and local settlements, MAR offers the most affordable source of new and safe water (Dillon, 2005). For village supplies in semi-arid and dry regions, MAR has the potential to significantly contribute to the UN Millennium Goal for Water Supply (ensuring environmental sustainability). In cities with well-planned drainage and sewage systems, there is a considerable potential for the passive reuse of stormwater and wastewater through aquifer storage for irrigation purposes and domestic supply (Dillon, 2005).

MAR approaches in conjunction with surface water utilisation are therefore essential to ensure that water demands are met. The City of Johannesburg (CoJ), Gauteng is the economic hub of South Africa which has a high population growth, leading to strain being experienced on its infrastructure. The water consumption in the CoJ (284.92L per capita per day) exceeds the recommended consumption of 50L per capita per day by the World Health Organization (WHO) which emphasises that over consumption is inevitable in the CoJ (Ndeketeya and Dundu, 2023). In addition to the growing demand of water, another obstacle faced in the CoJ is climate fluctuation (Ebrahim *et al*., 2020). The overexploitation of surface water resources brings about the issue of water insecurity (Mahlahlane, 2019). This study will aim to determine the hydrogeological suitability of an area for a potential MAR practice in Randburg, Johannesburg (Region B of City of Joburg) to provide means for alternate domestic water supply.

1.2 Research aims and objectives

Aim

The aim of the study is to assess the feasibility of managed aquifer recharge (MAR) schemes in an area of Randburg (region B of City of Johannesburg) through hydrogeological assessment for the purpose of recovering groundwater as an alternate water resource for domestic use to augment surface water supply.

Objectives

1. Map the geology, geological structures, and hydrogeology of the study area (hydrogeological characterisation).
2. Analyse the meteorological data of the site (specifically rainfall).
3. Determine the potential site for MAR scheme utilising various GIS software.
4. Identify source water for the potential site for the MAR scheme.

Chapter Two: Literature Review

2.1 Introduction

As fresh surface water becomes scarcer, groundwater resources become more significant and must be developed and safeguarded using optimal management practices (Abiye *et al.*, 2011). Managed aquifer recharge (MAR) approaches are usually most effective in regions of variable and low rainfall, providing means for an alternate supply of water (Dupont *et al.*, 2018; Ebrahim *et al.*, 2020). The recycling of water through aquifers is generally unplanned in squatter settlements, which may be described as indirect recharge or recharge that is not managed. The unplanned replenishment of aquifers highlights the importance of identifying a closed system to administer initiatives to conserve and upgrade water quality. Recognising the capabilities and constraints of various methods used within a water catchment and aquifer system play a role in how much MAR may fulfil its potential for water supplies (Dillon, 2005; Dupont *et al.*, 2018). The understanding of the hydrogeology, the current drainage infrastructure, room for water harvesting, economic, social, and legislative contexts, and human resources abilities all contribute to how MAR fulfils its full potential (Dillon, 2005; Ebrahim *et al.*, 2020). The implementation of MAR approaches globally has risen at a rate of 5% since the 1970s, despite groundwater extraction rates exceeding it (Dillon *et al.*, 2019). MAR practices may however exceed the rate of extraction where practices are advanced (Dillon *et al.*, 2019).

The following section explains in detail the concepts of importance for the study, namely: definitions associated with groundwater and groundwater flow dynamics, managed aquifer recharge and its various purposes, the types of managed aquifer recharge practices, the potential source waters for the practice, a review of the various methods that may be used to assess both the hydrogeological parameters of an aquifer and the selection of a suitable site for MAR, MAR practices in Africa and a general description of the site on a broad scale (Johannesburg).

2.2 Groundwater dynamics and MAR

Aquifers are strata which enable the flow and storage of water and may be recharged naturally either through meteoric water, or surface water bodies infiltrating the soil, or percolation through the rock (Page *et al.*, 2018). The geochemical processes taking

place in an aquifer determine a region's groundwater quality. The complexity of groundwater dynamics results in the increased difficulty of remediation (Assefa and Dinka, 2023). As a result, the knowledge of the hydrogeochemical features of aquifers, recharge dynamics and groundwater circulation processes in the weathered profile and fractured zones are essential for the long-term sustainability and management of the water resources of a nation and its surrounding areas. Small zones of aeration cause problems whereby they may be oversaturated during the rainy seasons. This then impacts the storage and water quality enhancement capacity of the aquifer. This shallow zone of aeration may also contribute to the contamination of the groundwater due to the self-remediating property of the area decreasing (Assefa and Dinka, 2023) as a large vadose zone remediates any polluted water before recharging the aquifer (Ebrahim *et al.*, 2020). Aquifers with high hydraulic conductivities are more susceptible to pollution (Assefa and Dinka, 2023) therefore previous understanding of natural water quality and groundwater circulation mediums may help with pollution control for the potential urban, agricultural, and industrial pollutants which may be present in an area (Abiye *et al.*, 2011).

Water stability and dependability in many water-stressed locations are determined by the percentage of water that is effectively stored for future use rather than the total amount of rainfall. By storing excess water into the ground during wet seasons to be used later during dry seasons, droughts can be mitigated. Reserving additional water in aquifers helps reduce evaporative losses (Arshad *et al.*, 2014). Recharge may be categorised into three groups, namely: unintentional recharge, including land cleaning and deep leakage under irrigation areas and infrastructure systems; unmanaged recharge, such as septic tank drainage; and managed recharge, which includes intentionally built infrastructure for later extraction (Page *et al.*, 2018). According to the findings of Arshad (2014), MAR can yield higher financial returns than surface reserves and other options (Arshad *et al.*, 2014). Nonetheless, there is much disagreement about whether it is more economical to keep water below the ground via regulated aquifer recharge or above ground in surface reservoirs. The cost of maintaining an infiltration basin can be considerably raised due to an increase in the turbidity of the source water brought on by hydrological variability (Arshad *et al.*, 2014). The clogging then increases the expenses of water quality treatment for aquifer storage and recovery (ASR) systems. The identification of appropriate sites for MAR

and the choice of the technique is reliant on the hydrogeology, slope, hydrology and land uses of the region (Dupont *et al.*, 2018; Page *et al.*, 2018; Sallwey *et al.*, 2019; Hani *et al.*, 2023).

2.3 Intention of MAR

The main intention behind MAR generally is to protect and enhance the water supply, followed by enhancing the quality of water, stabilising falling groundwater levels and eradicating potential seawater ingress (Malekmohammadi *et al.*, 2012; Dillon *et al.*, 2020; Ebrahim *et al*., 2020; Ulibarri *et al.*, 2021). An important aim of water management is elevating the security of the water resources for future use in times of heightened desertification and emergency. This can be done through MAR schemes which additionally aim to restore wetlands (Dillon *et al.*, 2019). Where MAR schemes have the purpose of augmenting water supply, the water resource is meant to meet peak demand, mitigate drought and emergency in places with high water demand (Page *et al.*, 2018) such as South Africa.

Coastal aquifers assist in meeting peak demand and preventing saltwater intrusions simultaneously as seen in the Atlantis scheme. This scheme recharges an inland aquifer for domestic supply and coastal aquifer for seawater intrusion prevention (Ebrahim *et al*., 2020). MAR plays a big role in the water management strategies and demand management to sustain, improve and secure groundwater systems due to the increasing intensity of changing climate. Enhancements in MAR have come about due to the hydraulic design of facilities, tracer studies, the management of clogging, the recovery efficiency and the changes in water quality changes of aquifers (Dillon *et al.*, 2019).

2.4 Types of MAR

Various kinds of MAR practices exist which include aquifer storage and recovery (ASR), aquifer storage transfer and recovery (ASTR), bank filtration, dune filtration, infiltration ponds, percolation tanks, rainwater harvesting, soil aquifer transfer (SAT), underground dams and recharge releases (Dillon, 2005). The methods which are most common are ASR, where water is inserted into and recovered from a single well and ASTR, which involves one well for injection and another for recovery. Where lithology is predominantly sedimentary, infiltration techniques are favoured for the implementation of MAR and therefore reduce costs relating to infrastructure. In regions

where lithology is dominated by crystalline rocks such as Johannesburg, a different approach is required such as injection techniques (Dillon, 2005; Dillon *et al*., 2019). The lack of precise well injection rates based on field observations resulted in Arshad (2014) evaluated an analysis conducted by Pyne (2005) which found that injection rates increased as aquifer transmissivities increased (Arshad *et al.*, 2014). Bank and dune filtration are related to the indirect induced recharge from a surface water body. Infiltration ponds and percolation tanks are used where water table aquifers are the target. The harvesting of rainwater utilises roof runoff as source water and uses vadose zone recharge (known as dry wells) to store reclaimed water or stormwater. SAT is linked to reclaimed water and is helpful in pathogen removal. If arsenic is present, a zone of oxidation should surround the well (Dillon, 2005; Dillon *et al*., 2019). The SAT practice may assist in elevating the quality of water, providing alternative water supply as well as improving aquatic environments. MAR alone however is not the solution to water supply deficit, therefore adding economic value to groundwater resources as well as implementing legislative measures may assist in the management of water demand and quality (Dillon, 2005; Dillon *et al*., 2019).

2.5 Source water for MAR

There are various approaches of MAR practices which consider the quality of the water recharging the aquifer (Dillon *et al.*, 2019). The source water for MAR globally is generally: water from the dewatering of mines, stormwater, reclaimed water, large water supply dams, water from a different aquifer, streams and lakes (Dillon *et al*., 2019; Ebrahim *et al.*, 2020). Generally, river water is used as the source water for MAR practices, as seen in Windhoek Namibia, however many sources may be used (Ebrahim *et al.*, 2020). In the Atlantis scheme in the Western Cape, urban stormwater and reclaimed water is utilised as the source for recharge and is common across South Africa due to restricted water resources. Remediation of wastewater is made possible due to a cellulose acetate membrane for reverse osmosis. Increased maintenance is required for reclaimed water to minimise clogging and pollution caused by mixing. In South Africa, the industrial and mining industries are largely dependent on groundwater as the source water for MAR schemes. This is inclusive of recovering water from one aquifer to recharge another aquifer or the dewatering of mines. This is seen in Kolomela, Sishen Mine and Elandsfontein (Dillon *et al*., 2019; Ebrahim *et al.*,

2020). Proper risk assessment is needed for stormwater to be used for recharge (Dillon *et al.*, 2019).

In urban areas, stormwater which is diverted to infiltration ponds or wells is utilised as the source water for most of the MAR schemes and therefore requires treatment. This water may be recovered later for the purpose of consumption or for irrigation. Treated wastewater may also be utilised as the source water for MAR practices that aim to assist in water supply and/or irrigation. This source water also allows for remediation processes to occur within the aquifer especially with the ASR and ASTR methods. The hydrochemical properties of the groundwater which are inclusive of pH, REDOX, salinity and temperature are of utmost importance for MAR to effectively take place. To avoid waterlogging, soil salinity and unstable slope occurrence, the quality of the source water needs to be well understood (Dillon, 2005; Arshad *et al.*, 2014; Dillon *et al*., 2019). Bhungroo Irrigation Technology (BIT) is a type of ASR technique effectively used in Ghana and India where rainwater is harvested as the source water (Magombeyi and Matambo, 2023).

2.6 MAR work in Africa

There are currently forty four MAR schemes in Africa (IGRAC, 2024). They are separated into various categories according to the types of MAR schemes being run based on data from the Global MAR portal (https://ggis.un-igrac.org/view/marportal/) as well as from literature review (Dillon *et al*., 2019). The MAR schemes are densely prevalent in nine of the countries on the continent with South Africa being the most dominant followed by Tunisia, which have aquifers made up of both sedimentary and hard rocks. South Africa currently has 19 active MAR schemes with the prominent approach being well, shaft and borehole recharge (IGRAC, 2024). It was identified that the most prominent MAR technique across the African continent was surface spreading/infiltration followed by introduction of water through wells.

Ebrahim *et al.* (2020) evaluated a study conducted by Murray (2017) that was based on guiding the Southern Africa Development Community (SADC) for the Groundwater Management Institute (SADC-GMI). The study paid attention to and analysed the Windhoek, Namibia MAR scheme as well as the Atlantis MAR scheme analysed by Bogan et al (2016) and Jovanovic et al (2017). Issues associated to the MAR schemes were inclusive of thin zones of aeration, as seen in the Atlantis scheme, where the

shallow zone of aeration becomes oversaturated during the rainy season thus affecting the storage capacity as well as the water enhancement capacity due to infiltration techniques being employed (Ebrahim *et al.*, 2020). Infrastructure design issues such as clogging, which may be as a result of thin soil cover and increased sediments in the soil (clays), also negatively affect MAR schemes (Arshad *et al.*, 2014; Dillon *et al.*, 2019; Ebrahim *et al.*, 2020). The abovementioned schemes are dominated by soft rock therefore infiltration techniques are most suitable for sites in those regions. Due to Johannesburg's geology being dominated by hard rock, injection techniques will need to be utilised once a suitable site is selected for MAR. Other MAR schemes in South Africa that use injection-based approaches, despite being dominated by metasedimentary rocks of the Cape Supergroup (Shone and Booth, 2005), include the Elandsfontein, Langebaan, Hermanus schemes and others in the Northern Cape (https://ggis.un-igrac.org/view/marportal/).

2.7 Review of methods

In order to assess whether an area is suitable for a managed aquifer recharge scheme, an understanding of its hydrogeological characteristics is required. The following methodology may be applicable in order to further comprehend an aquifer's characteristics.

2.7.1 Double ring infiltration tests

The double ring infiltration (DRI) test is conducted in order to determine the rate at which water passes through the soil thus giving the soil's infiltration rate (Zhao *et al.*, 2019). The test is conducted using two round rings, a small internal one, which shows a vertical infiltration rate and a larger external one, which helps retain moisture outside the internal ring thus limiting lateral motion of water within the inner ring. Both rings are hammered into the ground and once secured they are filled with water as seen in Figure 1. Over time, the water level in the smaller ring is monitored until the rate water is absorbed by the soil within the ring becomes constant. A disadvantage of the double ring infiltration technique includes the potential movement of soil despite one of its advantages being that it is easy to conduct (Mohuba, 2020). The potential movement of soil may provide inaccurate results due to either increased or decreased infiltration rates when the water flows preferentially through larger void spaces when the soil is disturbed. Gregory *et al.* (2005) utilised the double ring infiltration tests in the design

of golf courses due to the test providing information relating to the runoff estimates. The test was experimented with rings of varying diameters and the rings with 15- and 30cm diameters at constant head provided sufficient information regarding infiltration rate (Gregory *et al.*, 2005).

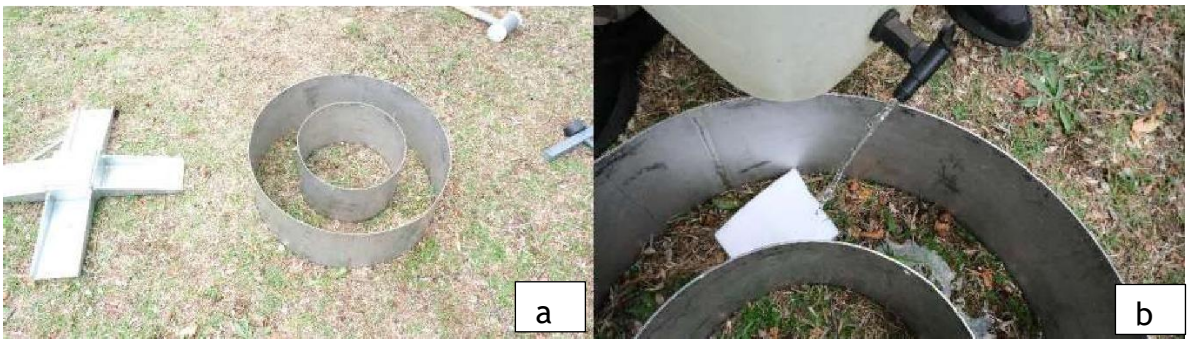

Figure 1 (a) Image of the tools used: Metal rulers with clips, Mariotte tube, hammer and the inner and outer rings (b) Image of the inner and outer rings being filled with water. Courtesy of Dr Khuliso Masindi

2.7.2 Electrical resistivity tomography

The ability to see the fluid dynamics and investigate the subsurface makeup has been transformed by the multifaceted set of investigative techniques that geophysics offers. One of these methods includes electrical resistivity tomography (ERT), also called DC resistivity. The method is utilised to examine subsurface conditions and therefore characterise the aquifer. The method measures the ability of the ground to resist electrical current and is dependent on the type of material present in the subsurface. Information about the water content, clay content and pore water conductivity are obtained from this technique (Binley *et al.*, 2015; George *et al.*, 2017). A series of steel/copper electrodes are placed into the ground at equal spacing, with current being inserted through the current electrodes (A and B) and the voltage electrodes (M and N) measuring the potential difference between the current electrodes (Onyebueke, 2020; Dildar *et al.*, 2023). The electrodes should be placed into the ground on a relatively flat surface as seen in Figure 3. Current travels from the positive current electrode to the negative current electrode in two-electrode systems. Current flow lines are perpendicular to the equipotential surfaces that the currents create as seen in Figure 2.

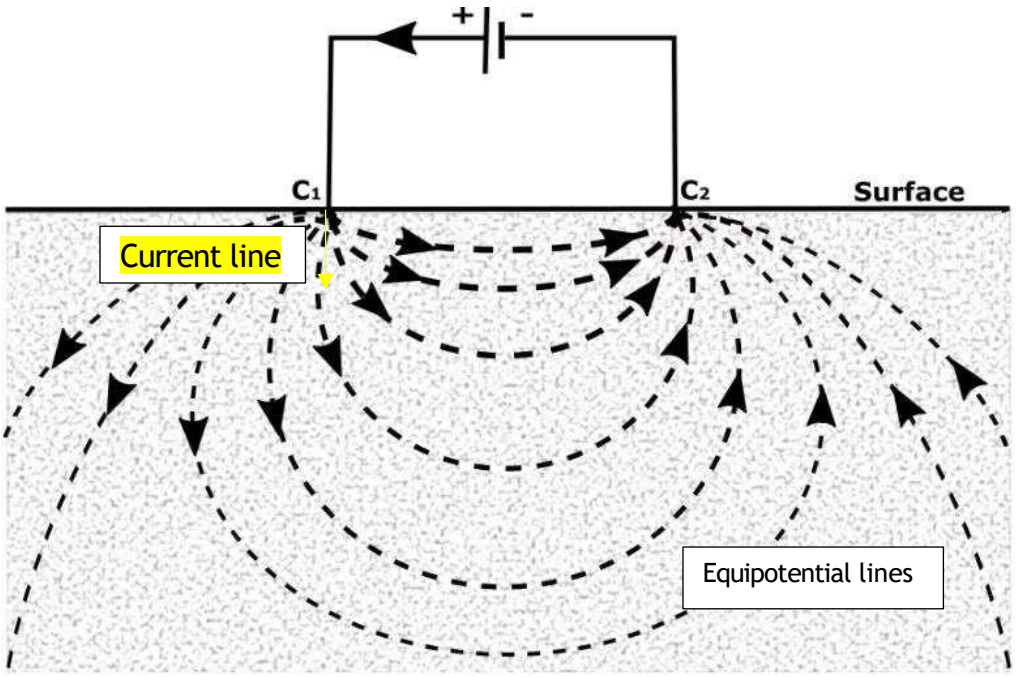

Figure 2: Sketch showing current lines being perpendicular to current lines. Modified from Onyebueke (2020).

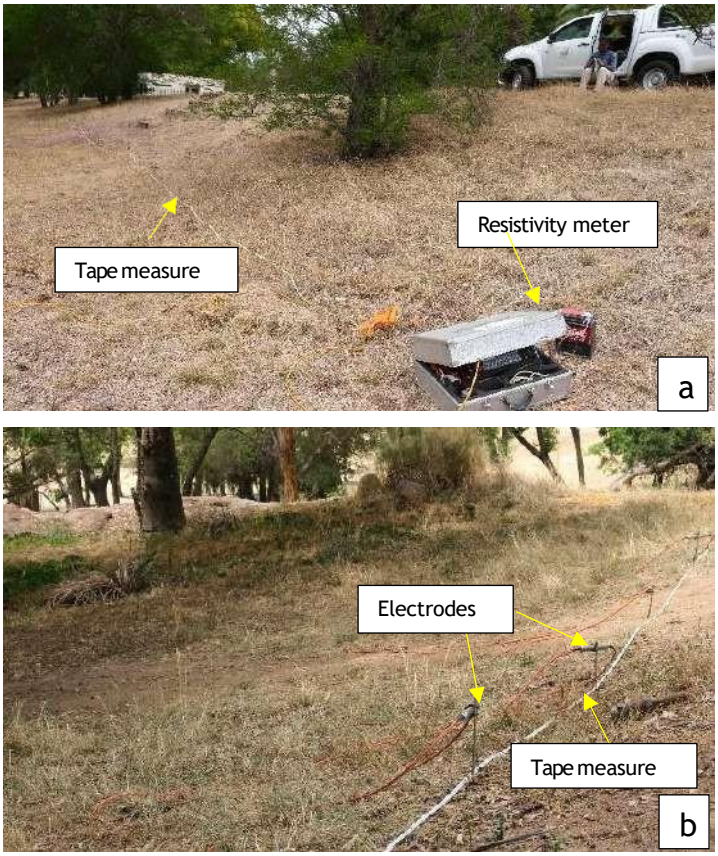

Figure 3: (a) Image of electrodes connected to the resistivity meter for ERT (b) Image of the electrodes connected along a tape measure for accuracy in spacing. Courtesy of Dr Khuliso Masindi

The potential difference (ΔV), the known current (I), and the geometric factor (K) that depends on the specific electrode design, can calculate resistance (ρ) using Ohm's law recorded in Ohm-meters (Ω-m) as shown in equation 1:

$$\rho = \frac{\Delta V}{I} \times K \qquad [1]$$

There are various arrays used in 2D resistivity studies such as: Wenner, Schlumberger, Dipole-Dipole configurations and others. The adjustment of the electrodes provides results in a profile which give information about the resistivity of the subsurface at various points as seen in Figure 4. For horizontal structures with vertical resistivity fluctuations, the Wenner arrangement offers an excellent resolution and a modest depth of examination. This array takes a shorter time to be completed and is less sensitive to weak signal strengths despite it giving less detailed data compared to the others. The current electrodes on one side and the potential electrodes on the other form two dipoles, which make up the dipole–dipole array. Compared to the Wenner array, this array reaches shallower depths and has a better horizontal resolution but a worse vertical resolution. The Schlumberger array is generally utilised for vertical soundings (Kneisel, 2006; Garofalo, 2014; Galazoulas *et al.*, 2015).

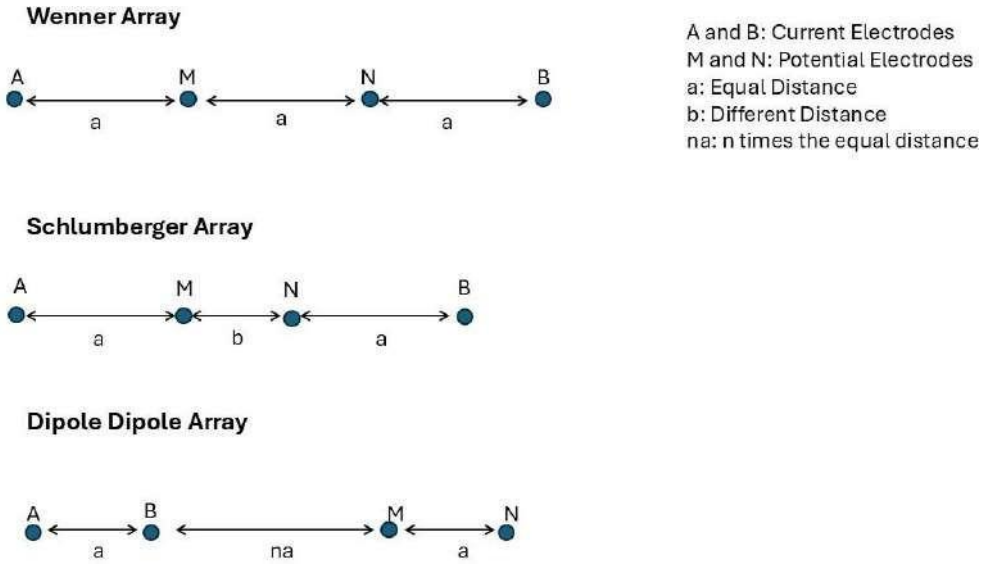

Figure 4: Diagram displaying the Wenner, Schlumberger and Dipole Dipole arrays, modified from Garofalo, 2014.

Temperature, pore water's chemical characteristics, void volume structure, and water saturation all affect a rock's resistivity. For majority of materials, the wide range of resistivity values is caused by different amounts of water (Kneisel, 2006). Fine-grained sediments such as clays and silts display low resistivity values due to their high-water holding capacity and therefore block direct recharge and retards water from reaching shallow or deeper aquifers (Galazoulas *et al.*, 2015). Water bearing rocks and topsoil tend to have low resistivity values (Eruteya *et al.*, 2017). Clays have resistivity values ranging between 1-100 Ωm and groundwater has a range between 10-300 Ωm (Kneisel, 2006). Electrical resistivity has been used for subsurface and aquifer characterisation and monitoring the vadose zone's response to infiltration-based MAR by Mawer *et al.* (2013). This method provides vital information on the physical properties of the subsurface which strongly impact infiltration-based MAR approaches (Mawer *et al.*, 2013). Electrical resistivity methods have also successfully aided in site suitability studies for MAR as seen in the study done by Behroozmand e*t al.* (2019) where the geology is dominated by sedimentary rocks.

This technique is beneficial as no drilling is needed however the results may be influenced by surficial activities leading to high uncertainty which can be resolved by drilling to confirm what the geophysical results show (Chambers *et al.*, 2006). However, the high uncertainty in the results may also be due to high ambiguity. The method aids in the characterisation of the subsurface to various materials having a characteristic resistivity value. Information about geological structures and features such as faults, fractures, weathered zones, fresh bedrock and groundwater presence are also obtained through this method (Dildar *et al.*, 2023; Gomo *et al.*, 2024). ERT may be used as a validation technique for MAR site selection.

2.7.3 Suitability mapping with GIS-MCDA

By integrating geographical information systems (GIS) with multi-criteria decision analysis (MCDA), which solves spatial problems, site suitability analysis for MAR can be accomplished. GIS-MCDA is the term for the combined application of these two separate scientific disciplines. It integrates the MCDA technique, which directs the decision-making process, with the geographical analysis capabilities of GIS. To assist the reduction of uncertainty, the fuzzy interference system (FIS) may also be applied additionally to this combined technique (Malekmohammadi *et al.*, 2012). Based on the goals of the study, the geospatial data describing the study region is combined and

weighted to begin the site selection process (Dupont *et al.*, 2018; Sallwey *et al.*, 2019; Hani *et al.*, 2023). Based on the objectives and preferences of the decision-makers, GIS-MCDA assigns a ranking to the entities that make up the research area. These entities are the fundamental component of GIS-MCDA and are sometimes referred to as criterion. These criteria include the hydrogeology of the area and surface properties such as the land use, slope, lithology and others (Dupont *et al.*, 2018). There is a plethora of potential reasons as to why an area may be unsuitable for the scheme such as the distance to the water source, which then disregards those areas in constraint mapping. Suitability mapping, as opposed to constraint mapping, classifies the study area according to its suitability for the use of MAR rather than excluding areas that are inappropriate for MAR (Sallwey *et al.*, 2019).

The process of assigning weights to the criteria and combining them using a decision rule is known as suitability mapping (Zhang *et al.*, 2019) and is conducted on GIS software such as ArcGis Pro. The criteria's weights indicate how important each criterion is in relation to the others and may be allocated either in the raster calculator, weighted overlay and weighted sum spatial analyst tools or through the use of the model builder tool. The rating method, ranking method, multi-influence factor (MIF), and pairwise comparison can all be used to provide weights to the criterion. Manual weight allocation on a preset scale is part of the rating and ranking process. The weights for the ranking approach are determined using ranks that have already been provided. According to one description, the MIF approach uses the number and significance of links between the criteria to determine weights from a graphical depiction of the criteria. According to Zhang (2019), weights are assigned for pairwise comparisons by comparing pairs of criteria based on a matrix (Zhang e*t al.*, 2019). This approach involves calculating the consistency ratio, which serves as a benchmark for the quality of the decision-maker's judgment and an indicator of the paired judgment's consistency. The decision rule specifies how the site suitability map is created by integrating datasets and their weights. Weights and values can be combined using more complex integration procedures, such as weighted linear combination (WLC), or threshold values (Boolean logic). WLC has advanced beyond derivatives such as analytical hierarchical processes (AHP), introduced by Saaty in 1980 (Zhang *et al.*, 2019) and ordered weighted averaging (OWA) (INOWAS, 2019). A sensitivity study should be performed to confirm the final suitability map. A sensitivity

analysis enables more reliable decision-making because the parameter values and weighting are the primary sources of ambiguity in the MCDA process (Magombeyi and Matambo, 2023). Sensitivity analysis is applied to show how various criterion weights affect the suitability map's spatial arrangement. Despite every site selection investigation needing validation of the generated maps, this step is frequently omitted or not disclosed (Sallwey *et al.*, 2019; Assefa and Dinka, 2023).

Chapter Three: Site description

3.1 Location

The study area is the municipal ward 88 which forms part of region B of the City of Johannesburg at a latitude of 26º09'01" S and a longitude of 27º59'02" E. It includes the areas such as Emmerentia, Northcliff and parts of Greenside as illustrated in Figure 5.

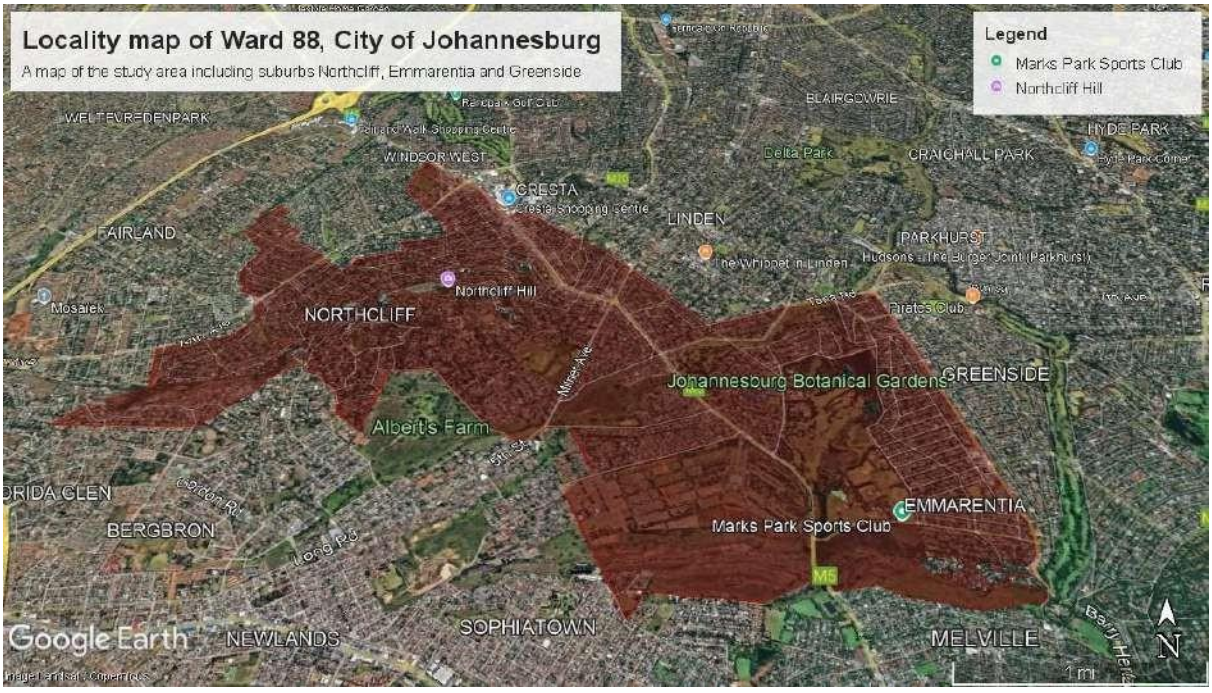

Figure 5: Locality map of study area, shaded in red, in municipal ward 88, CoJ.

3.2 Climate

Johannesburg has a sub-tropical, temperate climate due to its latitudinal position. The summer climate is hot with elevated air temperatures along with increased moisture content in the air whereas the winter climate is cold and dry. The annual rainfall

experienced in the summer season (October to April) ranges from 380mm to 907mm per annum (Leketa and Abiye, 2020) whilst the highest rates of evaporation are experienced in the winter seasons (April to September) at approximately 1600mm (Jombo, 2021). The past 10-year rainfall data from the South African Weather Services (SAWS) in Figure 6 indicate that a mean annual rainfall of 253.86mm per annum is experienced in the greater Emmarentia area, which was recorded at the Johannesburg Botanical Garden (Jhb Bot Tuine) weather station. The rain experienced is mainly convective with a frequency of thundershowers brought on by cumulonimbus and intermittent frontal downpour (Leketa and Abiye, 2020). The average annual air temperature ranges roughly between 18°C and 20°C (SAWS, 2024).

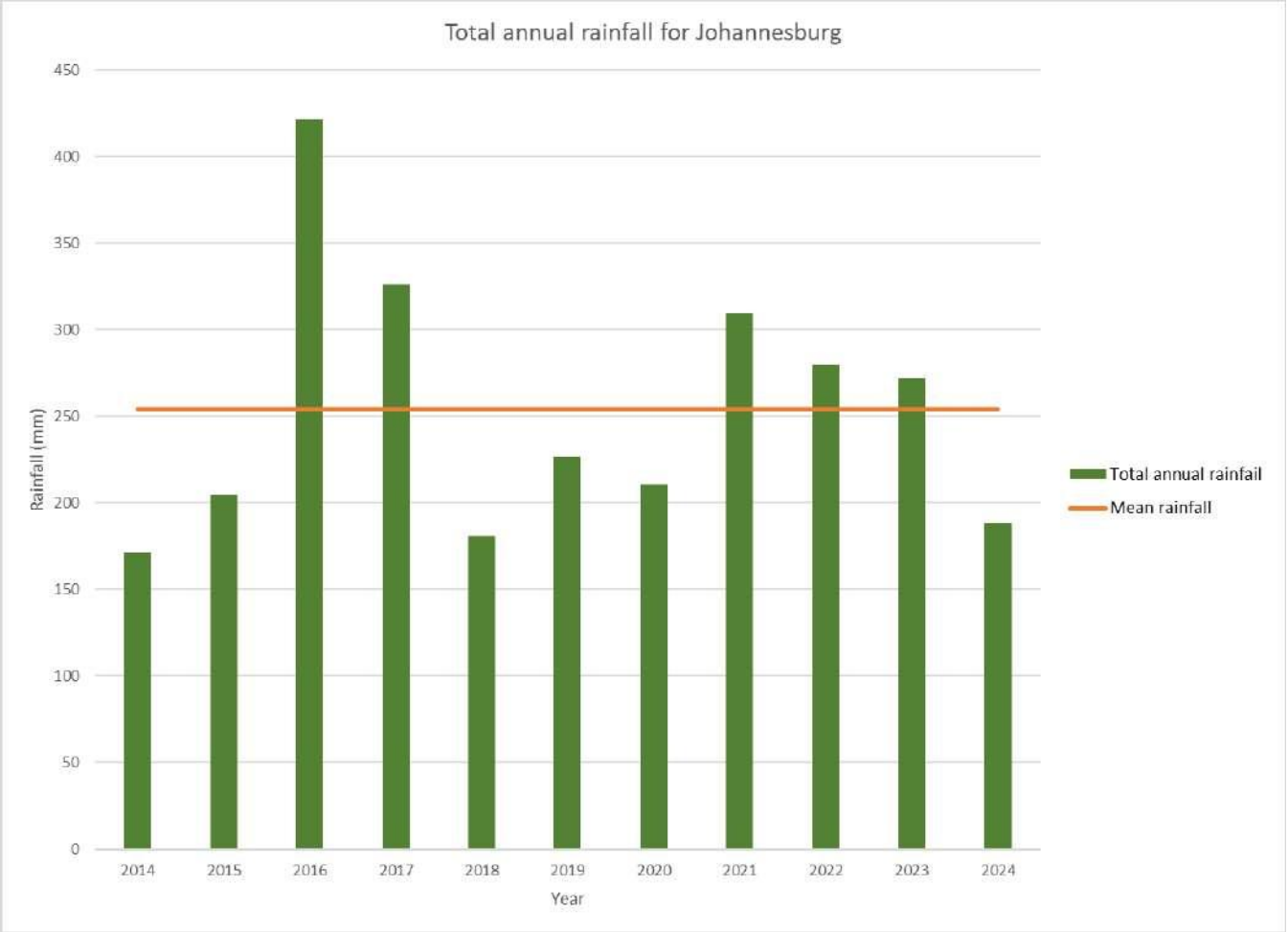

Figure c: Annual rainfall data for Jhb Bot Tuine station. Data provided by SAWS, 2024.

3.3 Geological framework

The area of study, which forms part of the Johannesburg Dome, is dominated by crystalline rocks such as granite, granodiorite, quartzite and diorite. The Karoo, Transvaal, Ventersdorp, and Witwatersrand Supergroups, and the Archean Basement

Complex dominate the geology of Johannesburg (McCarthy and Rubidge, 2005; Abiye, 2011; Leketa and Abiye, 2021). The lithological log data provided by the National Groundwater Archive (NGA) of the Department of Water and Sanitation indicate these rocks are present along with clays, some felsite and greenstone which are illustrated in Figure 7. The Halfway House Granite Suite and the Hospital Hill quartzites are located within this region. Some shales and serpentinites are present in the area as well.

Karoo Supergroup

The Karoo Supergroup is the youngest sedimentary basin comprising of meta-sedimentary rocks such as shales, mudstones, sandstones and diamictites. It outcrops mainly in the Kalahari basin. These lithologies make up the Dwyka and Ecca Groups of the Karoo Supergroup which were deposited about 300Ma (McCarthy and Rubidge, 2005; Abiye, 2011).

Transvaal Supergroup

The Transvaal Supergroup is a combination of meta-sedimentary and meta-volcanic rock including shales, banded iron formations (BIF), conglomerates and quartzites. These lithologies form part of the Pretoria and Chuniespoort Groups and the Black Reef Formation of the Transvaal Supergroup. The Supergroup was deposited 2650 Ma. ago due to the creation of a basin which resulted from continental shelf rifting leading to thermal subsidence. The Supergroup outcrops mainly in the northern parts of South Africa. The Black Reef Formation was deposited first followed by the Chuniespoort Group, which is divided into three classes: the Malmani Subgroup, the Penge Formation and the Duitschland Formation, and lastly the Pretoria Group (McCarthy and Rubidge, 2005; Abiye, 2011).

Ventersdorp Supergroup

The Ventersdorp Supergroup which dates back to 2700Ma outcrops around Vredefort, the Klipriviersberg south of Johannesburg and in the Suikerbosrand west of Heidelberg. The Supergroup is composed of andesitic lavas and tuff, quartz porphyry, calcareous shales, conglomerates and sandstones (Barnard, 2000; Abiye, 2011).

Witwatersrand Supergroup

The Witwatersrand Supergroup was deposited about 3Ga in an extensional environment and is predominantly meta-sedimentary. The Supergroup is divided into two groups: the older West Rand Group, classed into: the Jeppestown, Government

and Hospital Hill subgroups, and the younger Central Rand Group, classed into: the Johannesburg and Turffontein subgroups. The lithologies are inclusive of conglomerates, shales, quartzites, banded iron formations and siltstones (McCarthy and Rubidge, 2005; Abiye, 2011). The shales react to strain in a brittle manner (Liu and Qu, 2023).

Archean Basement Complex

All these successions overlie the Archean basement complex, of about 4Ga, which consists of weathered and tectonic-influenced granites, granodiorites, and gneisses. The Witwatersrand Supergroup unconformably overlies these oldest rocks (McCarthy and Rubidge, 2005; Abiye, 2011; Leketa and Abiye, 2021).

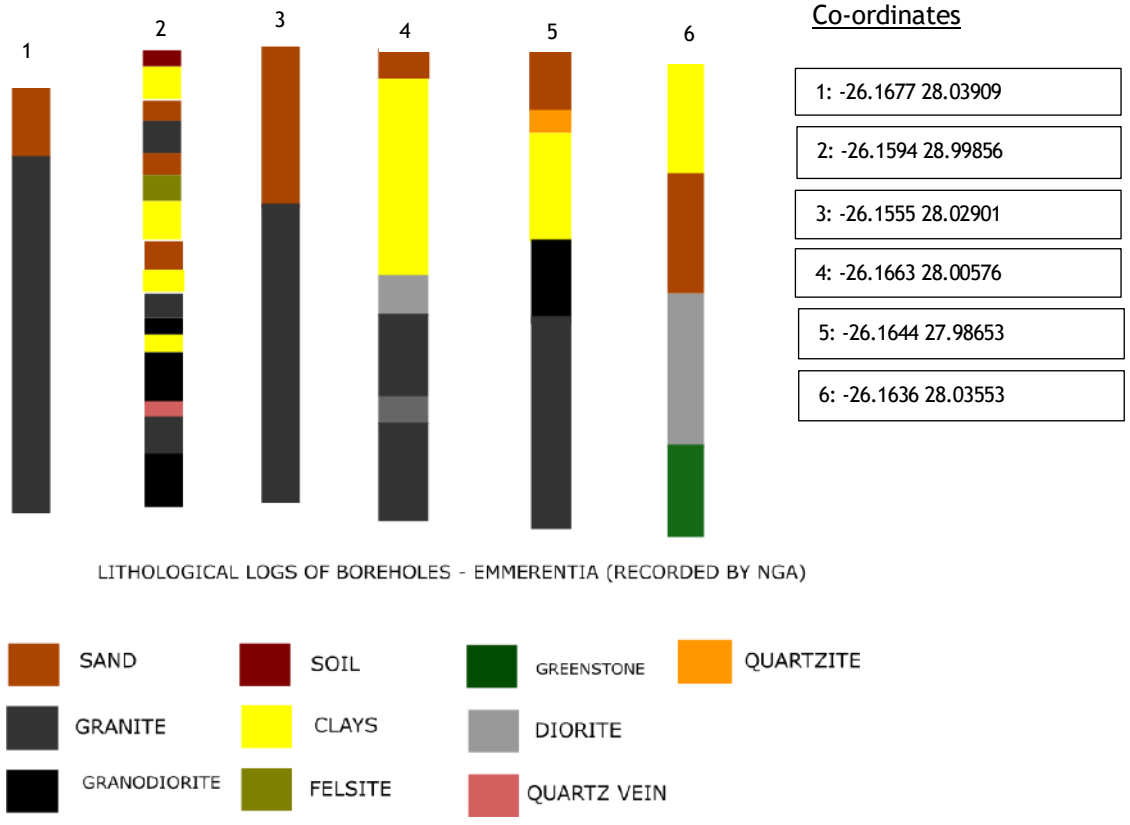

Figure 7: Lithological logs of borehole data. Data provided by National Groundwater Archive (NGA) of the Department of Water and Sanitation

3.4 Hydrogeological framework

Drainage basin

Johannesburg falls within the Upper Crocodile River Basin (UCRB) which has been affected by deformation events (Leketa *et al.*, 2019). These events produced

structures such as strike-slip faults and shear zones which allow for storage and circulation of water. The Black Reef quartzites forming the water divide between the northern Limpopo River Basin (north of Johannesburg) and the southern Orange River Basin (south of Johannesburg) are excessively fractured which allows for the suitable recharge of aquifers (Abiye e*t al.*, 2011).

Hydraulic characteristics

The West Rand Group is exposed at the Albert's Farm Spring in Roosevelt Park where highly fractured quartzites overlie low permeability shales (Leketa *et al.*, 2019). The presence of the spring displays the importance of the secondary porosity of the quartzite due to the primary porosity and permeability of fresh quartzite having very little significance. The basement complex is inclusive of granites and serpentinites which are highly weathered and fractured. These weathered and fracture zones increase the hydraulic conductivity of the rock, creating a shallow intergranular aquifer along riverbanks where sands and gravels overlie the bedrock (Leketa and Abiye, 2021). These various rock types have varying permeability and hydraulic conductivity values based on the conditions and environments they are in. Therefore, these materials also have varying specific yield values. Generally, hard rocks have very low matrix porosities, making their secondary porosities of utmost importance (Netsianda and Abiye, 2017). As depth increases, the fracture aperture and fracture density decrease which reduces the hydraulic conductivity of hard rocks (Singhal and Gupta, 1999). Fractured igneous and metamorphic rocks have a permeability and hydraulic conductivity range of $10^{-13}cm^2$ to $10^{-7}cm^2$ and $10^{-9}cm/sec$ 10^{-2}cm/sec, respectively (Woessner and Poeter, 2020). Shales have permeabilities ranging between $10^{-16}cm^2$ and $10^{-12}cm^2$ and hydraulic conductivity values ranging between $10^{-11}cm/sec$ and $10^{-7}cm/sec$ (Woessner and Poeter, 2020). Shales consist of feldspars which weather to clays (Weight, 2008). Clays have a specific yield range of 1-18% whereas shales and weathered granites range between 0.5-5% (Woessner and Poeter, 2020).

Aquifer yields

Due to the region having a semi-arid climate, baseflow is unusual which is attributed to the complexities of recharge mechanisms. Recharge is complex in these regions due to the elevated evapotranspiration rates which hinder meteoric water from infiltrating the soil and thus reducing percolation. This results in deep water levels persisting (Leketa and Abiye, 2021). The crystalline rock intergranular and fractured

aquifers hosted by the Witwatersrand Supergroup are low yielding (between 0.5-2L/s) compared to the karstic aquifers of the Transvaal Supergroup (>5L/s) also found in Johannesburg (Barnard, 2000; Abiye, 2011; Mahlahlane, 2019).

Groundwater occurrence

The establishment of a water-bearing horizon is restricted to the hydrostructures, namely: the shallow weathering zones, the occurrence of dissolution cavities in the dolomites, and fracture media due to regional variations in the extent of fracturing and weathering (Singhal and Gupta, 1999; Abiye *et al.*, 2011; Mahlahlane, 2019; Leketa and Abiye, 2021). These zones of weakness, particularly faults and dykes, may also act as barriers for water flow (Singhal and Gupta, 1999).

The aquifers present are shallow to deep (borehole readings range from 5-25m below surface) as shown by the groundwater levels in Figure 8 and weathered (NGA, 2024). In the study area, the valleys at the base of the steep hills host streams, which flow from high elevation areas to low elevation areas which indicates runoff from steep slopes, and dams.

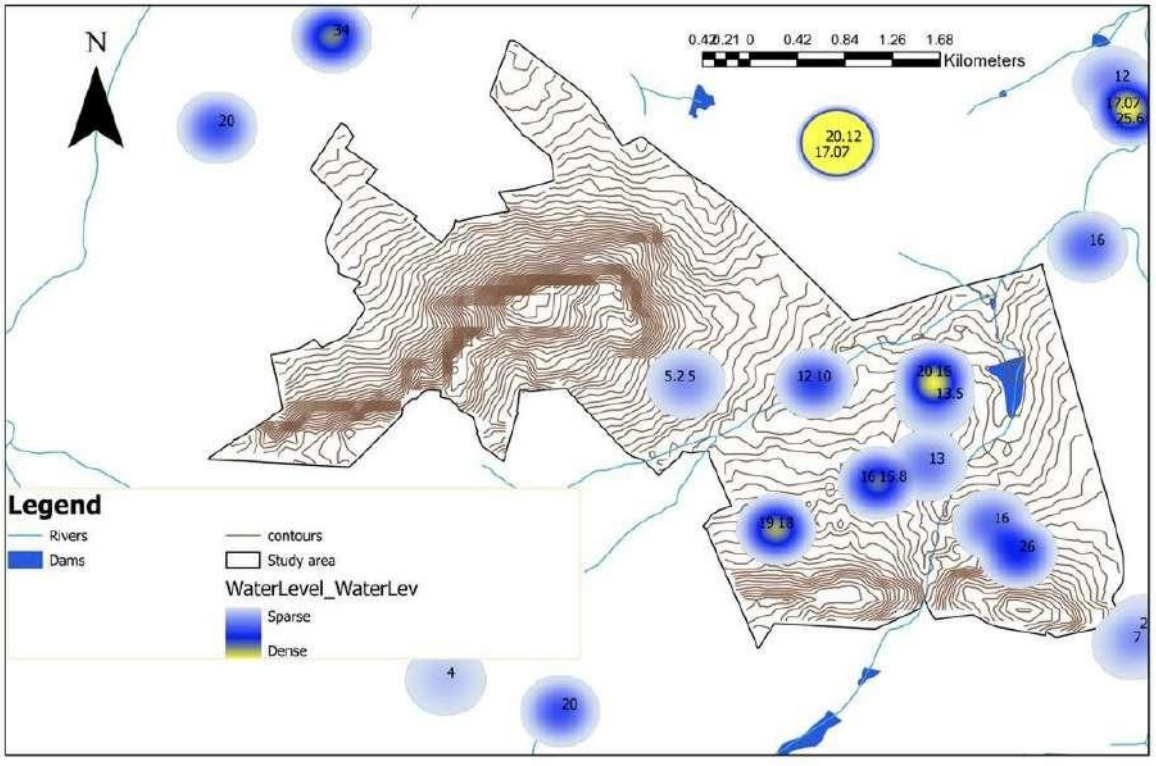

Figure 8: Groundwater levels with topographic contour lines, data from Council for Geoscience (CGS) and National Groundwater Archive (NGA) of the Department of Water and Sanitation

3.5 Topography

The area of study has areas of increased steepness as well as relatively flat regions. The densely spaced contour lines in the northwestern area of the study area represent a region of steep gradient. This area is therefore indicative of a hill whereby the geology present is resistant to erosion and weathering. This area is known to be the Northcliff Hill. The spacing of the contours is 5m which further emphasises the steepness of the area along with the digital elevation model (DEM) map with 30m resolution in Figure 10. The contour map in Figure 9 also illustrates the streams flowing within the valleys. Moving southeast of the study area, the slope decreases. In the south-southeastern part of the area of focus, two areas of densely spaced topographical contours which show a pinching out between the two dense regions indicate the presence of a steep slope or high relief area. This pinch out is a valley. This is seen in the area Melville which suggests that that area is the Melville Koppies.

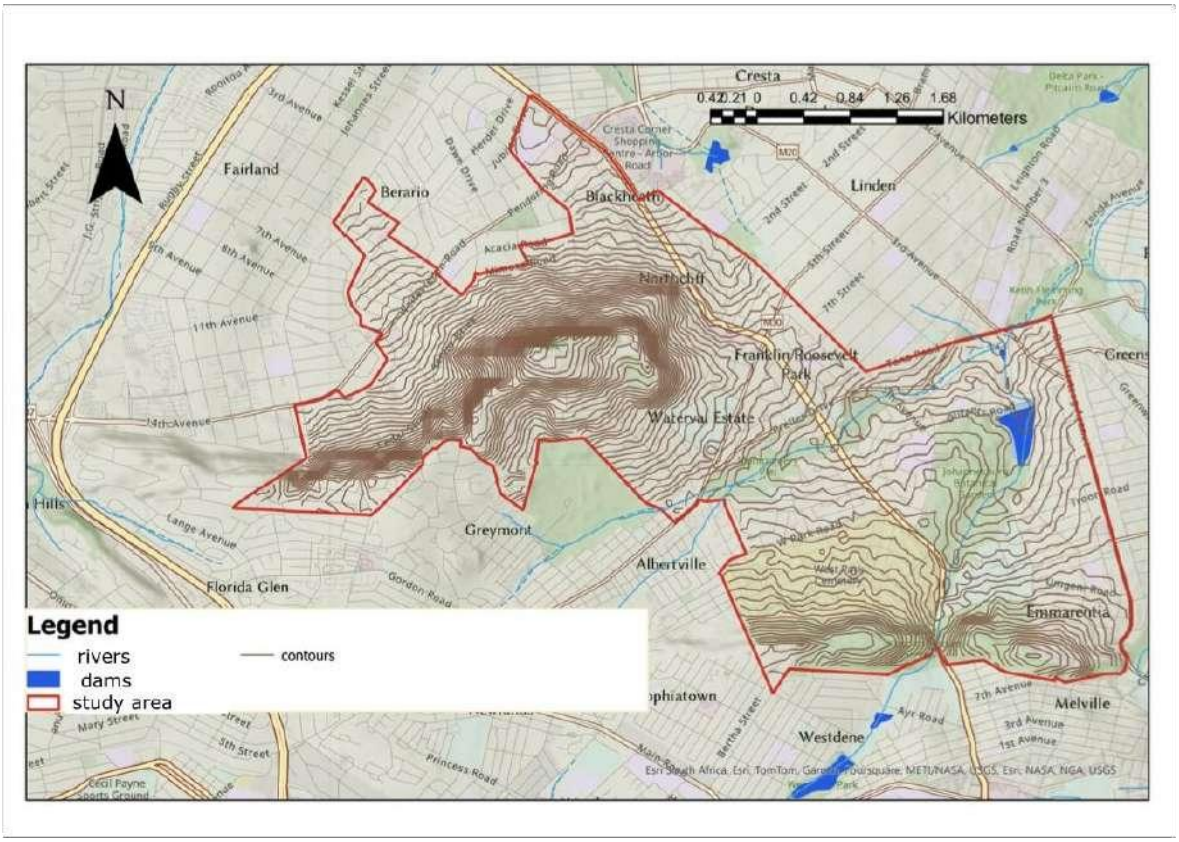

Figure 5: Topographic map of study area, data from Council for Geoscience (CGS)

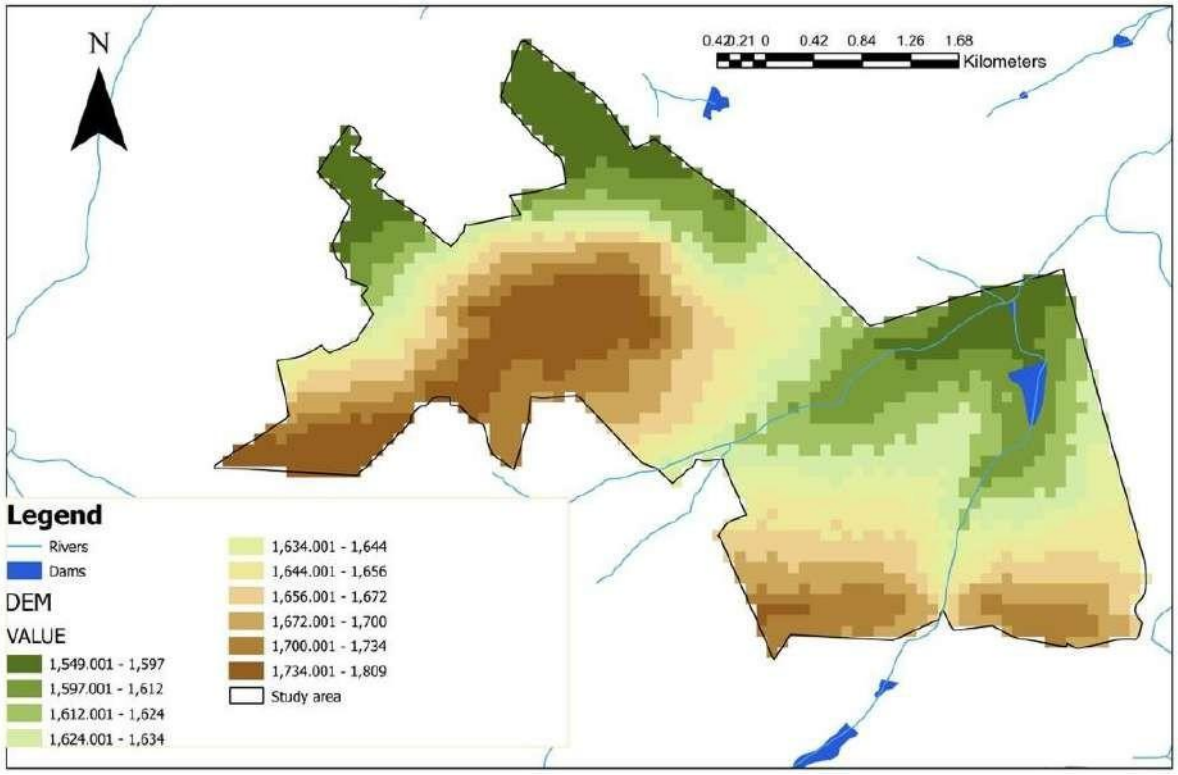

Figure 10: Digital Elevation Model (DEM) map of study area, data from USGS Earth Explora- U.S. Geological Survey, 2024

3.6 Land use and water supply

The city of Johannesburg is well-known for it being the economic hub of South Africa (Todes, 2012). Generally, mining activity and built-up urban areas make up Johannesburg. Johannesburg's main supply of water is surface water from the Vaal Dam. This dam receives water from the Katse Dam as a result of the water transfer scheme (Lesotho Highlands Transfer Scheme) which sources water from Lesotho to South Africa via transfer and delivery tunnels (Wendt, 2023; Sheridan, 2024). The accelerated population growth rate and delayed additional dam construction in Lesotho strains the water resources in Johannesburg resulting in increased intermittent water supply (IWS) (Sheridan, 2024). Johannesburg is renowned for its extensive industrialisation and widespread urbanisation, both of which demand enormous quantities of water. Groundwater is locally utilised in this region as an additional supply for industrial and residential purposes (Abiye *et al.*, 2011).

Municipal ward 88 of region B of the City of Johannesburg is mainly residential, vegetated with trees, surface water bodies, parks, and gardens. Region B has a population of just above 198 000 (Joburg.org.za, 2019). This region also hosts

industrial activity in the forms of office parks along with commercial activity (Jombo, 2021).

3.7 Soil

The greater Johannesburg region's soil is made up of Glenrosa and Mispah soil forms which are lithic (Jombo, 2021). These shallow soils generally have loam to silty clay textures (Assefa and Dinka, 2023) as they originate from shales. As a result, they have variable water holding capacity (Blackwell, 2016). Lithic leptosols (LPq), which have sandy loam- sandy loam clay textures, are usually found at shallow depths with outcropping rocks (Dijkshoorn, 2003; Sengani and Allopi, 2022). The LXh soil types (silty clay) have high clay content with loam textures (Sengani and Allopi, 2022). Peat soils (PTa) have high organic matter content which results in them having high water saturation as they are found under waterlogged areas (Gowthaman *et al.*, 2022). Glenrosa soils have an orthic A overlying a lithocutanic B horizon whereas the Mispah soils have an orthic A overlying hard rock. The Glenrosa soils are moderately sensitive to erosion whereas the Mispah soils are sensitive to erosion. The soils are prone to temporary wetness or artificial drainage (Blackwell, 2016). Soil influences how water infiltrates and/or percolates to an aquifer (Magombeyi and Matambo, 2023).

Chapter Four: Methodology

In this chapter, various techniques were employed to better understand the hydrogeological environment of the area of focus and to assist in achieving the objectives for this study. These methods were utilised to ultimately determine whether the area of focus would be suitable for potential subsurface storage (see

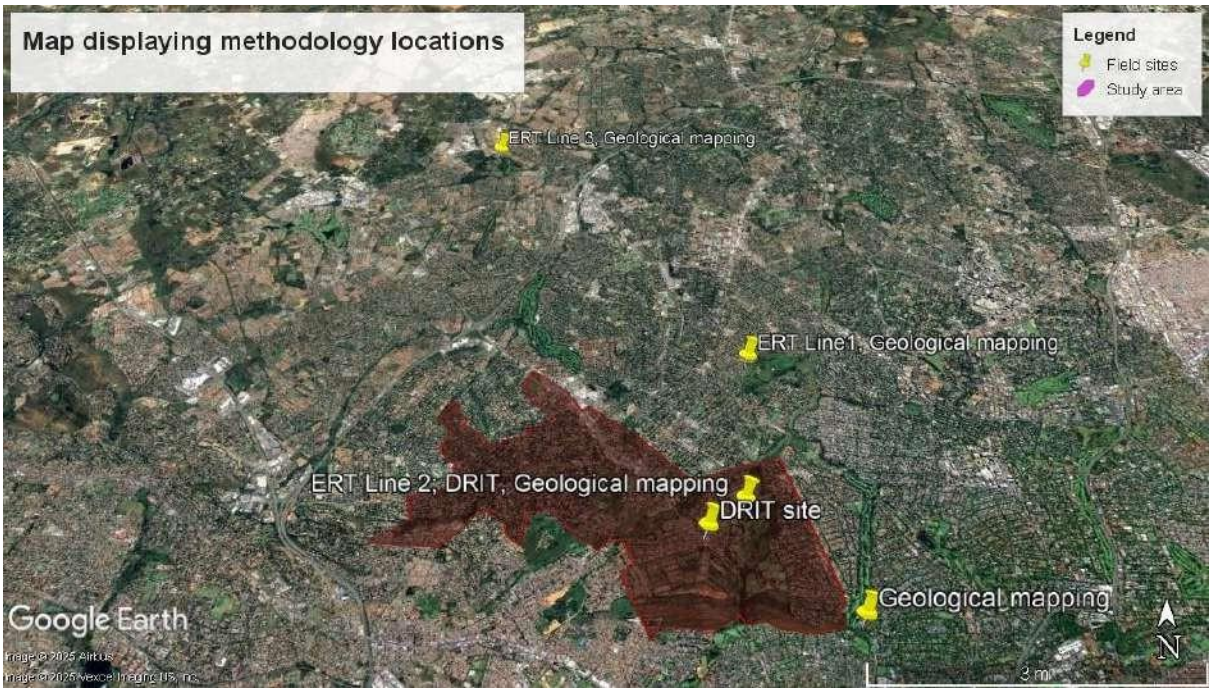

Figure 11).

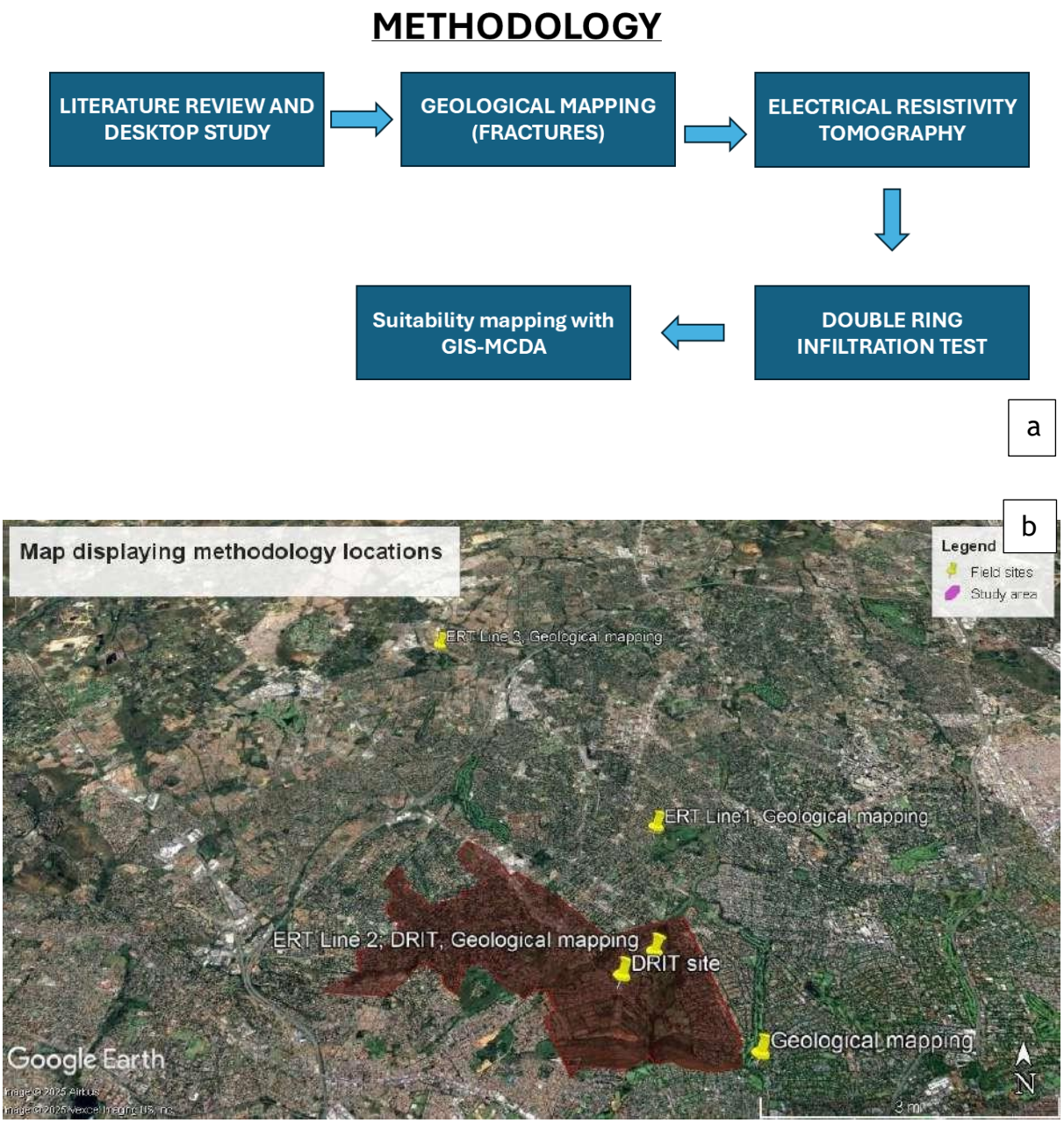

Figure 11(a): Methodology ffow process; (b) Locations where methodology was applied

4.1 Extensive literature review and desktop study

For a detailed understanding of the study site, it was of utmost importance to conduct preliminary studies prior to doing field work and assessment. This preliminary study was undertaken by reviewing pre-existing geological, hydrogeological and land cover maps of the area. The review further aided in the characterisation of the hydrogeological environment and the identification of both lineaments and fracture zones. Furthermore, an investigation was done whereby grey literature and pre-existing data of the area were reviewed to quantify the hydraulic properties of the

various rock materials, such as their hydraulic conductivity, permeability, and yield. The grouping of various lithologies based on their hydraulic properties into primary and secondary porous media was done to categorise the types of aquifers that were present within the area of focus.

4.2 Field work

Field investigations were conducted to verify the key findings from the pre-existing maps and literature that were reviewed. Field work included geological mapping, a hydraulic test and a geophysical technique.

4.2.1 Geological mapping

Mapping of the outcropping geology within the area of study was conducted whilst focusing on the joints and fractures exposed as seen in Figure 12. The general strike of the joints and fractures of the outcropping rocks were measured using a compass clinometer.



Figure 12: (a) Image of fractured quartzite outcrop (b) Measuring of fracture strike at stop 1 (c) Image of the shales exposed at stop 1 (d) Image of the dolerites exposed at stop 4. Courtesy of Dr K Masindi

4.2.2 Electrical resistivity tomography

The geophysical method of electrical resistivity was utilised to examine subsurface conditions and therefore characterise the aquifer (Binley *et al.*, 2015; George *et al.*, 2017). Information relating to fractures, faults and groundwater presence were revealed through this method by how the subsurface reacted to the presence of electrical current. This was done by placing the current electrodes and the potential electrodes in the ground and shooting current into the ground as seen in Figure 13. In total, 56 electrodes were utilised for the entire profile length, and each electrode was poured with water before any current was released. The electrodes are all connected to the resistivity meter. This method was performed at 3 different sites in Emmerentia. The sites were selected where there were open flat areas within the residential areas, as well as where there were outcropping rocks. The Wenner, Schlumberger and Dipole-Dipole arrays were used in a 110m profile length with a 2m spacing between each electrode. The method measures how much the ground resists electrical current flow and is dependent on the type of material present in the subsurface. This was done by placing the current electrodes and the potential electrodes in the ground. The data from this method were entered into the Res I Py software for de-spiking to form 2-D resistivity inverse pseudo-sections (https://gitlab.com/hkex/resipy#downloads).

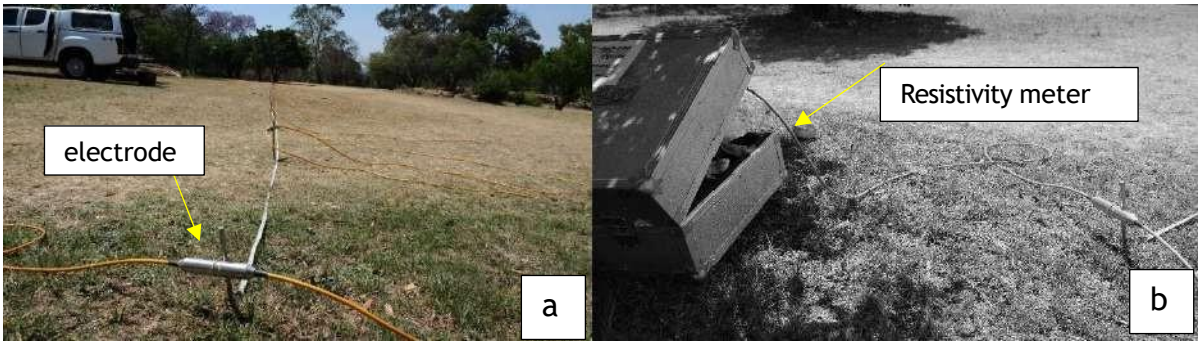

Figure 13: (a) Electrical resistivity in the field (Golden Harvest Park)- image of the 5c electrodes (b) image of the resistivity meter. Courtesy of Dr K Masindi

4.2.3 Double ring infiltration test

The double ring infiltration test was conducted in order to determine the rate at which water passes through the soil, giving the constant infiltration rate of the soil. The test was conducted with two rings (a small inner ring and a big outer ring) which were hammered into the ground as seen in Figure 14. A driving plate was used to hammer the rings into the ground. Water was then filled within the two rings by pouring onto a sponge to reduce soil layer disturbance, and the water level was monitored over time

in the smaller ring as the water drained into the soil. A measuring bridge and a floating measuring rod recorded the water level changes. As the water levels decreased over time, the change was recorded in consistent time intervals. The change in the water level was recorded from a reference point, which was the initial reading seen whilst the inner ring was filled to the top. As the floating measuring rod dropped whilst the water drained through the soil, the values recorded as seen on the rod increased. The data was recorded on excel and graphs created for interpretation. The sites selected for the infiltration test were as a result of open vegetated areas within the study area as seen in Figure 15. Due to the initial desktop analysis, not many sites were required as one soil texture, sandy clay-sandy loam clay, dominated throughout the various soil types present in the study area.

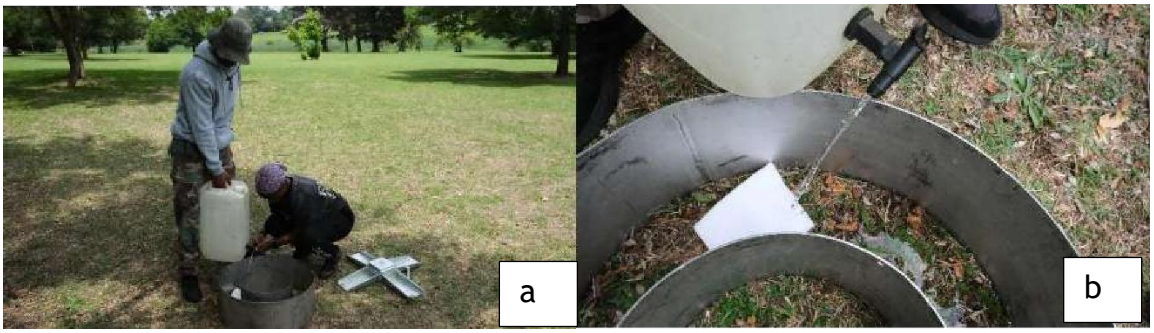

Figure 14: (a) Double ring infiltrometer test in the field (b) Image of the double ring infiltrometer. Courtesy of Dr K Masindi



Figure 15: Map showing DRIT sites

4.3 Suitability mapping with GIS-MCDA

The main objective of this study was to find the most suitable site for MAR practices therefore suitability mapping needed to be conducted. Multi Criteria Decision Analysis (MCDA), sometimes referred to as Multi Criteria Evaluation (MCE), is a collection of methods and approaches for organising geographical decision issues and for creating, assessing, and ranking alternative choices. A frequent application of MCDA is the integration of spatially referenced data with a computer-based geographic information system (GIS). GIS-MCDA is a procedure that, based on the judgment of the decision-maker, combines and transforms geographical data to produce information for decision-making (Dupont *et al.*, 2018; Sallwey *et al.*, 2019).

Various hydrogeological parameters (criterion) and surface properties needed to be considered in this process but for this study lithology, slope, distance to source water, groundwater level, soil texture and land use were of focus. This is as a result of data availability. Regarding the lithology, hard fractured rocks were better suited for injection-based MAR whereas highly porous, soft rock were better suited for infiltration-based MAR. These criteria were all analysed in ArcGis Pro through the use of spatial analyst geoprocessing tools such as the ‘reclassify’ and ‘weighted overlay’ features for ranking and the creation of suitability maps. The ‘reclassify’ tool assisted with the ranking of the criterion in raster format whereas the combination of the ranked criteria was done with the ‘weighted overlay’ tool. A sensitivity analysis uses the same weighted overlay approach by assigning different weights to different criteria to determine which weights are of more significance (Sallwey, *et al.*, 2019; Magombeyi and Matambo, 2023). The analysis identifies which criteria require further accurate and precise information (Assefa and Dinka, 2023).

To address spatial issues correctly, such as identifying appropriate locations for MAR implementation, GIS-MCDA approaches were required. These techniques consisted of multiple steps as illustrated in Figure 16. Due to the complexity of every site, a suitability map is subjective based on the availability of data and context of the study area which results in no uniform technique for MAR suitability mapping. Transparency in displaying the steps in the methodology used is vital to establish some reliability to the suitability map (Dupont *et al.*, 2018).

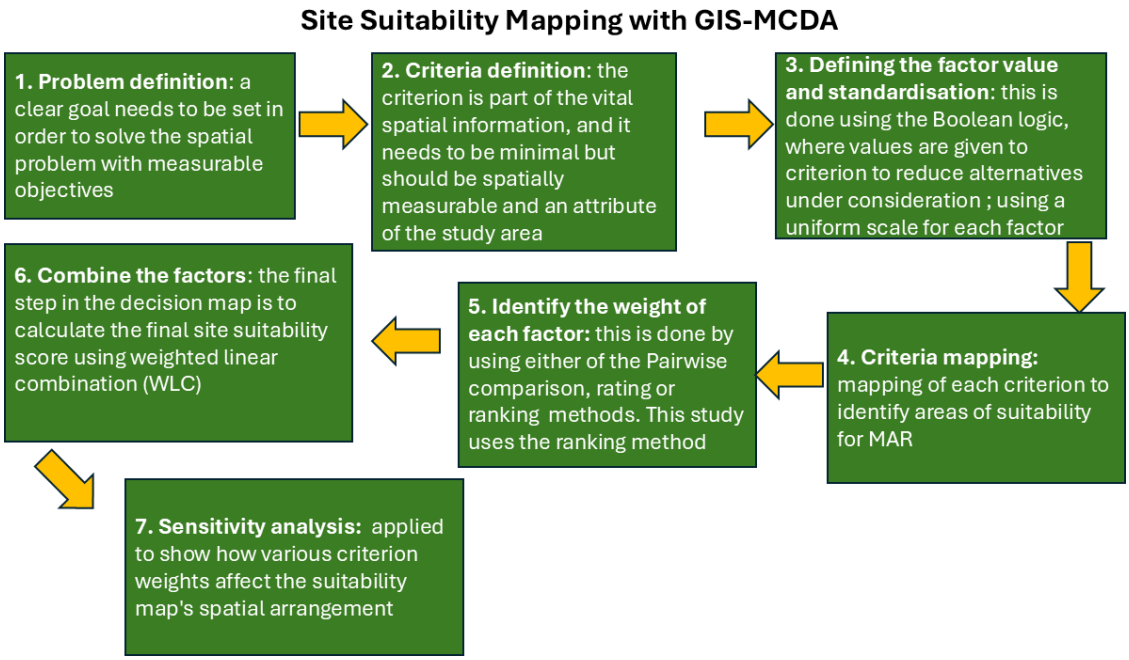

Figure 1c: GIS-MCDA Steps (Dupont et al., 2018; Sallwey et al., 201S; Zhang et al., 201S; Hani et al., 2023)

Chapter Five: Results and discussion

5.1 Literature review and desktop study key findings

5.1.1 Geological and hydrogeological setting

The various rock types and geological structures were analysed during the desktop study (see Figure 17). No large-scale structural features such as lineaments were identified on the terrain imagery and geological reports in the study site. However, the granodiorite, gneiss and migmatite, dunite, harzburgites, and serpentinite (basement rock) lithologies on a larger scale area, which also lie within the study area displayed a lineament traversing through them further north of the study area. This zone of weakness may have significantly enhanced the hydraulic conductivities, permeabilities and specific yields of the material. The enhancement may have created potential groundwater occurrence zones (Netsianda and Abiye, 2023). Due to this zone of weakness, the permeability values for the basement rocks may be closer to $10^{-7}cm^2$ than to the $10^{-13}cm^2$ and hydraulic conductivity values closer to $10^{-2}cm/sec$ than $10^{-9}cm/sec$, resulting in them potentially having fracture and matrix porosities (Woessner and Poeter, 2020). Fractures were observed on the granite outcrops at stop 3 in section 5.2. The granites at the various locations displayed variable extents of weathering. This suggests that the permeability of these rocks was enhanced as a

result of the secondary porosity caused by weathering. This may correspond to the remote sensing findings of Netsianda and Abiye (2023), which provided results that stated that the W-E and N-S oriented fractures in the rocks found in Johannesburg corresponded to potential groundwater occurrence zones (Netsianda and Abiye, 2023). Leketa and Abiye (2021) identified that the fracturing and weathering occurred on a regional scale and formed the shallow intergranular aquifer (Leketa and Abiye, 2021). The fractures and weathering together may contribute to the matrix porosity and fracture porosity which may accommodate water within the void spaces. The shales within the study area were not fractured resulting in the hydraulic conductivity and permeability values for them being very low (closer to $10^{-11}cm/sec$ and $10^{-11}cm/sec$, respectively) (Woessner and Poeter, 2020). These two classes of rocks had low specific yields, ranging between 0.5-5% (Woessner and Poeter, 2020), which meant that very little void space was present due to tightly spaced crystals and sediments opposing the flow and storage of water. However, during weathering process the water holding capacity of the rocks increases (Weight, 2008). The final stage of weathering produces clays which have high water holding capacities due to their high porosity but low permeabilities (Woessner and Poeter, 2020). The quartzites displayed very strong weathering and fracturing (see section 5.2). This suggested that a secondary porosity, hence enhanced permeability, was present (Singhal and Gupta, 1999; Netsianda and Abiye, 2017). Due to the outcropping quartzites in the study area displaying strong weathering and fracturing, their hydraulic conductivity and permeability values may lie closer to $10^{-7}cm^2$ (hydraulic conductivity) and 10^{-2}cm/sec (permeability). This may accommodate for the storage and flow of water (Woessner and Poeter, 2020). Therefore, these quartzites may potentially act as a reservoir for groundwater. Summer rainfall is experienced in the study area (see Figure 6) which may contribute to groundwater recharge on a small scale due to focused recharge being most prominent in the area as a result of the crystalline rock predominance and deep water levels (Leketa *et al.*, 2019; Leketa and Abiye, 2021).

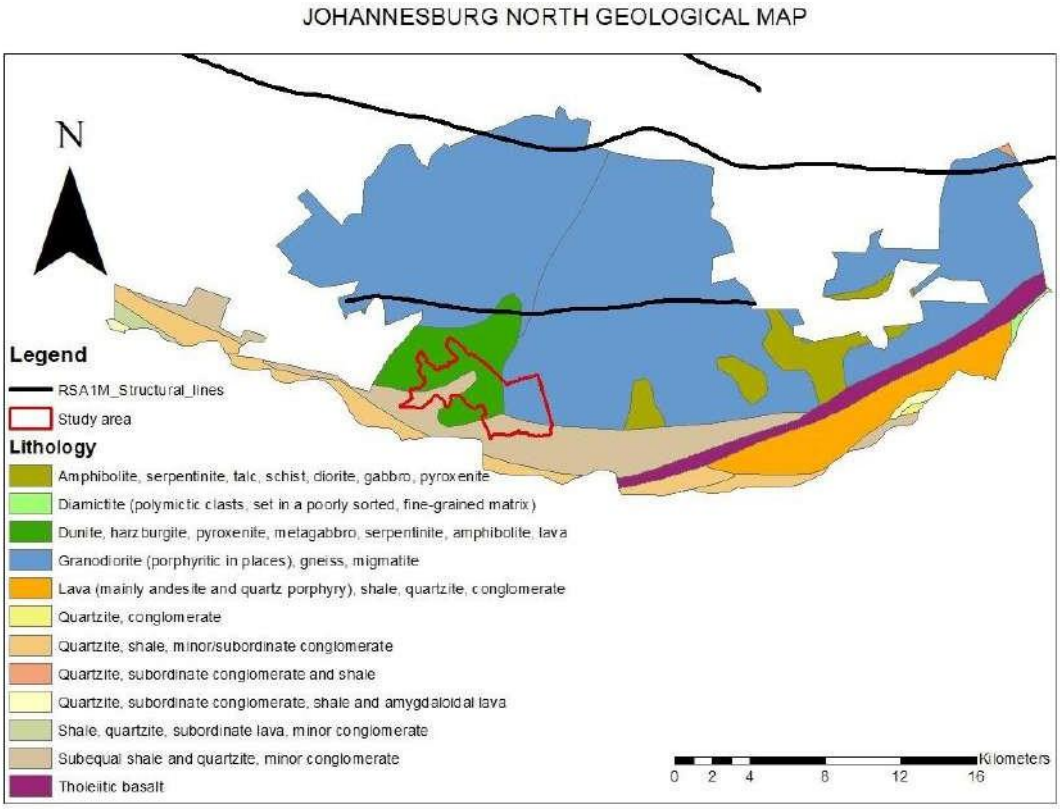

Figure 17: Map of Johannesburg North displaying the geology and structural lines, data from Council for Geoscience (CGS)

5.1.2 Topography

The digital elevation model (DEM) data (see Figure 10) allowed for the elevation and slope of the study area to be analysed. There are two regions with significant zones of high elevation and thus steepness. These are the Northcliff Hill and the Melville Koppies. These areas may have been suitable source areas for groundwater recharge whereas more gentle surfaces at lower elevations were good sites for groundwater discharge (Woessner and Poeter, 2020). The gentle surfaces may also allow infiltration which indirectly recharges the aquifer but due to the presence of clay-rich soils, the water may be retained (Galazoulas *et al.*, 2015; Gomo *et al.*, 2024). Aquifers tend to discharge water at lower elevations and gentler slopes where streams and rivers are located (Woessner and Poeter, 2020). Due to aquifers generally being located at shorter distance from sites with a gentle slope and low elevation, this suggests that artificial and managed aquifer recharge (MAR) was better suited at these sites.

5.1.3 Soil

The dominant soil type identified in the study area was lithic, with sandy loam-sandy clay loam textures, which was derived from shales meaning that the presence of clays is likely when weathered (Weight, 2000). These textures were present in all three soil types in the area, namely LXh, which are soils with loam and high clay content; PTa, which are peat with high organic content; and LPq, which are lithic leptosols found at shallow depths with rock outcrops. The soils are attributed to being located at shallow depths having variable water holding capacities. These soils tend to be underlain by hard resistant rock at shallow depths (Blackwell, 2016).

5.2 Geological mapping

Table 1: Orientation of rocks and field geological assessments

	Latitude	Longitude	Rock Type	Orientation
Stop 1	26.17244ºS	28.01598ºE	Quartzite	262º, 270º (W-E)
			Shale (slightly magnetic)	270º (W-E)
Stop 2	26.159772ºS	27.99424ºE	Clayey soil (fine grained) = weathered shale(red/maroon in colour)	-
Stop 3	26.16195ºS	28.00173ºE	Sandy soil (coarser grained) = weathered shale (brown)	-
			Clays (orange streak)	-
			Serpentinite (greenish colour- soapy)	-
			Quartzites	W-E
			Granites	-
Stop 4	26.14960ºS	27.99687ºE	Dolerite	-

The stops were selected on the basis that the areas were in an open public space, such as parks and other recreational areas, or areas which were easily accessible and near surface water bodies such as dams and streams. At the first stop as displayed in Table 1, the fractured quartzites created blocky structures which were caused by the multiple orientations of the fractures on the surface of the outcrops. The major fractures showed a W-E orientation with the minor fractures showing a N-S orientation which Netsianda and Abiye (2023) found in their study. At this stop, there was an inferred contact with shales that were iron-rich which showed a W-E trend as well. The shales had defined layering that broke off easily along the bedding plane with barely any fractures. This indicated the shale's brittle response to stress and strain (Liu and

Qu, 2023). The change in lithology indicates the change in the rock type porosity and permeability properties. Generally, shales are fine-grained and quartzites are crystalline but as a result of the deformation observed on the outcropping quartzites, enhanced permeability is expected due to the fracturing introducing a secondary porosity to the outcrop. This enhanced permeability is observed is at the Albert's Farm Spring, where the quartzite fractures are regional. These highly fractured quartzites overlie low permeability shales (Leketa and Abiye, 2021). The Albert's Farm is about 9km away from the stop. At the second stop, the soils that were observed were reddish/maroon in colour. The soils were hard when dry and clayey when wet which suggested that the soils were lithic (Blackwell, 2016). At the third stop, a coarser soil was identified which was brown in colour. The soil had a sandy clayey texture due to the increased size of grains. The soil's thickness at this stop was observed to be much thicker than at stop 2. More clay material/sediments were encountered at this stop displaying a yellow-orangey streak which further confirms the lithic origin of the soil. Outcrops of a greenish coloured serpentinite were identified, and a soapy texture was felt upon field investigation. This metamorphic rock showed slight weathering which may have contributed to its secondary porosity (Singhal and Gupta, 1999; Netsianda and Abiye, 2023). Highly weathered granites and quartzites formed a miniature watershed at stop 3. The weathering contributed to the secondary porosity of the rocks and may have been able to potentially accommodate groundwater (Singhal and Gupta, 1999; Netsianda and Abiye, 2017; Leketa and Abiye, 2021). At the fourth stop, dolerites were identified with large crystals and a stream flowed above them.

5.3 Electrical resistivity tomography

Electrical resistivity surveys were conducted at the Botanical Gardens, Delta Park and Golden Harvest Park. The results from Delta Park and Golden Harvest Park were not included in this section as they lie outside of the study domain.

5.3.1 Botanical Gardens

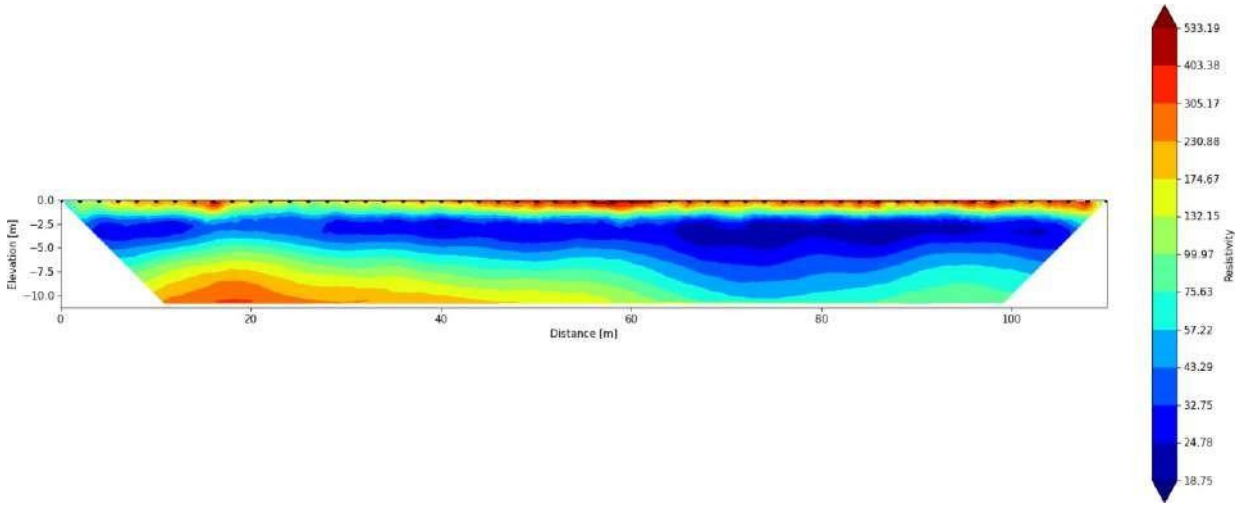

Figure 18:Wenner array pseudosection for the Botanical Gardens line

A resistivity section along the 110m line that was analysed at the Botanical Gardens based in Emmerentia, Randburg using the Wenner array is illustrated in Figure 18. Slight variability in the subsurface layering is seen in the profile. Between the elevations of 0 and -1m, high resistivity is seen in the colours ranging from yellow, to orange and eventually red right at the top. From approximately 174.67 Ωm (yellow) to 403.38 Ωm (red), the resistivity values rise. This might indicate that there is dry or compacted material near the surface, like sandy soil. On the other hand, it could suggest low moisture content or little clay, both of which are characteristics of materials with high resistance. The orange and red colours represent high to very high resistivity. Low to moderate resistivity levels (18.75 Ωm to 75.63 Ωm) are indicated by the predominance of dark and lighter blue in the 2.5–8 m depth range along the 60-110m lateral distance. This could possibly be considered as a layer of coarser grained water bearing substrate such as weathered material or the thin film in the beginning of the profile may represent fine sediments inclusive of clays and silts which retard water flowing to shallow aquifers (Galazoulas *et al.*, 2015; Onyebueke, 2020; Dildar *et al.*, 2023). The contrast between lighter and darker blue indicates some variability, which could be brought on by different subsurface layer compositions or moisture contents in this layer. In contrast to the low-resistivity zone, the section's first 60m laterally shows a shift to primarily high resistivity at a depth of 7.5m, indicating a distinct underlying layer. This might point to the existence of a strata with increased compaction or resistance, including a dry region or fresh bedrock. A major

geological border or transition, such as the interface between a saturated layer and a resistant basement, may be suggested by the stark difference (Onyebueke, 2020; Gomo *et al.*, 2024; Dildar *et al.*, 2023).

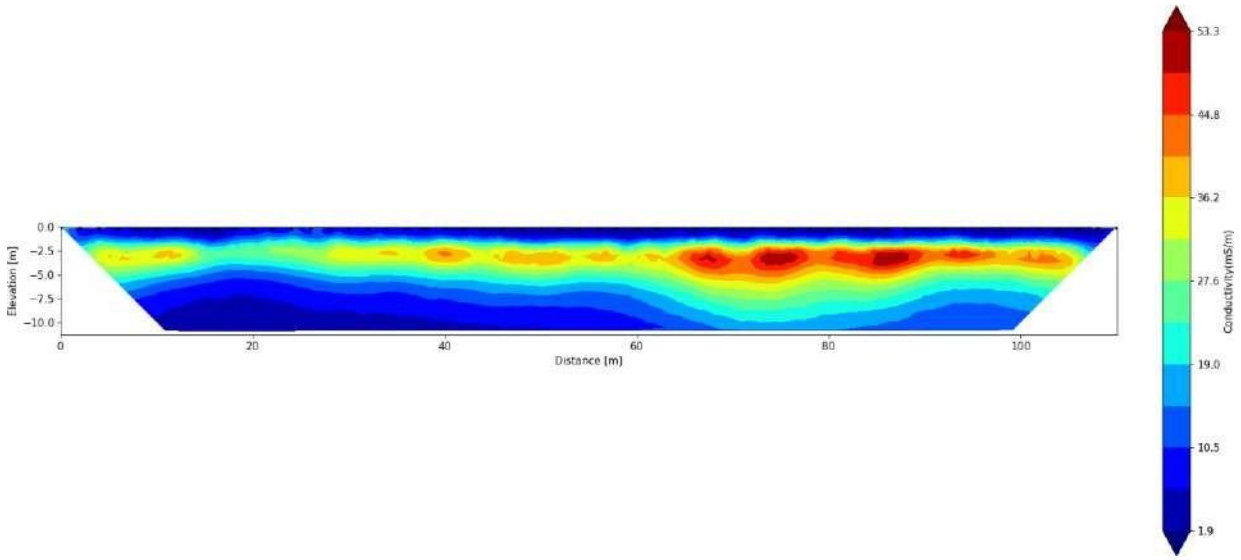

Figure 15: Wenner Conductivity map for the Botanical Gardens line

In Figure 19, the zones of electrical conductivity for the Botanical Gardens are displayed through the use of Wenner array. Electrical conductivity measurements ranging from 44.8 to 53.3 mS/m show areas with elevated conductivity, and the observation of red and orange zones between 60-110 m laterally at depths between 2.5m and 5 m suggests that the underlying material in this region is potentially characterized by: high moisture content or clay enriched material. The presence of water, especially dissolved ions, makes water-logged soil or sediments extremely conductive. Clay minerals' high electrical conductivity is a result of their structural capacity to retain ions and water (George *et al.*, 2017; Gomo *et al.*, 2024). A layer of moist clay or silt, either a component of semi-confined or water table aquifer or an area impacted by water seepage from surface water sources, could be represented by that region given the depth range.

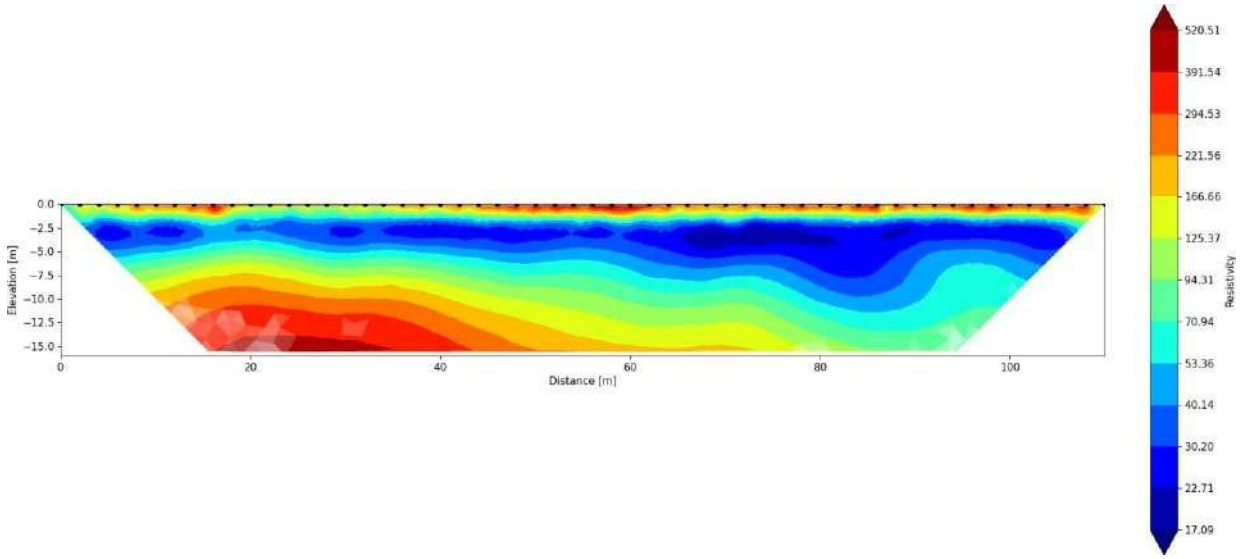

Figure 20: Schlumberger pseudosection for the Botanical Gardens line

The pseudosection in Figure 20 displays a resistivity section along the 110m line that was analysed at the Botanical Gardens based in Emmerentia, Randburg using the Schlumberger array. Slight variability in the subsurface layering is seen in the profile. Between the elevations of 0 and -1m, high resistivity is seen in the colours ranging from yellow, to orange and eventually red right at the top. The yellow represents about 174.67 Ωm of resistivity (moderate), the orange represents about 230.88 Ωm and the red represents about 403.38 Ωm. The presence of resistant materials in the first meter below surface, such as low moisture soils which are inclusive of compacted strata, is suggested by the elevated resistivity values in this layer. Dark and lighter blue hues predominate in the zone 2.5m to 10m below surface in the last 50m of the line, which correlates to low resistivity values (18.75 Ωm to 75.63 Ωm), which are suggestive of either clay-rich or saturated soils (Gomo *et al.*, 2024). This may be a water-bearing unit and therefore potentially an aquifer. Diversity in the subsurface layer composition or increased moisture content is suggested by the difference between light blue (low resistivity) and dark blue (extremely low resistivity). This might be an indication of underlying variation, including variations in the porosity of the layer. Both dark and light blue areas persist at depths between 2.5 and 7.5 meters below the surface throughout the first 60 meters of the line, which is suggestive of low resistance. This could be an area with mixed sediments, such as silts and clays that alternate and have different moisture contents, or it could be a region with isolated water pockets where the spread of groundwater is not consistent. A move to more resistive material,

such as deep bedrock or compacted layers, is suggested by the shift to primarily moderate to high resistivity values seen deeper than 7.5 meters below the surface. This could be the bottom of a conductive zone. The variation in resistivity from low to high may suggest varying lithology. This is links to the lithic soils which are characterised by shallow hard rock presence (Blackwell, 2016).

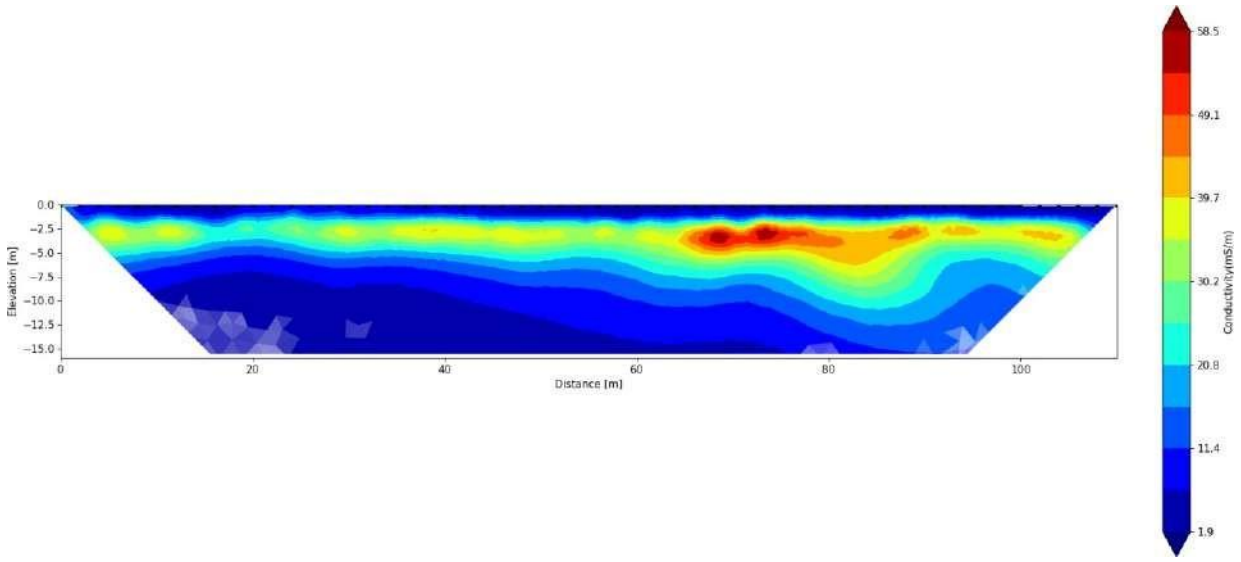

Figure 21: Schlumberger Conductivity map for the Botanical Gardens line

In Figure 21, the zones of electrical conductivity for the Botanical Gardens are displayed through the use of the Schlumberger array. In the first 60 meters of the line, at a depth of 2.5 to 5 meters below the surface, there are red and orange regions with high conductivity values (44.8 to 53.3 mS/m), which indicates subsurface conditions with increased electrical conductivity. The presence of moisture alone or the saturation of soils or sediments could be the cause of this (Gomo *et al.*, 2024). Increased cation exchange capacity and water retention in clay-rich strata may also result in higher conductivity (Galazoulas *et al.*, 2015; George *et al.*, 2017). The highest zone of conductivity is seen after 60m along the profile length which could be a sign of isolated conditions such a clay deposit, derived from the lithic soil (Blackwell, 2016), or a perched groundwater reservoir. Low electrical conductivity over the rest of the subsurface indicates the predominance of resistive materials, particularly unsaturated materials including fresh bedrock or compacted soils. This further reiterates the characteristic associated with sandy clay loam soils which are lithic in nature (Blackwell, 2016; Dupont *et al.*, 2018)

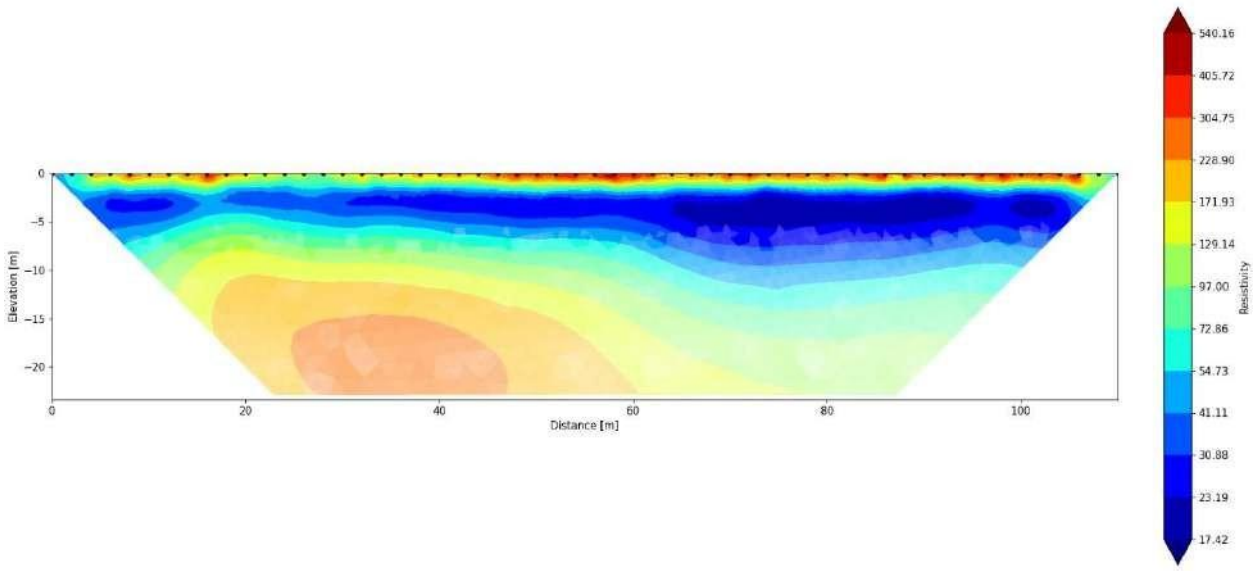

Figure 22: Dipole-Dipole pseudosection for the Botanical Gardens line

The pseudosection in Figure 22 displays a resistivity section along the 110m line that was analysed using the Dipole- Dipole array at the Botanical Gardens based in Emmerentia, Randburg. Slight variability in the subsurface layering is seen in the profile. Colours ranging from yellow (174.67 Ωm) to red (403.38 Ωm) indicate high resistivity values in the first meter below the surface, indicating an absence of moisture in soils or limited water content. The near-surface materials are represented by this shallow zone and are impacted by vegetation, consolidation, and surface runoff. The yellow represents about 174.67 Ωm of resistivity (moderate), the orange represents about 230.88 Ωm and the red represents about 403.38 Ωm. Dark blue and lighter blue hues predominate in the last 50m along the profile between 1m and 8m depth, with resistivity values ranging from 18.75 Ωm (dark blue) to 75.63 Ωm (light blue). These low values indicate either saturated strata with high porosity or permeability or the presence of clay-rich sediments, which have the ability to hold water (Gomo *et al.*, 2024). The difference between light and dark blue could indicate variations in water content, with lighter blue showing less saturated areas and darker blue showing more saturated areas. This area most likely consists of a clay-rich deposit, associated to the soil texture, or a conductive zone of water-bearing sediments, which could be an aquifer. Low resistivity, which suggests an amalgamation of saturated clays and silts or a localisation of moisture where water distribution is unequal, is shown by the persistence of dark and light blue zones in the first 60m down the profile line at a depth of 5m below the surface. A noticeable transition to moderate to high resistivity readings

occurs below 5m, indicating the change to dry or resistive materials like weathered bedrock or compacted layers.

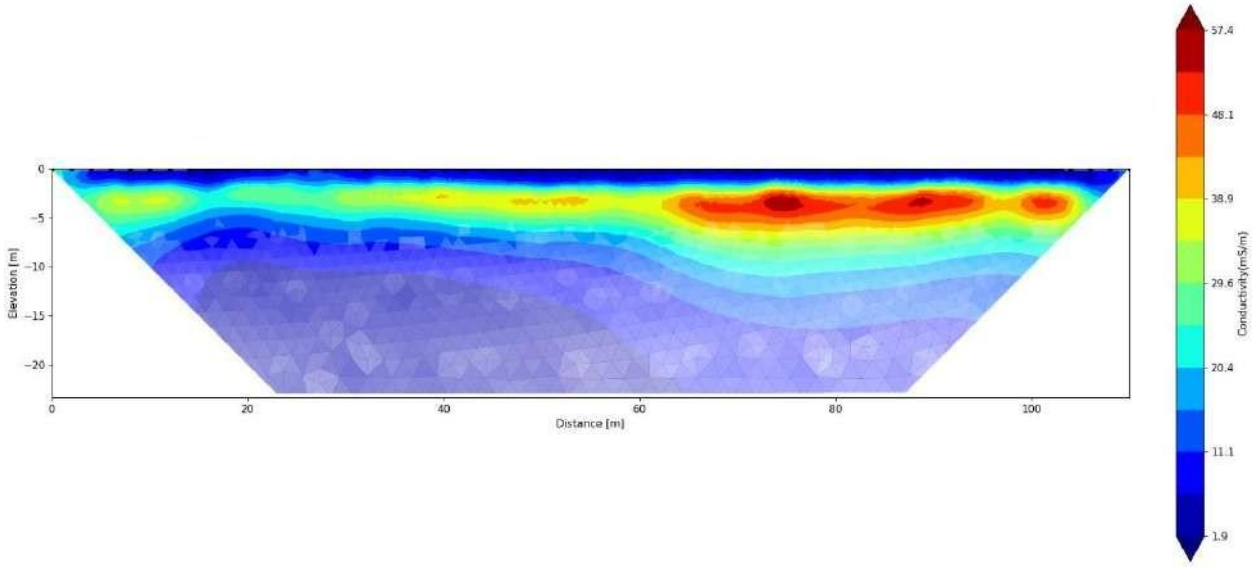

Figure 23: Dipole-Dipole Conductivity map for the Botanical Gardens line

In Figure 23, the zones of electrical conductivity using the Dipole-Dipole array for the Botanical Gardens are displayed. At depths ranging from 2.5m to 5m along the first 60m of the profile, subsurface regions with increased electrical conductivity are highlighted by the presence of red and orange zones with conductivity values between 44.8 and 53.3 mS/m. This may be due to the presence of saturated material, especially if the water has dissolved salts or ions or due to the presence of clay-rich material, which hold moisture and ions and thus boost electrical conductivity quite dramatically (Galazoulas *et al.*, 2015; George *et al.*, 2017; Gomo *et al.*, 2024). Low electrical conductivity is found in most of the subsurface, suggesting that resistive materials predominate. Due to the vary high electrical conductivities displayed in the last 50m of the profile length in all three arrays, it is likely that a shallow aquifer is present within the first 5m below the surface at the Botanical Gardens. This may be the shallow intergranular aquifer discussed by Leketa and Abiye (2021).

5.4 Double ring infiltrometer test

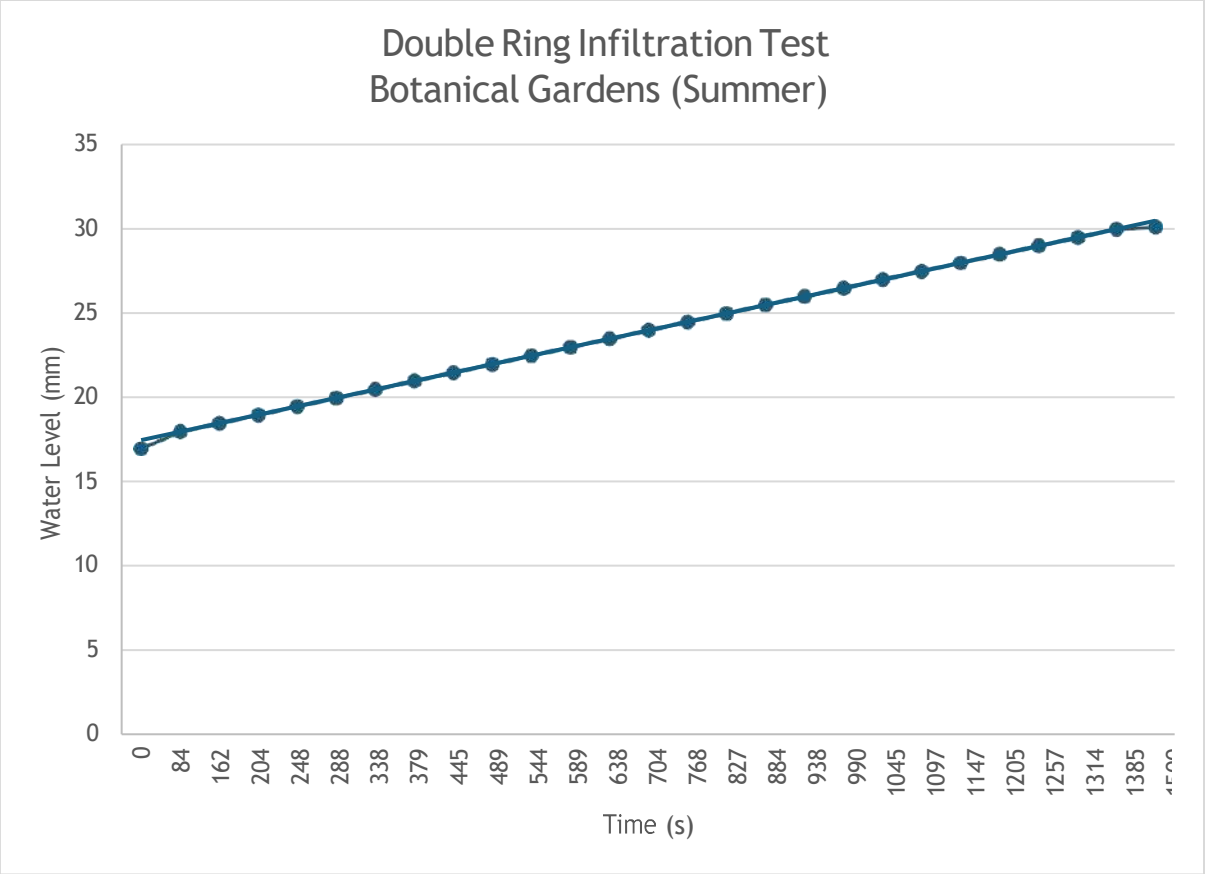

Figure 24: Infiltration vs time graph displaying the results for the DRIT performed at the Botanical Gardens in Emmarentia, Randburg in the summer season

The initial water level seen on the floating measuring rod was 17mm as illustrated in Figure 24. As time progressed, the water level within the inner ring decreased, resulting in the floating rod's values increasing as the rod itself decreased along with the water level. This explains why the graph displays a linear increase due to it being based on the rod's increasing values which are dependent on the water levels. At 1385 seconds (23.08 minutes), the water level recorded was 30mm. This means that from the initial time, the water decreased by 13mm. At 1500 seconds (25 minutes), the water level recorded was 30.1mm. This is a 0.1mm decrease from the 23-minute reading. At this point, the change in water level stabilised which may mean that the infiltration capacity of the soil had been reached (Mohuba, 2020). During the rainy season, infiltration rates decrease with time until constant infiltration is reached (Leketa and Abiye, 2021). The infiltration capacity here was found to be 0.524 mm/min. This is expected due to the soil texture in the area being clay-rich (sandy clay loam) (Netsianda and Abiye, 2023). The expected constant infiltration rates are meant to be relatively low to moderate due

to the presence of clays (Dupont *et al.*, 2018; Leketa and Abiye, 2021). The presence of moisture in the soil surface due to the rain season suggests that increased rainfall intensity would have promoted runoff rather than infiltration (Leketa and Abiye, 2021).

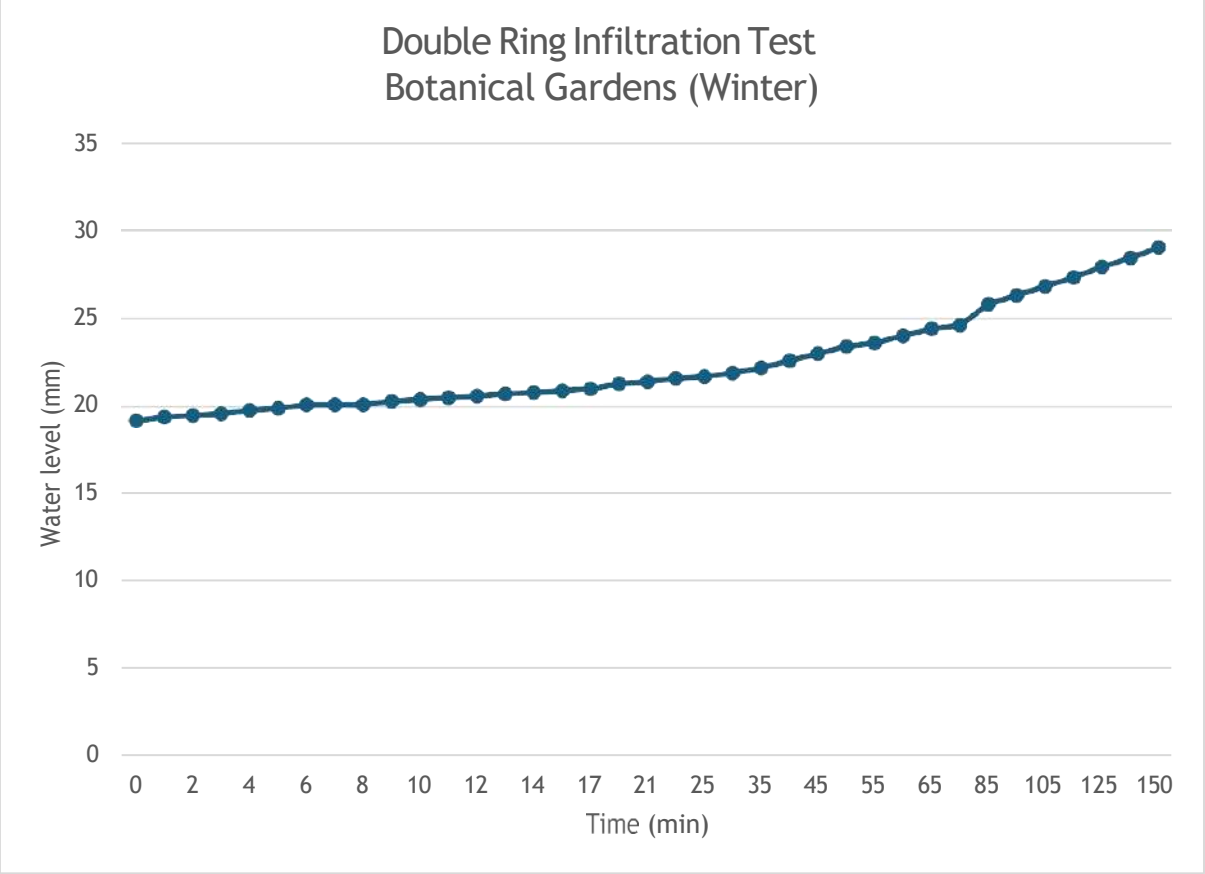

Figure 25: Infiltration vs time graph displaying the DRIT performed at the Botanical Gardens in Emmarentia, Randburg in the winter season

The initial water level recorded was 19.2mm as shown in Figure 25. The decreasing water level within the inner ring resulted in the readings on the rod increasing which accounts for the linear increase in Figure 25. The water took a slightly longer time to reach infiltration capacity during the winter season. This was as a result of the soil being dry due to the lack of rain/moisture compared to the summer season (see Figure 24) which allowed for more infiltration to occur. In the summer season, the soil was saturated due to the presence of rainfall and the clays in the soil retaining the moisture. This resulted in the soil reaching infiltration capacity much quicker than the dry winter season test (Galazoulas *et al.*, 2015; George *et al.*, 2017). The estimated constant infiltration capacity of the soil in the round was found to be 0.07 mm/min. This highlighted that the soil took a longer time to reach infiltration capacity in winter.

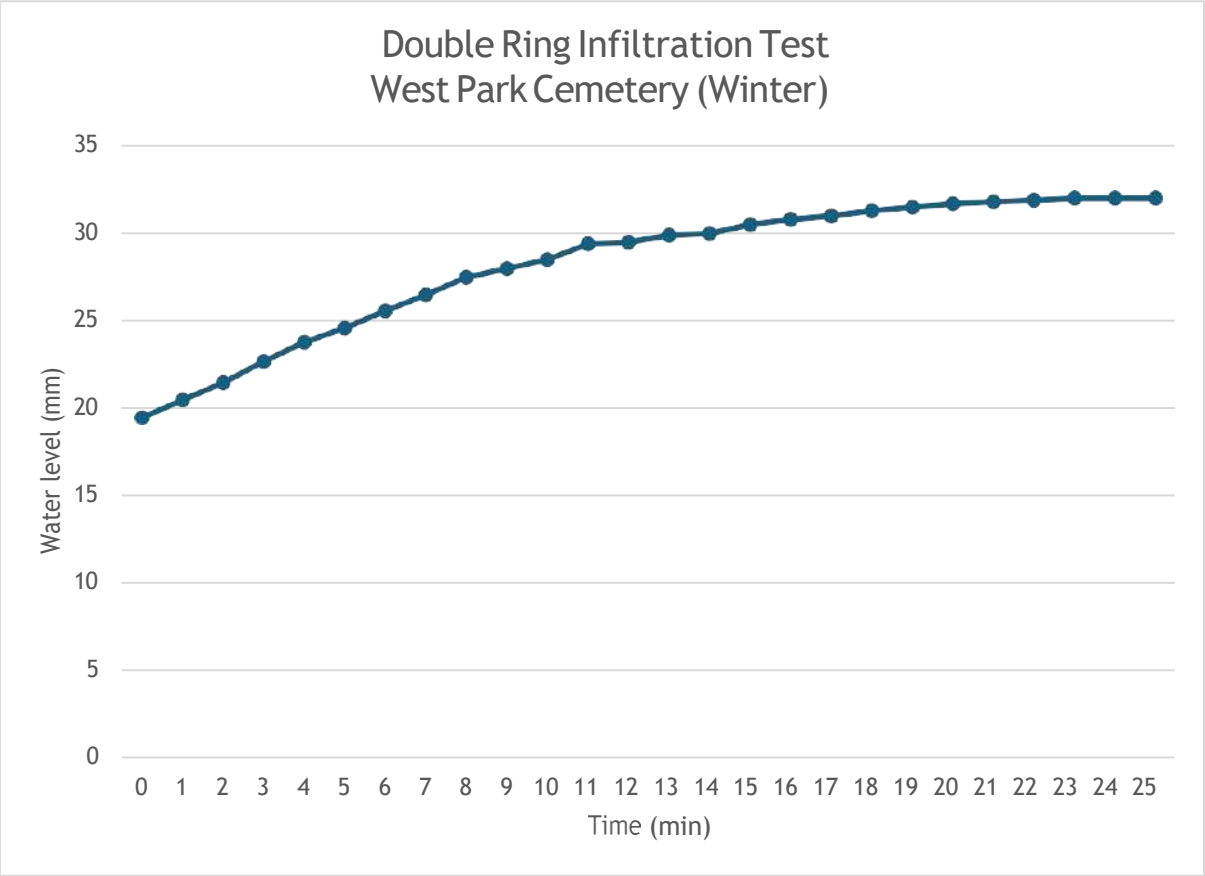

Figure 2c: Infiltration vs time graph displaying the DRIT performed opposite West Park Cemetery in Emmarentia, Randburg in the winter season

The initial water level seen on the floating measuring rod was 19.5mm as illustrated in Figure 26. As time progressed, the water level within the inner ring decreased, resulting in the floating rod's values increasing. This explains why the graph displays a linear increase due to it being based on the rod's increasing values which are dependent on the water levels. The water drained through the soil at a fast rate due to the dryness of the soil. At 23 minutes into the test, the soil infiltration seemed to stabilise where the water level remained at 32mm for the last 3 minutes of the test suggesting that infiltration capacity had been reached (Mohuba, 2020). The infiltration capacity of the soil at this site was similar to the summer reading of the Botanical Gardens test (0.5 mm/min).

5.5 Suitability mapping with GIS-MCDA

5.5.1 Problem definition

Due to the issue of constrained surface water resources in Johannesburg, the implementation of injection MAR methods, namely the aquifer storage and recovery

(ASR) method, was proposed to assist in the water availability issue. The main supply of surface water in Johannesburg is from the Vaal River which is part of an inter-basin transfer scheme with the Lesotho Highlands. The increased intermittent water supply (IWS) in Johannesburg raised concern with regards to the current water demand and supply (Wendt, 2023; Sheridan, 2024). The purpose of MAR in this context was to provide alternate water supply for domestic purposed in the region.

The most ideal site for injection-based MAR is generally located close to the source water, on a gentle slope and should be underlain by a deeper aquifer which means that underlying geology and hydrogeology are more significant than the surface characteristics (Sallwey *et al.*, 2019).

5.5.2 Criteria definition

For MAR suitability mapping, various factors/criterion needed to be considered based on data availability and the objective of the study. For the purpose of this study: slope; lithology; distance to source water; soil; groundwater level; and land use/cover were being considered as illustrated in table 2. These intrinsic factors influence groundwater recharge making them most significant.

1. **Slope as a criterion**: Slopes of 0 to 5% are appropriate for creating recharge basins or percolation sites because steeper slopes result in increased construction costs, runoff, soil erosion and difficulty to access the aquifer (Hani *et al.*, 2023; Magombeyi and Matambo, 2023). The slope data was derived from the digital elevation models (DEM), Shuttle Radar Topography Mission (SRTM) 1 Arc-second Void Filled, from USGS Earth Explorer (https://earthexplorer.usgs.gov/). The slope data which was then translated to a slope map and a slope criterion map as shown in Figure 27 and Figure 28. The densely spaced contour lines in the northwestern area of Figure 9Figure 25 is therefore indicative of a hill whereby the geology present is resistant to erosion and weathering, known as Northcliff which corresponds to the steepness (25.4935%). Areas of high elevation are known to receive recharge from rainfall prior to evaporation whereby runoff redistributes the water which allows for recharge. In Johannesburg, the fractured and weathered quartzites at higher elevations experience this type of recharge (Leketa *et al.*, 2019). The aquifers generally receive this water via the vertical fractures in the crystalline rock.

Lower elevation and gentler slopes seen in the east of the study area are known to be discharge areas (Woessner and Poeter, 2020). These areas have higher groundwater potential due to them being flat. This means that artificial recharge and therefore MAR is better suited at the gentler slopes due to the proximity of streams and dams. Indirect recharge may occur where these surface water bodies are present. This means that the steeper slopes are less likely to be considered for artificial recharge and therefore MAR. In the south-southeastern part of Figure 27, two areas of an elevated slope are present which show a pinching out between them, indicating a valley. This is seen in the area Melville which suggests that that area is the Melville Koppies. In this valley, a stream flows through. The valley may have increased groundwater potential. This stream is the same stream in the northeastern part of Figure 27. This stream flows from a point of higher elevation which then goes through the Emmerentia Dam where the Botanical Gardens are located.

2. **Lithology as a criterion**: Hard rocks with secondary porosities (fractures porosity and matrix porosity), which dominated the study area, may be appropriate for MAR through injection MAR methods. These rocks would be classified either as fractured and/or weathered igneous or metamorphic (crystalline) rocks.
3. **Water level as a criterion:** By eliminating the majority of biological loads and lowering chemical concentrations, the aquifer's soil in the unsaturated zone improves sewerage effluent treatment. For injection MAR approaches, the deeper aquifer is being targeted, as seen in some of the boreholes (20-25 mbgl) of the study area, are of significance (Magombeyi and Matambo, 2023).
4. **Soil as a criterion**: Due to deeper aquifers being targeted for injection MAR approaches, the soil should facilitate for the construction of a well and reduce the potential for clogging of the well. The predominant soil texture in the area is sandy clay – sandy loam clay (Blackwell, 2016).
5. **Distance to source as a criterion**: The closer the source water is to the proposed sites, the cheaper the cost of infrastructure and therefore the more feasible MAR becomes. 0-4km away from the source tends to be the most suitable distance for the practice to be feasible (Hani *et al.*, 2023). In the study area, the closest source is the Emmarentia Dam. Johannesburg, which is where

the Emmarentia Dam is located, is located on the watershed which divides the Orange River Basin and the Limpopo River Basin (Turton *et al.*, 2006; Abiye *et al.*, 2011).

6. **Land use/cover as a criterion**: Areas with open/available space are most suitable for MAR practices. The injection methods require minimal open space however sufficient space is required for the construction that needs to take place. The most favourable sites would be where recreational land is located. Majority of the study area is occupied by various forms of urban built-up, mainly residential.

5.5.3 Defining the factor value and standardisation

The value range for each factor/criterion was determined from pre-existing data as well as literature (Hani *et al.*, 2023) as a guide. The grouping of values is shown in Table 2.

Table 2: Criteria definition, description and factor value determination. Dupont, 2018, Sallwey et al., 2015.

CRITERIA	DESCRIPTION	DEFINING RANKING
SLOPE	The slope of an area plays a significant role in the recharge of aquifers and therefore in MAR. Steep slopes are not ideal locations for groundwater recharge whereas a gentle slope/flat area is more ideal for the recharge of aquifers and thus MAR.	0-3%: flat= highly suitable 3-8%: undulating= suitable 8-15%: rolling= moderately suitable 15-30%: moderately= low suitability 30-60%: steep= unsuitable
LITHOLOGY	The aquifer's capacity to recharge and recover water, as well as its potential storage area, are significantly influenced by the geological formations that make it up (Dupont *et al.*, 2018). Crystalline rocks are generally not ideal for direct and/or indirect recharge to occur due to the structure of the crystals in the rocks. When the rocks have undergone weathering and gain secondary porosity, the likelihood of recharge increases and thus the presence of groundwater and MAR.	Sedimentary rocks: highly suitable Igneous and metamorphic rocks (fractured): moderately suitable Igneous and metamorphic rocks (unfractured): unsuitable
WATER LEVEL	Usually, sites where groundwater levels are falling, MAR is useful due to the availability of aquifer storage (Dupont *et al.*, 2018). For ASR the deeper aquifers are the targets.	25-30m bgl: highly suitable 20-25m bgl: suitable 15--20m bgl: moderately suitable 10-15m bgl: low suitablity 5-10m bgl: unsuitable

SOIL	The soil is important as clay-rich soils could block the injection borehole if any clogging occurs. However, due to the MAR being injection based, the soil is not as important.	Clay-rich soils: low suitability
DISTANCE TO SOURCE WATER	MAR is most suitable when the proposed site is close to the source water of the practice. In this research, the proposed source water is either the Emmerentia Dam	0-2 km from source: highly suitable 2-4 km from source: suitable 4-6 km from source: moderately suitable 6-8 km from source: low suitability >8 km from source: unsuitable
LAND USE/COVER	MAR is most suitable in regions where there is less built-up area/available space for the aquifer to be recharged. In this research, the proposed method of MAR is ASR which requires space for infrastructure.	Recreational sites (urban and school sports grounds): highly suitable Urban built-up: unsuitable

To standardise the various factors, the same scale is used across each of the criteria maps as seen in Table 3.

Table 3: Standardisation of factor values

RANKING/STANDARDISATION
1- Unsuitable 2- Low suitability 3- Moderately suitable 4- Suitable 5- Highly suitable

5.5.4 Criteria mapping

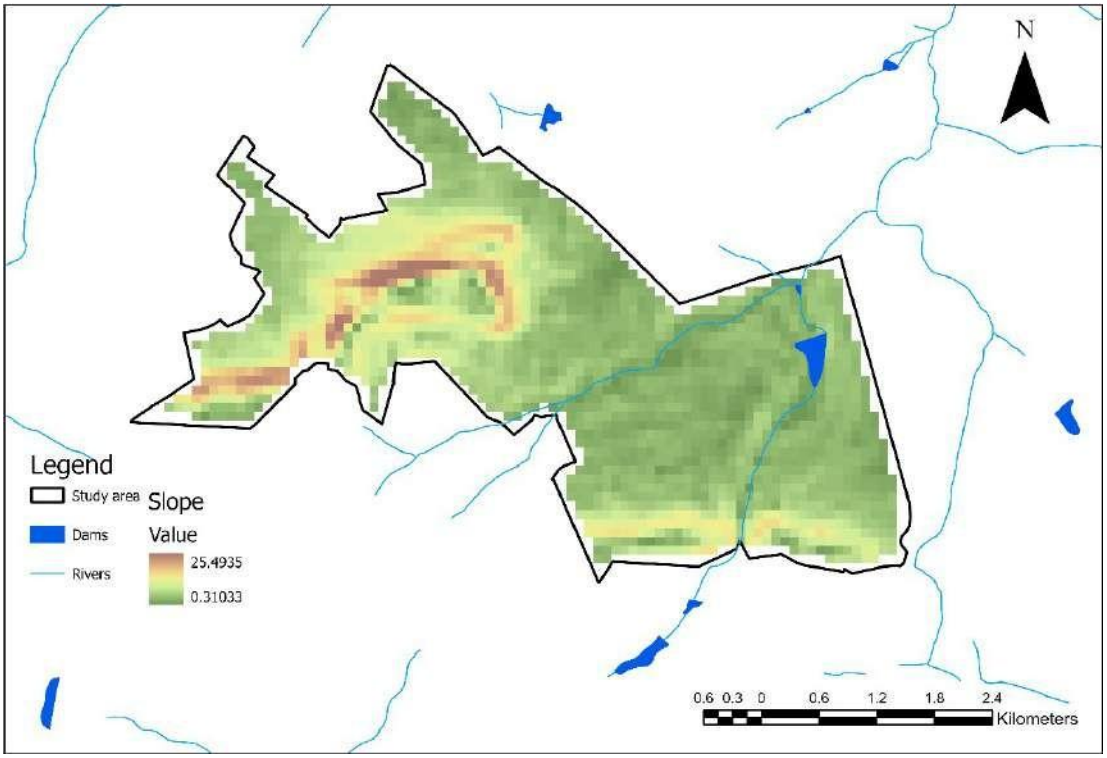

Figure 27: Slope map, data from USGS Earth Explorer- U.S. Geological Survey, 2024

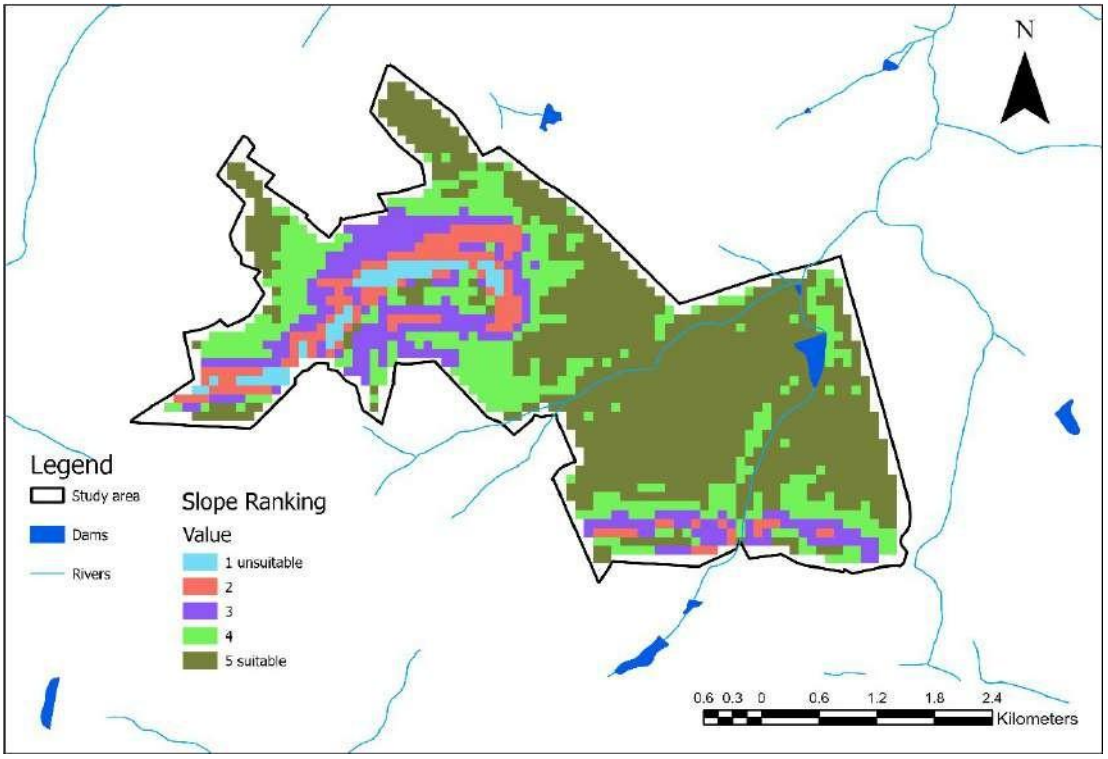

Figure 28: Slope criterion map, data from USGS Earth Explorer - U.S. Geological Survey, 2024

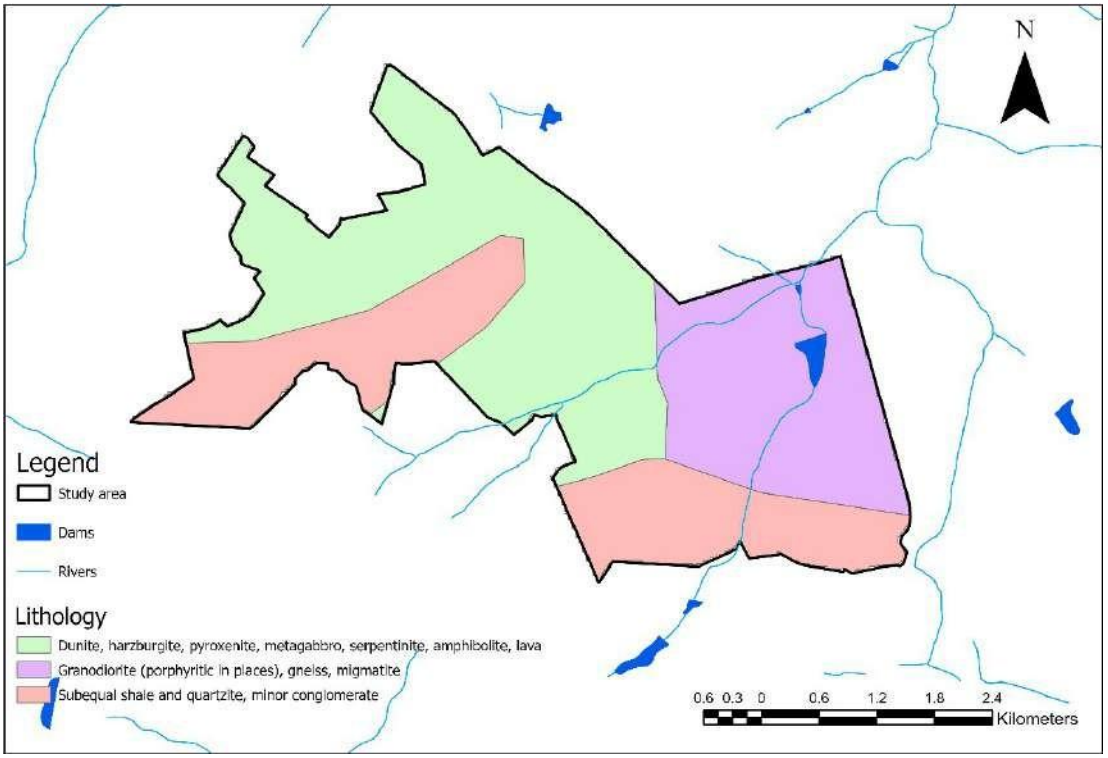

Figure 2S: Lithology map, data from Council for Geoscience (CGS)

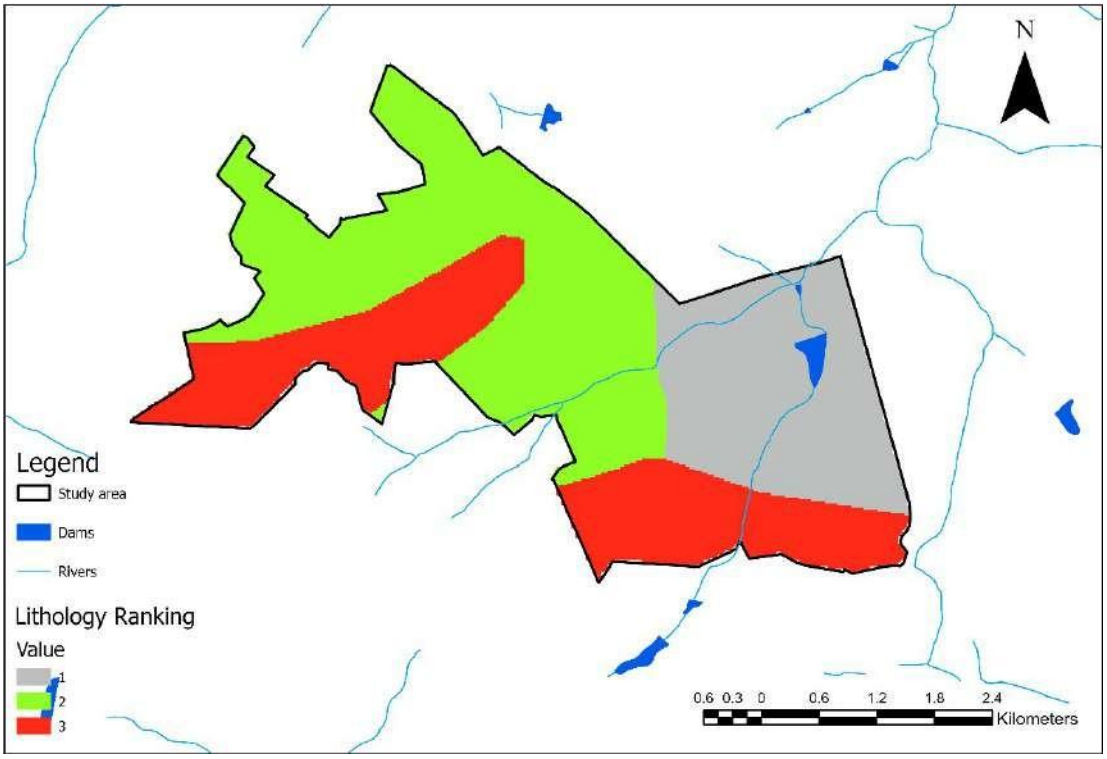

Figure 30: Lithology criterion map, data from Council for Geoscience (CGS)

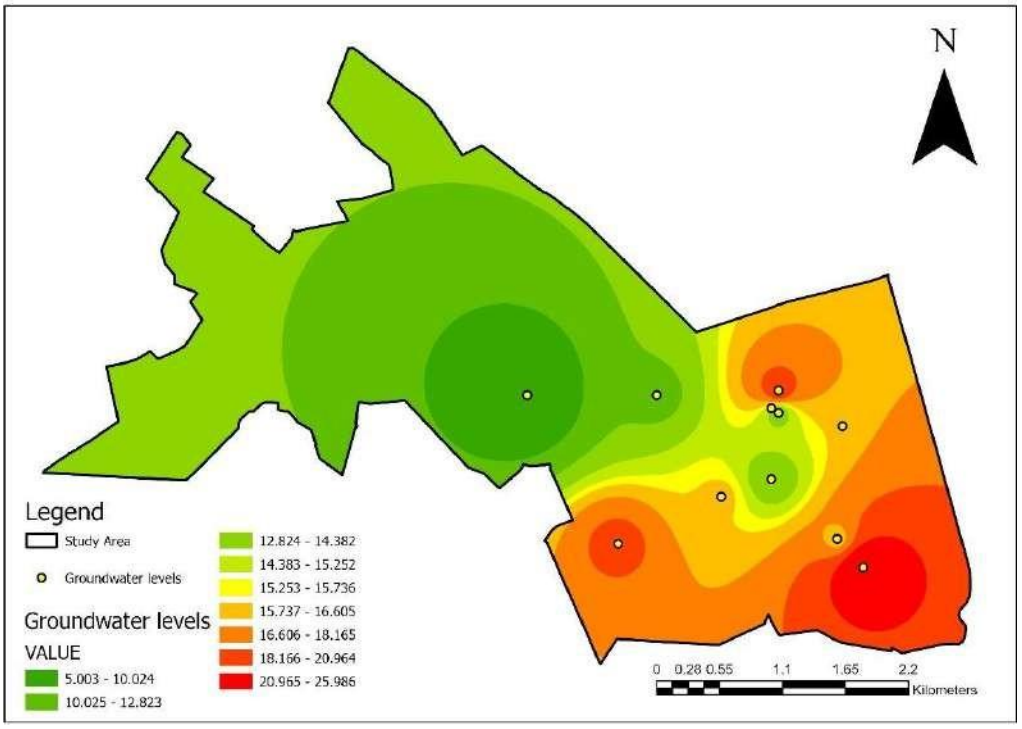

Figure 31: Water level map, data from National Groundwater Archive (NGA) of the Department of Water and Sanitation

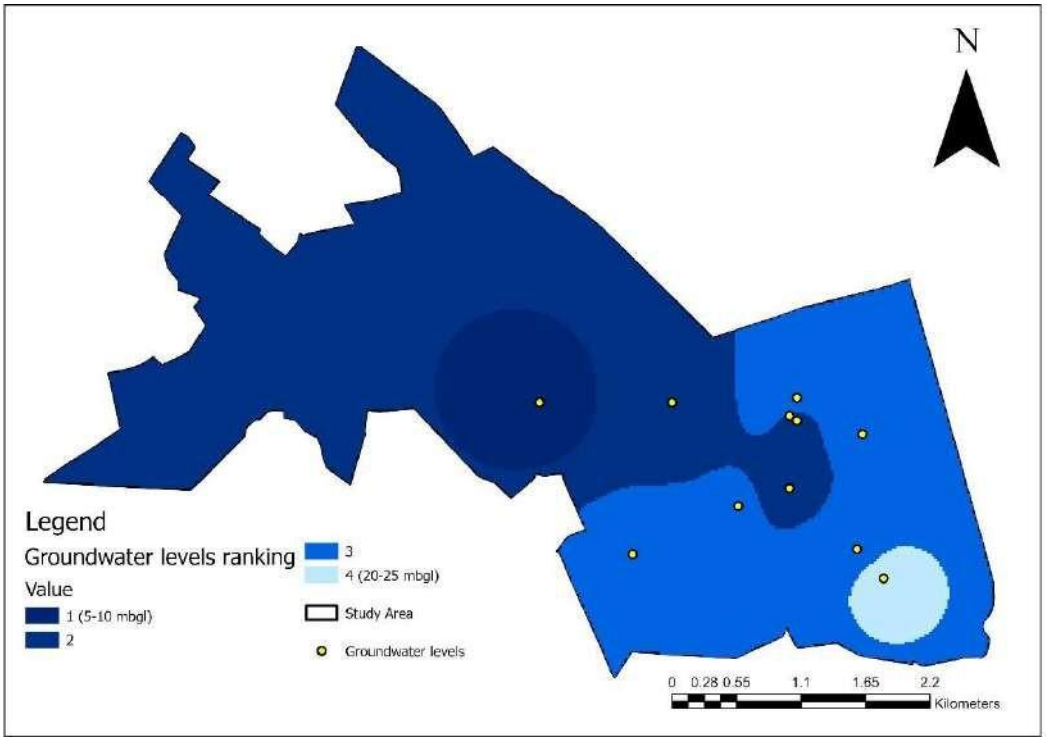

Figure 32: Water level criterion map, data from National Groundwater Archive (NGA) of the Department of Water and Sanitation

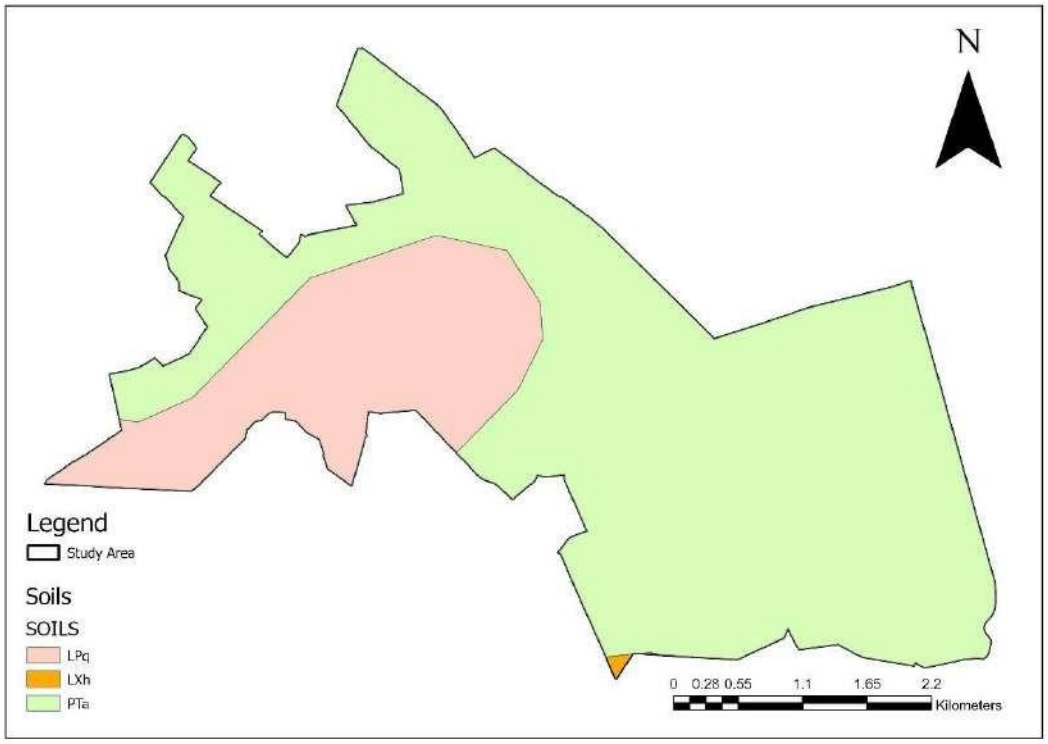

Figure 33: Soil map, data from Soil and Terrain Database (SOTERSAF) for South Africa.

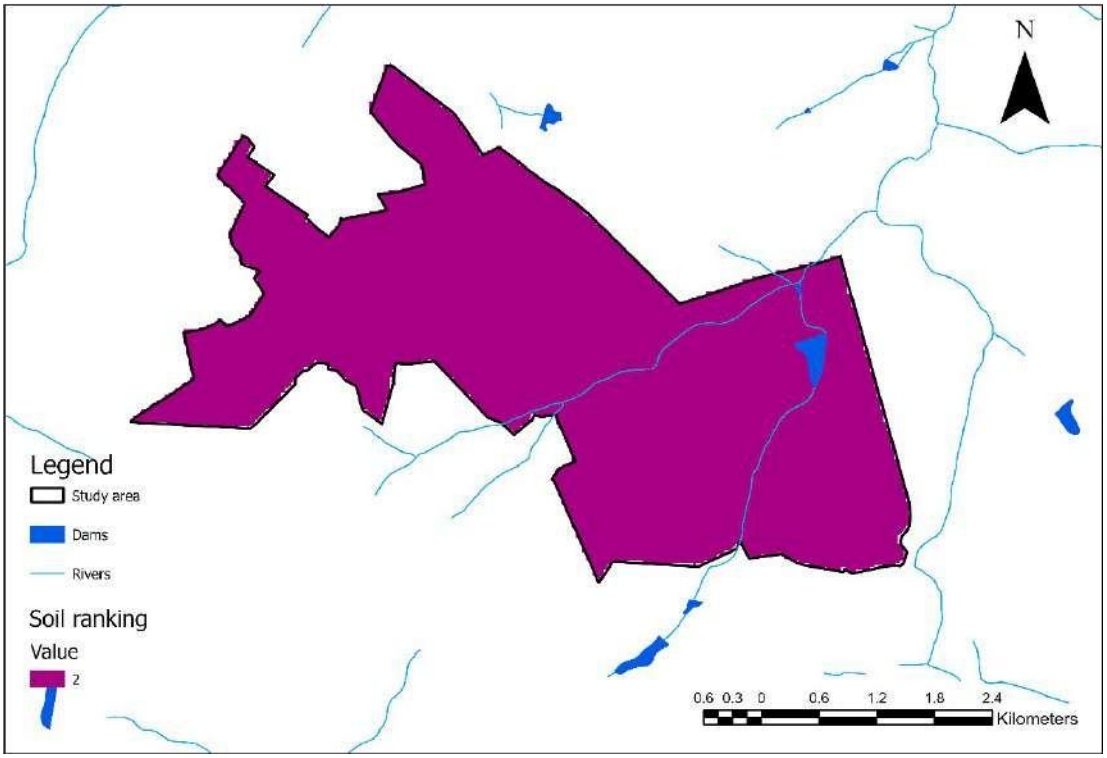

Figure 34: Soil criterion map, data from Soil and Terrain Database (SOTERSAF) for South Africa.

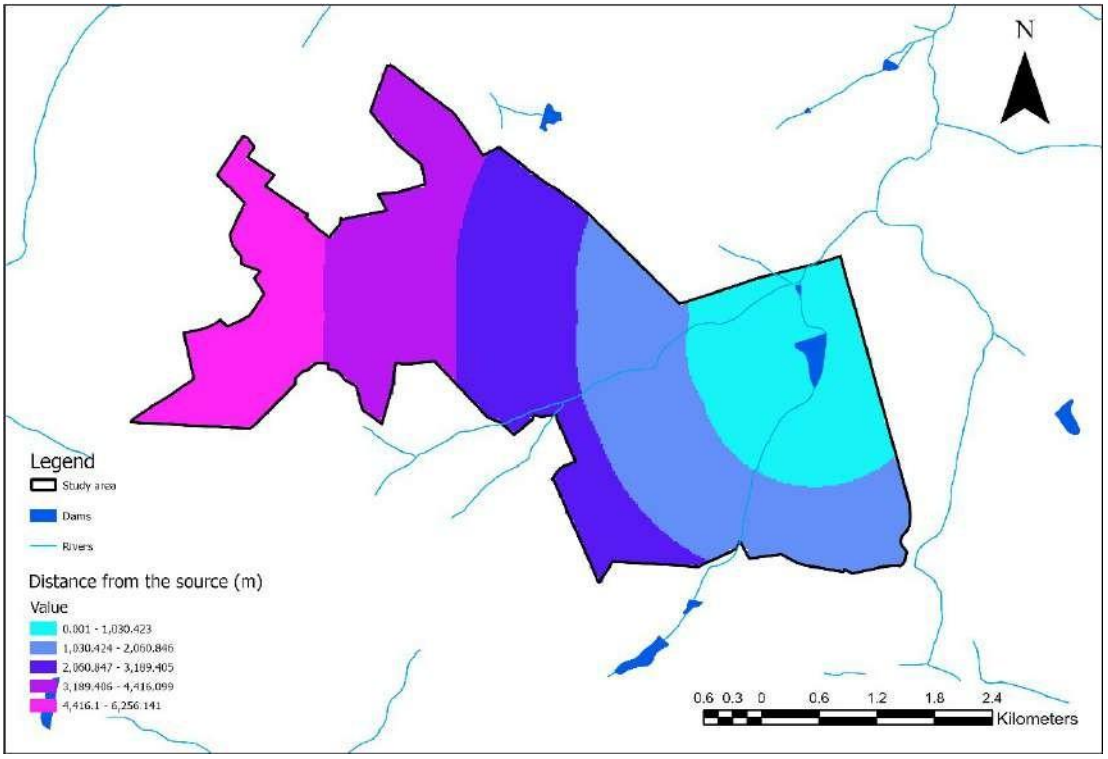

Figure 35: Distance from the source map, data from Council for Geoscience (CGS)

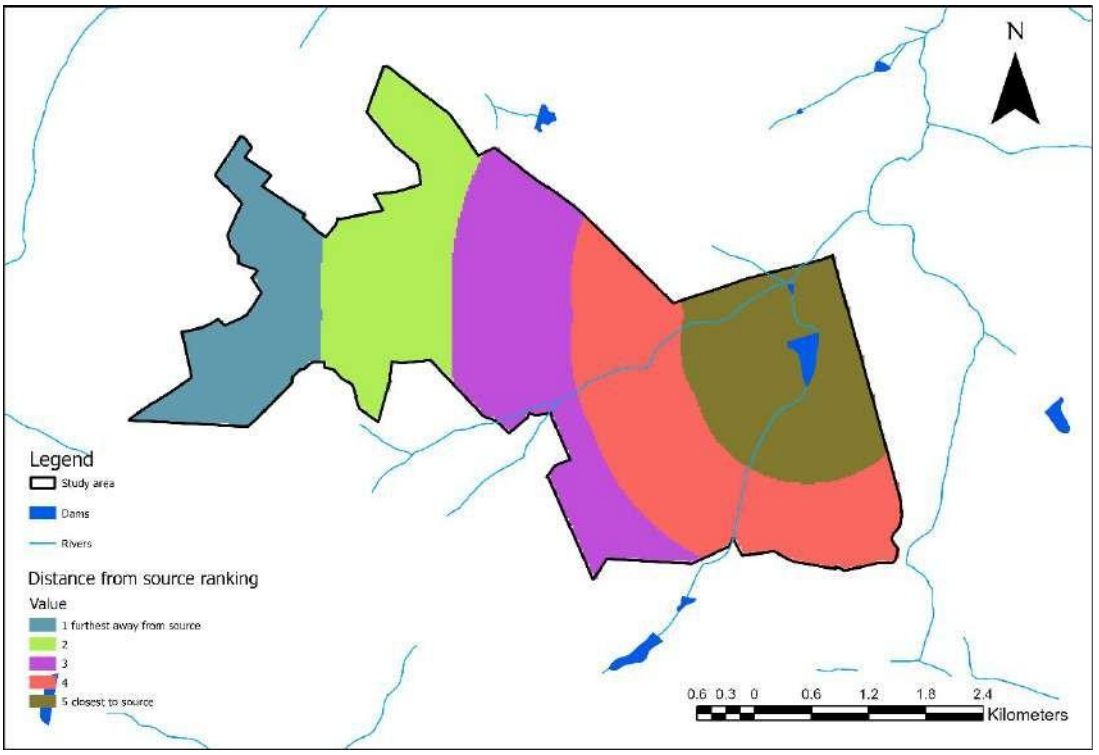

Figure 3c: Distance from the source criterion map, data from Council for Geoscience (CGS)

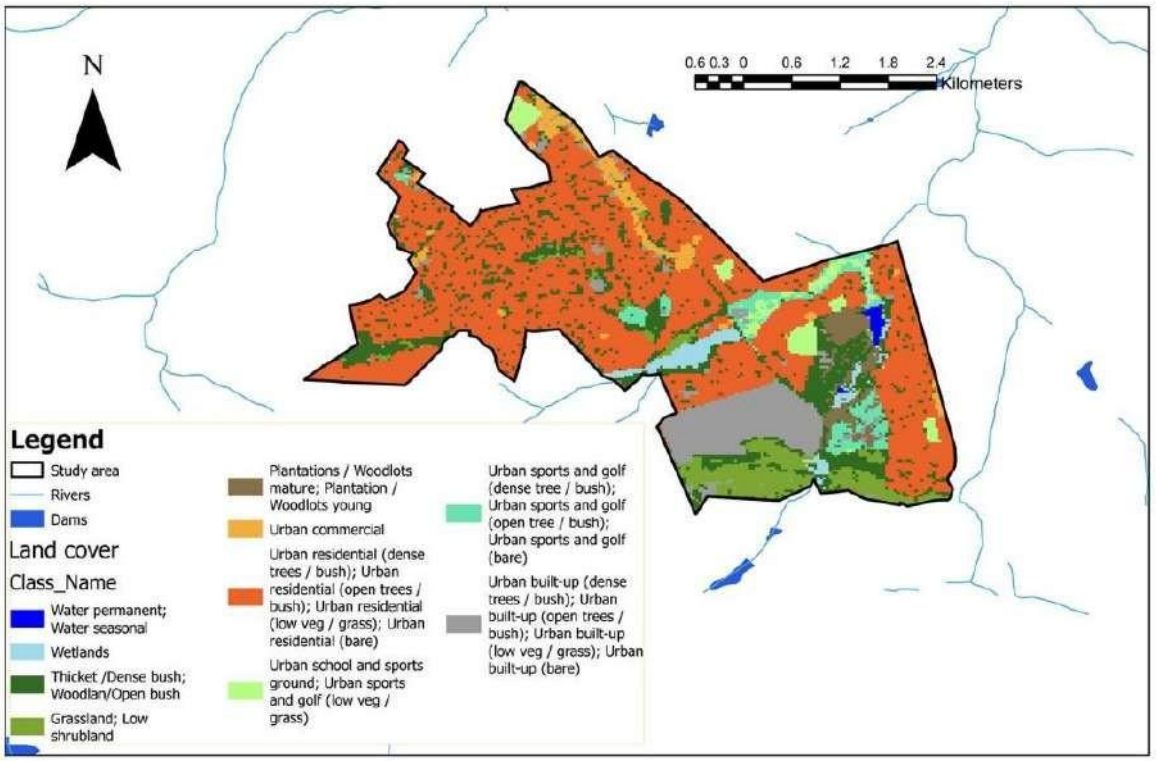

Figure 37: Land cover map, data from Council for Geoscience (CGS)

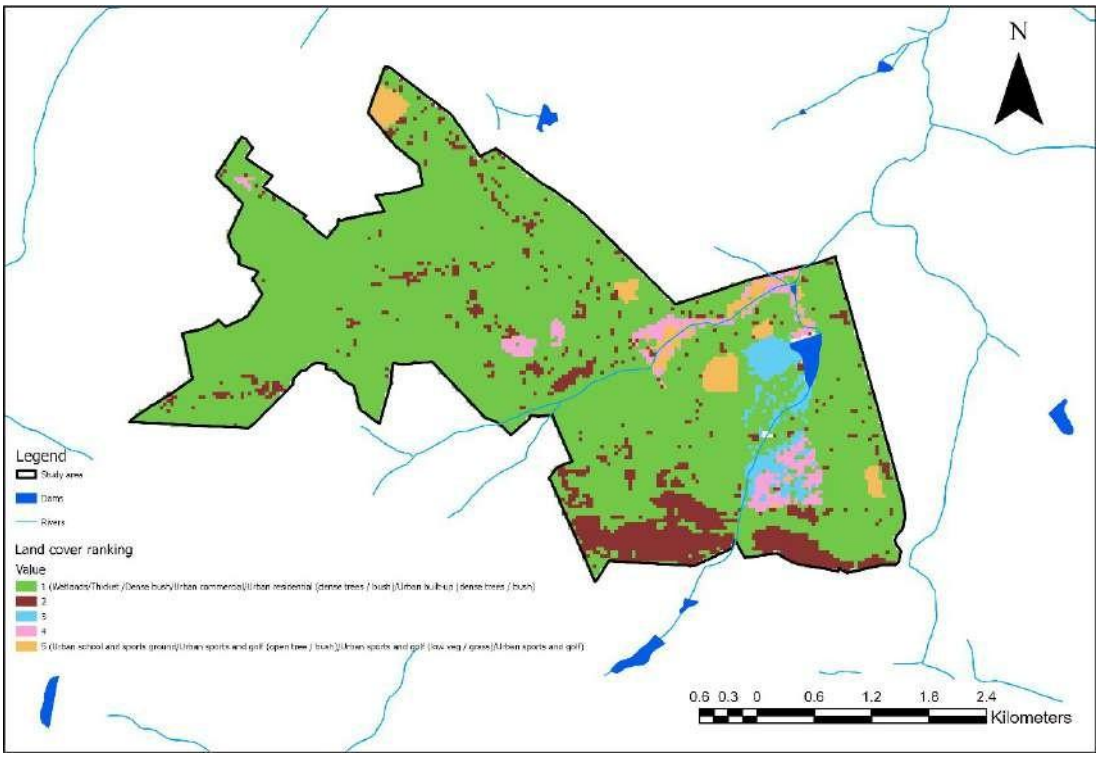

Figure 38: Land cover criterion map, data from Council for Geoscience (CGS)

Maps of slope, lithology, water level, soil, distance to source and land use were created along with their classifications/rankings according to their suitability in Figure 27-Figure 38. Due to the study area having great variability in slope, it was seen that certain regions are unlikely to be recognised as potential artificial recharge sites and having a low suitability for MAR due to their steepness (25.49%) as shown in Figure 27. However, the steepest areas only made up a small percentage of the study area which resulted in majority of the study area being likely for consideration of artificial recharge and highly suitable for MAR due to the relatively flat slope (0.31%). This was further emphasised in Figure 28, where the blue area represents an unsuitable area for MAR, which showed the top of the Northcliff Hill. This area has resistant hard rock which thus means that minimal erosion can occur resulting in the steep slope. Steep slopes have low groundwater potential therefore the area is unsuitable for MAR. Steep slopes increase construction costs for injection-based MAR thus making these areas unsuitable for injection-based MAR (Hani *et al.*, 2024).

The surrounding area in Figure 28 varies from low to moderately suitable for MAR as shown in the pink and purple colours respectively. This was also shown in the southeastern region of the study area, which is where Melville Koppies is located. The most suitable areas for MAR were shown in the light and dark green colours and was further emphasised in Figure 28 due to the gentleness of the slope. Gentle slopes have higher groundwater potential thus making them most suitable for artificial recharge and therefore MAR (Woessner and Poeter, 2020).

The lithology map created in Figure 29 with the available data illustrates that both the Northcliff Hill area and the Melville Koppies areas consisted of predominantly shales and quartzites, which are part of the Witwatersrand Supergroup (Leketa and Abiye, 2021). The Supergroup consists of meta-sedimentary lithologies and due to the coarseness of the data, this resulted in this class of rocks being the most suitable for MAR out of the three classes presented in Figure 30. This was confirmed by the results of the geological mapping, literature review and desktop study, and electrical resistivity which indicated the predominance of fractured and weathered quartzites in the study domain. The northeastern part of the study area is dominated by granodiorites, granites and gneisses which are igneous plutonic rocks and metamorphic rocks respectively. These crystalline hard rocks were classified as unsuitable for MAR,

particularly for injection-based approaches, due to their high resistance to tectonic activity such as fracturing, as well as their low primary porosity and permeability (Singhal and Gupta, 1999; Woessner and Poeter, 2020; Leketa and Abiye, 2021). The third class of rocks seen in the northwestern and central areas of the study area are ultramafic rocks which consist of dunites, harzburgites and pyroxenites which are either pyroxene-rich or olivine-rich (Weight, 2008). These rocks were also classified as crystalline but underwent weathering which introduced a secondary porosity which altered their hydraulic properties, allowing them to be moderately suitable for injection-based MAR processes (Singhal and Gupta, 1999; Leketa and Abiye, 2021).

The water level map created in Figure 31 with the data provided by the National Groundwater Archive (NGA) of the Department of Water and Sanitation is not very visible due to each point being small, however, the range of groundwater level was recorded and illustrated for the purpose of the suitability mapping. The deepest water level seen within the area of study ranged between 15m bgl to 20m bgl which ranked as having moderate suitability for MAR as seen in Figure 32. Outside the study area, two boreholes recorded water levels of about 25m bgl and 34m bgl, which ranked as highly suitable for MAR (see Figure 8). This was due to injection-based MAR targeting the deeper aquifer for subsurface storage. Shallow water levels (5m to 10m bgl) and therefore either perched or water table aquifers were not the target for the intended MAR approach, resulting in them ranking as unsuitable sites for artificial recharge and therefore unsuitable for MAR (Arshad *et al.*, 2014; Dillon, *et al.*, 2019).

Three soil types namely, LXh, PTa and LPq soils dominate the study area, which all share a soil texture, sandy loam-sandy clay loam, as seen in Figure 33. Sandy loam soil has 10-20% clay and sandy clay loam has 20-35% clay which means the soil is clay rich (Blackwell, 2016; Dupont *et al.*, 2018). This was further emphasised in the ERT data in sections 5.1; 5.2; 5.3 and 5.4. Due to the clay content, the soil has low suitability for MAR. However, due to the proposed technique being injection based, it held little weight because the technique requires a well. The soil should be considered to assist in the reduction of the potential clogging of the well and waterlogging (Arshad *et al.*, 2014).

The map illustrating the distance from the source water showed that the closer an area is to the source, in this case the Emmarentia Dam, the more suitable the area is for MAR practices (Hani *et al.*, 2023) as seen in Figure 35 and Figure 36.

The land use map and its ranking map created in Figure 37 and Figure 38 show that majority of the study area was covered by built-up urban residential use, as expected due to the study area being a ward within the metropolitan city (Todes, 2012; Leketa and Abiye, 2020). This made majority of the study area unsuitable for MAR due to most of the land being occupied by urban residential areas, urban built-up areas and urban commercial areas. The proposed MAR approach required open space for drilling of a well therefore densely vegetated areas such as grasslands and thickets, wetlands and built-up areas range from unsuitable to moderately suitable areas for MAR. Open recreational areas such as school and urban sports grounds, parks and golf parks were highly suitable for injection-based MAR.

5.5.5 Weighting of each criterion

The rating method was applied to the weighting application for each criterion (INOWAS, 2019). This method is based off the review of available data and field surveys, the local geology and land use which aided the selection of weights for each criterion. This meant that the criteria are ranked from being least important (1) to the most significant (6):

1. **Soil (5%)**: due to the study intending to use injection methods as opposed to infiltration/spreading methods, soil is not as important as the other parameters as well as the fact that only one soil type dominates the study area. The self-remediating property of the vadose zone (where the soil is located) is not as vital for injection methods due to the construction of a well therefore soil is the least important factor. Soil may be taken into consideration when looking at the water used for MAR to avoid potential clogging.
2. **Distance to water source (5%)**: the Emmarentia dam is the closest dam in the study area, with the area having a radius of about 6 km maximum. This means that the distance is not that important for this site suitability analysis.
3. **Lithology (10%)**: from field work, some of the granites were fractured and highly weathered whereas others were unfractured. The quartzites observed

were highly fractured and weathered. The observed serpentinites were broken/fragmented. The map illustrating the lithology displays the geology on a coarser/more general scale so it is not entirely accurate for the zoomed in study area. The map shows the prevalence of granites, granodiorites and quartzites are in the area which are crystalline rocks which are generally unsuitable for drilling when fresh. When weathered, the secondary porosity increases their hydraulic conductivities and permeabilities which therefore facilitates for storage and flow of groundwater (Netsianda and Abiye, 2017).

4. **Water level (15%)**: for injection MAR methods, the deeper aquifer is being targeted therefore sites which have the deepest water levels are of most significance (Arshad *et al.*, 2014).

5. **Slope (25%)**: for drilling of the injection well, the deeper aquifer is only going to be reached on a gentler/flatter slope due there being less distance between the surface and the aquifer, therefore making it easier to drill and reach the aquifer.

6. **Land use (40%)**: the study is densely occupied by built up and urban residential areas with some regions for recreation. The injection well methods require open space for construction of the well and the availability of open land is of utmost importance for injection MAR methods.

5.5.6 Final suitability map (combination of weights)

The final suitability map considered all the criterion and with various weights of importance discussed in section 5.5.5, combined the criteria and created an end map for decision making based off of the most important criteria. The criteria importance is subjective and may differ from decision-maker to decision-maker (Dupont *et al.*, 2018; Hani *et al.*, 2023). For this study's objective, the most important criteria were analysed, and the final suitability map was created for the intention of an injection-based MAR approach (see Figure 39).

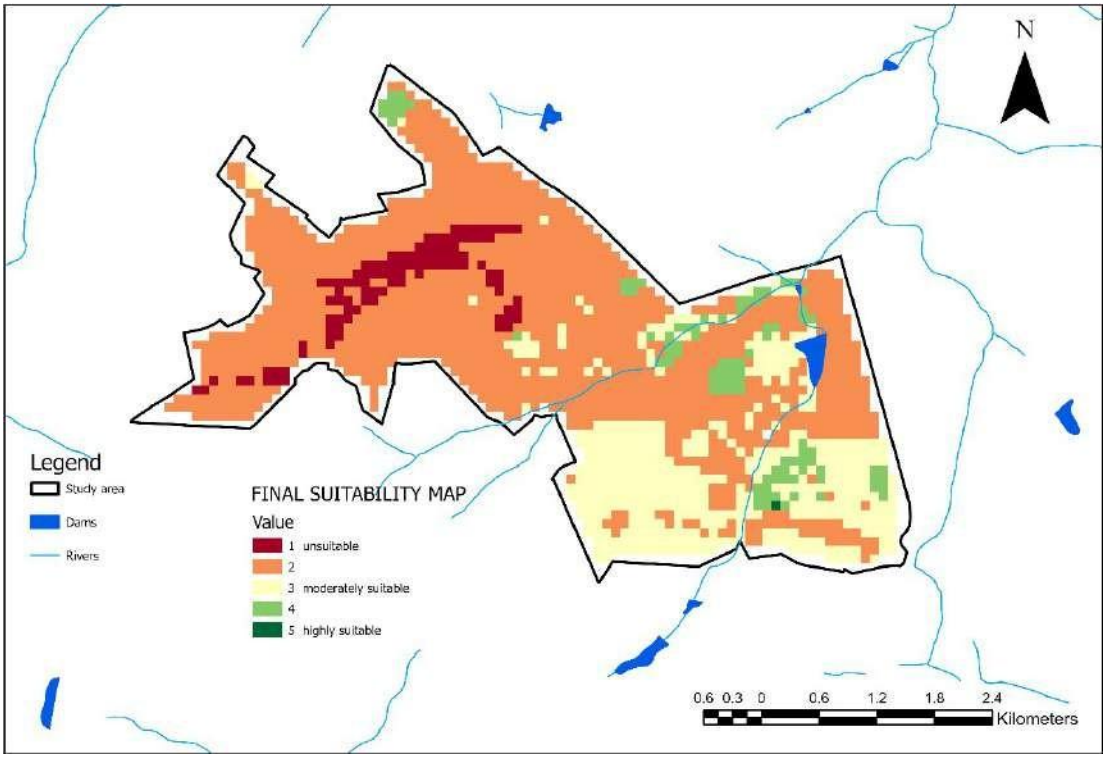

Figure 3S: Final suitability map, data from Council for Geoscience (CGS), USGS Earth Explorer- U.S. Geological Survey, 2024, National Groundwater Archive (NGA) of the Department of Water and Sanitation, and Soil and Terrain Database (SOTERSAF) of South Africa

The final suitability map produced, with land cover, slope and water level being the top 3 most important criteria for MAR schemes in urban areas, showed a small area of high suitability for MAR at the base of the Melville Koppies. Suitable areas for the proposed MAR scheme were located around the highly suitable area, near the Emmarentia Dam and in the top left corner of the study domain. These areas were all recreational land cover (urban and school sports grounds, parks and golf) and had flat to undulating slope with relatively deep-water levels. The water levels of the present boreholes ranged from low (13m bgl) to moderate (21m bgl) suitability of MAR. These areas were within the proximity of streams and dams which reiterated that gentle slopes were linked to having high groundwater potential and may be discharge regions as well (Woessner and Poeter, 2020). Focused recharge may occur from the surface water bodies as expected (Leketa and Abiye, 2021) however, recharge is dependent on various factors inclusive of rainfall intensity (Leketa and Abiye, 2021). The most unsuitable area for MAR in the study domain was at the Northcliff Hill, where highly fractured, resistant quartzites were present with a moderately steep slope. A borehole at the base of the hill recorded very shallow water levels (5m bgl) which was not the

targeted aquifer for the proposed MAR scheme. This area was also furthest away from the source water (Emmarentia Dam) of the proposed MAR scheme further decreasing its suitability. The area was also covered by dense bush and urban residential areas surrounding the hill which contributed to its unsuitability. The areas ranked at '2' represented low suitability regions for MAR due to them mainly being covered by urban residential and built-up land which were not ideal for injection-based MAR approaches. The lack of water level data in these areas also contributed to the low suitability of MAR approaches. The highest points of the Melville Koppies had low suitability for MAR however, as the slope changed from moderately steep to undulating, the area then displayed moderate suitability for MAR. The land cover in the 'moderate suitability' region was mainly grasslands, dense bush and urban residential areas. The region of moderate suitability closest to the Emmarentia Dam was as a result of the land cover criterion having the highest weighting, and due plantations being given a low ranking with regards to the proposed MAR practice for this study.

The proposed injection method for the scheme was therefore the aquifer storage and recovery (ASR) technique due to space constraints in the urban setting.

5.5.7 Sensitivity analysis

A sensitivity analysis was applied to show how various criterion weights affect the suitability map's spatial arrangement (Magombeyi and Matambo, 2023). This analysis helped determine the importance of a criterion. For this study, two of the top three criteria were selected. These were the slope and water level criterions. Their weights were altered to that of the assigned land cover weight (40%) in the final suitability map (see Figure 39). The land cover criterion in the sensitivity analysis maps took the original weighting of the altered criterion in each scenario (see Figure 40 and Figure 41).

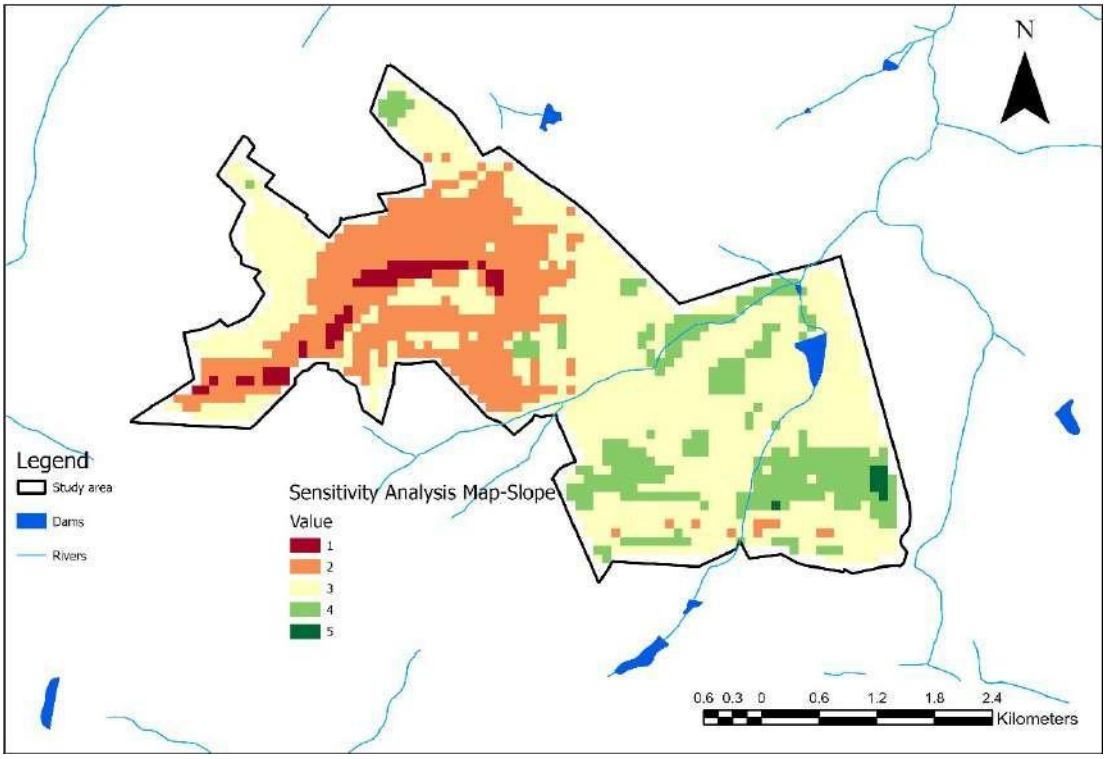

Figure 40: Sensitivity Analysis Map (slope altered), data from Council for Geoscience (CGS), USGS Earth Explorer- U.S. Geological Survey, 2024, National Groundwater Archive (NGA) of the Department of Water and Sanitation, Soil and Terrain Database (SOTERSAF)

In the sensitivity analysis map (see Figure 40) whereby, the slope was assigned a weighting of 40% and land cover replaced to 25%, most of the study domain was classed as ‘moderately suitable’. Northcliff Hill and surrounding areas display ‘unsuitable’ and ‘low suitability’ areas for MAR due to the slope being too steep. The land cover in this area had a minimal effect on the suitability of injection-based MAR approaches. The dominant ‘moderate suitability’ class displayed the effect that land cover had on the suitability of MAR, seeing that the slope is relatively flat in the region however the land cover is mainly urban residential. At the Melville Koppies, the area of ‘moderate suitability’ also displayed the effect that land cover had on the MAR suitability. Despite the slope ranging from rolling to moderately steep, the land cover being grasslands and thickets resulted in the region being classed as ‘moderately suitable’. Minor areas of MAR ‘suitable’ and ‘low suitability’ were illustrated in the same region as well, resulting from the slope being relatively flat at the top of the Koppies, and the change in slope from the top to bottom of the Koppies respectively. The areas classed as ‘suitable’ for MAR were mainly located in the valleys where streams flow,

which is attributed to the flatness of the slope (Woessner and Poeter, 2020). A small portion of the study area was classed ‘highly suitable’ for MAR due to the flatness of the slope. This map confirms that slope has a significant effect on the spatial arrangement of potential injection-based MAR.

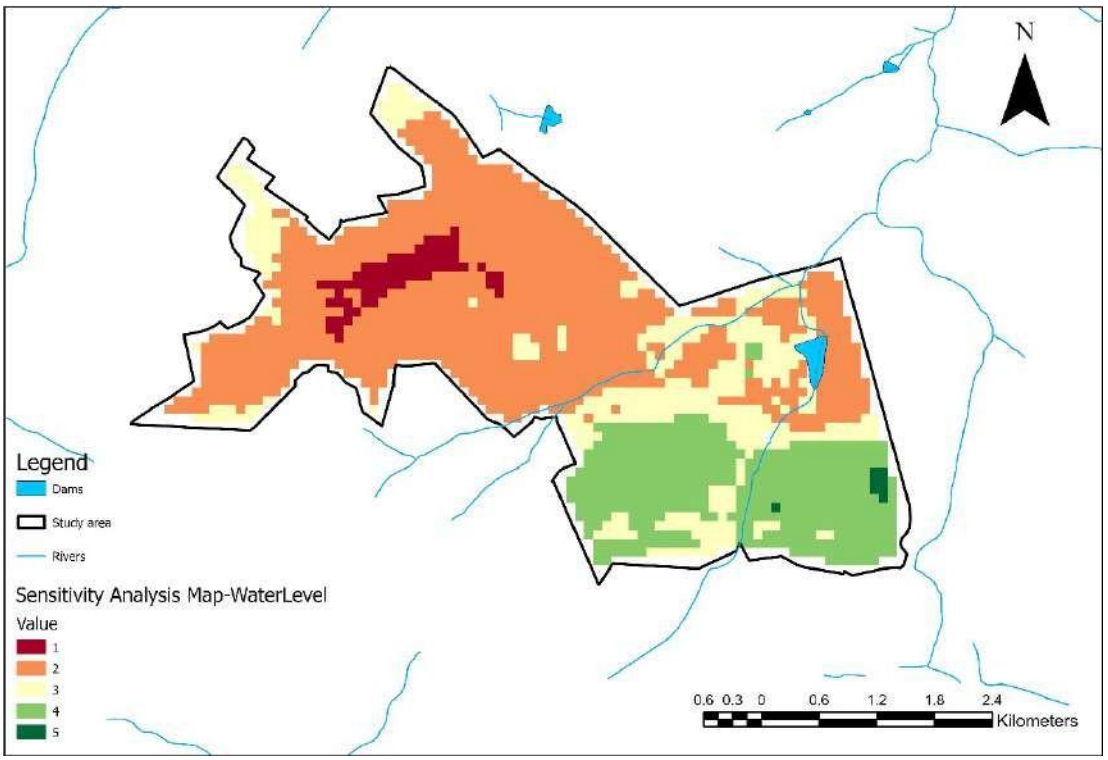

Figure 41: Sensitivity Analysis Map (water levels altered), data from Council for Geoscience (CGS), USGS Earth Explorer- U.S. Geological Survey, 2024, National Groundwater Archive (NGA) of the Department of Water and Sanitation, and Soil and Terrain Database (SOTERSAF) of South Africa

In the sensitivity analysis map (Figure 41) whereby, water levels were assigned a weighting of 40% and land cover replaced to 15%, most of the study domain was classed as ‘low suitability’ for MAR which may be the result of the lack of data and the available data at the base of the Northcliff Hill being ranked as ‘low suitability’ due to its shallow nature. The areas classed ‘moderately suitable’ for MAR had water levels ranking from low to moderately suitable. The areas classed ‘suitable’ and ‘highly suitable’ for MAR were recorded to have relatively deep-water levels which were the targeted aquifers. These areas were seen in the Melville Koppies region. The map displays the variability in suitability of injection-based MAR and the effect that water levels have on suitability mapping.

Both the slope and water level criteria have a significant impact on the suitability mapping which causes variability in the outcomes of decision-makers. The level of importance of the land use, slope and water level criteria is subjective which results in the differing of final maps decision-maker to decision-maker. This suggests that more accurate and detailed information on the criterion are required (Sallwey, *et al.*, 2019; Assefa and Dinka, 2023; Magombeyi and Matambo, 2023).

Chapter Six: Conclusions and Future Work

6.1 Conclusions

The study aimed to investigate the suitability of managed aquifer recharge (MAR) schemes to augment domestic water supply in Randburg, City of Johannesburg. The Emmarentia Dam was selected as the potential source water for the injection-based scheme through GIS-based methods, geological mapping, review of literature and desktop analysis. The outcomes of the research contribute to water resource management and water demand issues in metropolitan areas.

The methodology employed to assist in location of suitable sites for MAR in the study area included literature review and desktop analysis, field work and suitability mapping through GIS-MCDA. The key findings of this study included the dominance of lithic soils which are clay rich. The sandy loam-sandy clay loam texture of the soil allows the soil to retain water and thus eventually reach a low constant infiltration rate during rainy seasons. The crystalline rocks in the area are heavily fractured and weathered on a regional scale. This results in their initial hydraulic properties such as permeability, hydraulic conductivity, porosity, and specific yields increasing. The enhancement of their hydraulic properties allows for the potential storage and flow of groundwater.

The study area has both shallow intergranular and deep fractured aquifers, confirmed by the geophysical method employed as well as by the literature. The deeper aquifers were of focus due to the proposed MAR scheme requiring deep wells to fulfil its purpose. The suitability mapping with GIS-MCDA determined that suitable areas for MAR were located closest to the potential source water, the Emmarentia Dam. These areas were also mainly urban and school open sports grounds, golf and recreational parks which had open natural space for injection-based approaches such as the aquifer storage and recovery (ASR) systems. The GIS-based techniques also emphasised the importance of land cover, slope, and water levels as criteria for the study considering the urban setting of the study domain. The study also highlighted the complexity of employing MAR schemes in highly urbanised settings, especially injection approaches. The sensitivity analysis determined that land cover, slope and water levels had a significant impact on the outcome of the MAR suitability maps.

In conclusion, this pilot study introduces the initial step for decision-makers to further invest into the idea of MAR schemes reducing the pressure on surface water resources in metropolitan cities. Therefore, MAR becomes a part of water resource management strategies to meet water demands sustainably. With further investment, more testing can take place to further validate the hypothesis of this study and thus contribute positively to the potential water insecurity issues in the City of Johannesburg and potentially in South Africa.

6.2 Future work and limitations

The limitations faced in the study included the lack of data, inclusive of data obtained from hydraulic testing, such as pumping and slug tests, of the aquifers via boreholes at each testing site. This was as a result of limited access to existing boreholes in the study area. The lack of data was also inclusive of restrictions in data resolution. Another limitation faced was the location of the study area lies within metropolitan municipal boundaries, resulting in the majority of the recreational spaces being state-owned and controlled which limited access for intensive fieldwork. The financial and time constraints were the main contributors to the limitations faced which resulted in fieldwork commencing later in the year.

Based on the outcomes of this research, the following could be explored for future work:

- Conducting the hydraulic tests such as slug tests and borehole yield tests. This would assist in gaining accurate insight on the present aquifers' hydraulic properties. Additionally, monitoring the aquifer recharge rates and groundwater levels over time would give accurate information about the storage capacity of the aquifer.
- Conducting water quality tests on the source water, to ensure that clogging of the ASR system does not occur or to reduce the rate at which it may occur. The testing of water quality compliance with the water regulations for drinking in South Africa which reiterates the importance of water quality for this study. The vulnerability of groundwater to pollution can be modelled using DRASTIC to assist in avoiding the potential contamination from urban activities in the study domain. This can be used in conjunction with the GIS-MCDA to further strengthen the decision-making process.

- Introducing the socio-economic implications of the MAR schemes in the study area to have a holistic outlook on the feasibility of the ASR approach in an urban setting. This includes financial and legal implications of the proposed scheme.

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Appendices

The appendices may be found on the google drive linked below:

https://drive.google.com/drive/folders/1tMUB0h9s73Qq5_oGpN5JkyqsCYvFbdez?usp=drive_link