Identifying potential areas suitable for Managed Aquifer Recharge in Saldanha Bay, Western Cape

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Environmental & Water Science, Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape

Ashleigh Tomlinson 3459005

Supervisor: Dr Jaco Nel

Co-Supervisor: Dr Sumaya Clarke

June 2022

Declaration

I, Ashleigh Tomlinson, declare that '*Identifying potential areas suitable for Managed Aquifer Recharge in Saldanha Bay, Western Cape'* is a dissertation of my own work and does not infringe upon the ethical principles set out in the University of the Western Cape General Calendar (Part 1), Section 4

Ashleigh Tomlinson

ATomlinson

June 2022

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"It takes a village to raise a child"

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Abstract

Identifying potential areas suitable for Managed Aquifer Recharge in Saldanha Bay, Western Cape

A. Tomlinson, MSc Thesis

Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape

The West Coast in the Western Cape of South Africa is a water-scarce area. Pressure from population and industrial growth, recurring droughts and climate change has resulted in an increasing urgency in the West Coast to increase the available water resources. Saldanha Bay is dependent on both surface water and groundwater as part of its bulk water supply system for domestic, agricultural and industrial purposes. Where the natural groundwater recharge is no longer sufficient to meet the growing groundwater needs, practices such as Managed Aquifer Recharge can be used to improve the sustainability of these groundwater resources. The Lower Berg aquifer systems, focusing on the Langebaan Road and Hopefield wellfields, were evaluated to determine whether Managed Aquifer Recharge systems could be implemented nearby to improve the sustainability of this scarce water resource.

This study aims to identify areas near the Saldanha Bay Local Municipality wellfields, suitable for Managed Aquifer Recharge to maximize the water available during periods of limited surface water supply. The Managed Aquifer Recharge study site identification conducted a comprehensive geohydrological assessment of the Lower Berg aquifer system. This includes an understanding of the quality and quantity of the source water available for recharge, the aquifer structure and hydraulic properties, the storage capacity of the aquifer, and the compatibility of the recharged water with the groundwater.

The research methods included Time Domain Electromagnetic (TDEM) airborne geophysical surveys, infiltration tests, pumping tests and hydrochemical analysis. The Time Domain Electromagnetic surveys provided clarity on the various aquifer geological properties. Descriptions of the lithologies of the subsurface were used alongside the geophysics data to delineate layers within the aquifer unit that would support the injection or infiltration and storage of water for Managed Aquifer Recharge. Infiltration and pumping tests shed light on the horizontal and vertical hydraulic properties of the aquifer. This gave an indication of which layers are most suitable for collecting and storing water and whether injection or infiltration Managed Aquifer Recharge techniques are required. PhreeqC modelling outputs helped predict the outcome of the mixing between groundwater at Langebaan Road and Hopefield wellfields, and potential Managed Aquifer Recharge water resources which included the West Coast District Municipality pipeline, Vredenburg Wastewater Treatment Plant and the Berg River water.

Geological features were delineated through TDEM surveys and inferred five suitable Managed Aquifer Recharge sites in the deeper parts of the aquifer. The sites include the Langebaan Road wellfield, Region A, the Hopefield wellfield, Region B and Region C. Higher hydraulic conductivities in the deeper aquifer zones, identified by infiltration and pumping tests, showed that Langebaan Road is better suited to borehole injection. In contrast, higher hydraulic conductivities in the shallower aquifer zones at Hopefield showed that Hopefield has the benefit of infiltration Managed Aquifer Recharge techniques as an additional option. PhreeqC outputs exhibit that both the West Coast District Municipal pipeline water and the Berg River water show promising results as potential source water resources for Managed Aquifer Recharge as compared to the Vredenburg Wastewater Treatment Plant, which would require a considerable amount of treatment to reduce the elevated levels of nitrates (> 30 mg/L), chloride (> 400 m/L), sodium(> 250 mg/L) and ammonium (> 50 mg/L) before injection and after mixing has taken place.

Based on this research, it is concluded that the Saldanha Bay Local Municipality can support Managed Aquifer Recharge to improve groundwater sustainability in the five regions, mentioned above. Both borehole injection and infiltration are recommended as Managed Aquifer Recharge applications in the Saldanha Bay Local Municipality. Borehole injections are best suited for Managed Aquifer Recharge at the Langebaan Road wellfield where there is an extensive clay layer separating the shallow and deeper aquifer, and at Region A in high yielding deeper aquifer zones. Infiltration galleries/basins are best suited at the Hopefield wellfield, Region B and Region C where higher-yielding shallow aquifer zones are present together with missing clay layers. From a water quality perspective, all three source water resources have the potential to support Managed Aquifer Recharge however, the WDCM pipeline water is best suited.

Recommendations for future Managed Aquifer Recharge studies would include drilling to confirm the regions identified as having missing clay layers; To investigate the potential pressure difference caused by clay lenses throughout the aquifer; To increase the spatial distribution of pumping tests and infiltration tests in the area. It is also recommended that an in-depth study of groundwater risk associated with Managed Aquifer Recharge, focusing on clogging risks, takes place before the Managed Aquifer Recharge scheme commences.

Keywords: Managed Aquifer Recharge, Groundwater Sustainability, Hydrogeological Characterisation, Groundwater Management, Time Domain Electromagnetic Geophysics, Artificial Recharge, Aquifer testing, Geochemical Mixing Model, PhreeqC, Lower Berg Aquifers

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List of abbreviations

°C	degrees Celsius
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transport and Recovery
CSIR	Council for Scientific and Industrial Research
D-T-H	Down-the-hole
EC	Electrical Conductivity
HP	Hopefield
IB	Infiltration Basin
IG	Infiltration Gallery
K	hydraulic conductivity
LR	Langebaan Road
m	metre
m/day	metres per day
mamsl	metres above mean sea level
MAR	Managed Aquifer Recharge
mbgl	metres below ground level
mS/m	milli Siemens per metre
NGA	National Groundwater Archive
SAWS	South African Weather Services
SBLM	Saldanha Bay Local Municipality
SWL	Static Water Level
TDEM	Time Domain Electromagnetic
WCDM	West Coast District Municipality
WF	Wellfield
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1 Introduction

Groundwater is one of the most in-demand natural resources because of its environmental, social, and economic importance, as well as its multiple uses. In the absence of surface water supplies, groundwater resources become the freshwater supply sources within a region (Zaidi et al. 2015). Groundwater is under immense human pressure in most countries. This pressure includes changes in land use, urbanization, water demand increase, and intensive agriculture and can lead to the degradation of the quality and the quantity of the groundwater if the rate of groundwater extraction exceeds the natural recharge rate. According to Voudouris (2011), the use of groundwater resources has become intensive in coastal areas over the last decade due to urbanisation, tourism development and the expansion of agricultural land. Many aquifer systems are reported to be affected by depletion and quality deterioration due to unsustainable management. For this reason, recycled water is a new source of water that needs to be taken into account in planning integrated water resources management (Voudouris, 2011).

The West Coast in the Western Cape of South Africa is a water-scarce area and is demarcated as a semi-arid region. The local population in the West Coast District largely depends on groundwater to augment their bulk water supply. Due to pressure from population growth, industrial growth, recurring droughts and climate change, there is increasing urgency in the West Coast to protect the groundwater resource. Where the natural groundwater recharge is no longer sufficient to meet the growing groundwater needs in the West Coast, practices such as Managed Aquifer Recharge can be used to balance water supply and demand.

Managed Aquifer Recharge (MAR) is expected to become necessary in most countries as the growing population requires more water, and the storage of water is needed in times of water surplus to provide in times of water shortage (Dillon, 2009). In general, water storage has always been by means of surface water structures such as dams but recently, dam sites are becoming scarce (Bouwer, 2002). In addition, dam sites have a variety of disadvantages such as evaporation losses, the accumulation of sediment, structural failure and many other adverse ecological, environmental and socio-cultural effects. With the addition of a growing population to these conditions, there is a clear need for the storage of water for supply that does not have such adverse effects. Underground storage via MAR has the advantage of very minimal evaporation loss – depending on the method used. According to Bouwer (2002), the economic and environmental aspects of MAR are also favourable.

Managed Aquifer Recharge is a globally accepted practice to control the depletion of water in overexploited aquifers within arid and semi-arid regions that have limited surface water supply (Tzoraki et al. 2018). MAR practices allow for (Dillon, 2005; Murray and Tredoux, 1998):

- the intentional banking and treatment of water within aquifer units;
- the potential to replenish depleting aquifers within arid and semi-arid regions, which is important as it allows for an increase in the availability of water in dry seasons;
- the re-pressuring of aquifers with falling groundwater levels and;
- the subsequent prevention of saltwater intrusions

According to Dillon (2009), the cheapest and simplest form of Managed Aquifer Recharge occurs when the aquifer is unconfined, soils are permeable and there is sufficient space to construct recharge ponds. Confined aquifers are preferred when establishing a MAR scheme aimed at having sufficient drinking water as it allows for water quality protection provided by the aquitard.

A limiting factor in applying groundwater Managed Aquifer Recharge is the lack of suitable sites. Dillon (2009) listed essential elements requires for every successful MAR project. These included:

- sufficient demand for recovered water;
- an adequate source of water for recharge;
- a suitable aquifer in which to store and recover the water;
- sufficient land to harvest and treat water and;
- the capability to effectively manage a project

This research study will address the first three essential elements listed for a successful MAR project.

1.2 Significance of the study

The purpose of this study is to identify areas suitable for Managed Aquifer Recharge to maximize the water available and enhance the natural groundwater recharge in areas during periods of limited surface water supplies. The West Coast experiences a semi-arid climate with evaporation rates exceeding rainfall rates with rainfall mostly occurring within the winter season. No major river systems apart from the over-allocated Berg River is available for water supply. This coupled with the need for water supply in dry periods (summer season) in the area means that alternative methods of storing and supplying water need to be investigated. The overall population and industrialization of the area is expected to increase throughout the years and systems need to be put in place to ensure that there is sufficient drinking water available throughout the seasons to meet the demands.

1.3 Selection of study area

The local area under investigation was the Saldanha Bay Local Municipality (SBLM) with a focus on Langebaan Road and Hopefield, as they are the sites for the two existing wellfields in the region. Three main aquifer systems were considered as part of the MAR within the Saldanha Bay Local Municipality area, that is, both the shallow and deeper Langebaan Road aquifer systems and also the shallow aquifer system at Hopefield. It is also to be noted that the Elandsfontein aquifer system, situated to the south of Hopefield, forms part of the Lower Berg aquifer systems, however, this area is not of focus for this research study.

1.4 Research question

Based on hydrogeological and hydrochemical parameters, which sites are suitable for Managed Aquifer Recharge?

1.5 Aim and Objectives

This study aims to use hydrogeological and water quality parameters to determine possible areas suitable for Managed Aquifer Recharge within the Saldanha Bay Local Region. The focus of Managed Aquifer Recharge will be on wellfield optimization. The criteria used to determine the sites suitable for MAR include:

1. Water resources for MAR;
2. Aquifer structure;
3. Aquifer hydraulic parameters;
4. Space to store water and;
5. Water quality

The following objectives are set to meet this aim and include:

1. The delineation of aquifer zones most suitable for Managed Aquifer Recharge;
2. Understanding the aquifers' vertical and horizontal properties;
3. Determine the hydrochemical and geohydrological characteristics of the aquifer

1.6 Approach

This study consists of three components:

1. Desktop study
2. Field work
3. Data analysis and interpretations

1.6.1 Desktop study

This includes a short review of the different methods that can be used to characterise the subsurface to determine suitable sites for MAR. Also, all previous work done in the study area that directly relates to this study is evaluated and incorporated within Chapter 2. Literature used was in the form of published and unpublished reports, local and international journal articles as well as books.

1.6.2 Research methods

This research looks at a quantitative approach to characterise the Lower Berg aquifer system in the Saldanha Bay Local Municipality to determine the most suitable sites for Managed Aquifer Recharge. The research methods included Time Domain Electromagnetic airborne geophysical surveys, infiltration tests, pumping tests and hydrochemical groundwater analysis. The Time Domain Electromagnetic surveys provided clarity on the various aquifer geological properties. Descriptions of the lithologies of the subsurface were used alongside the geophysics data to delineate layers within the aquifer unit that would support the injection or infiltration and storage of water for Managed Aquifer Recharge. Infiltration and pumping tests shed light on the horizontal and vertical hydraulic properties of the aquifer. This gave an indication of which layers were most suitable for collecting and storing water and whether injection or infiltration Managed Aquifer Recharge techniques were required. PhreeqC modelling outputs helped predict the outcome of the mixing between groundwater at Langebaan Road and Hopefield, and potential Managed Aquifer Recharge water resources which included the West Coast District Municipal pipeline, the Vredenburg Wastewater Treatment Plant and the Berg River excess water collected at the Misverstand Dam.

1.6.3 Data Interpretation

A combination of software programmes and hydrogeological principles was used to analyse field data. The software included mainly AQTESOLV Pro for the saturated infiltration analysis and constant discharge tests, as well as Phreeqc for the groundwater/source water mixing models. The TDEM data was analysed by looking at the basic principles of electromagnetic surveys in which the different conductivities of aquifer materials were established. Other means of data analysis, such as the static water leaching analysis were determined using the percolation column method (1314) as set out by U.S.EPA, and the unsaturated zone infiltration analysis, which was done using numerical models. Lastly, credited labs Vinlab H_20 and Aquatico carried out all the hydrochemical analyses of both the groundwater and source water using both the colormetric method and the Elements Inductively Coupled Plasma (ICP-OES) method.

1.7 Thesis Scope and Structure

1.7.1 Scope of Research

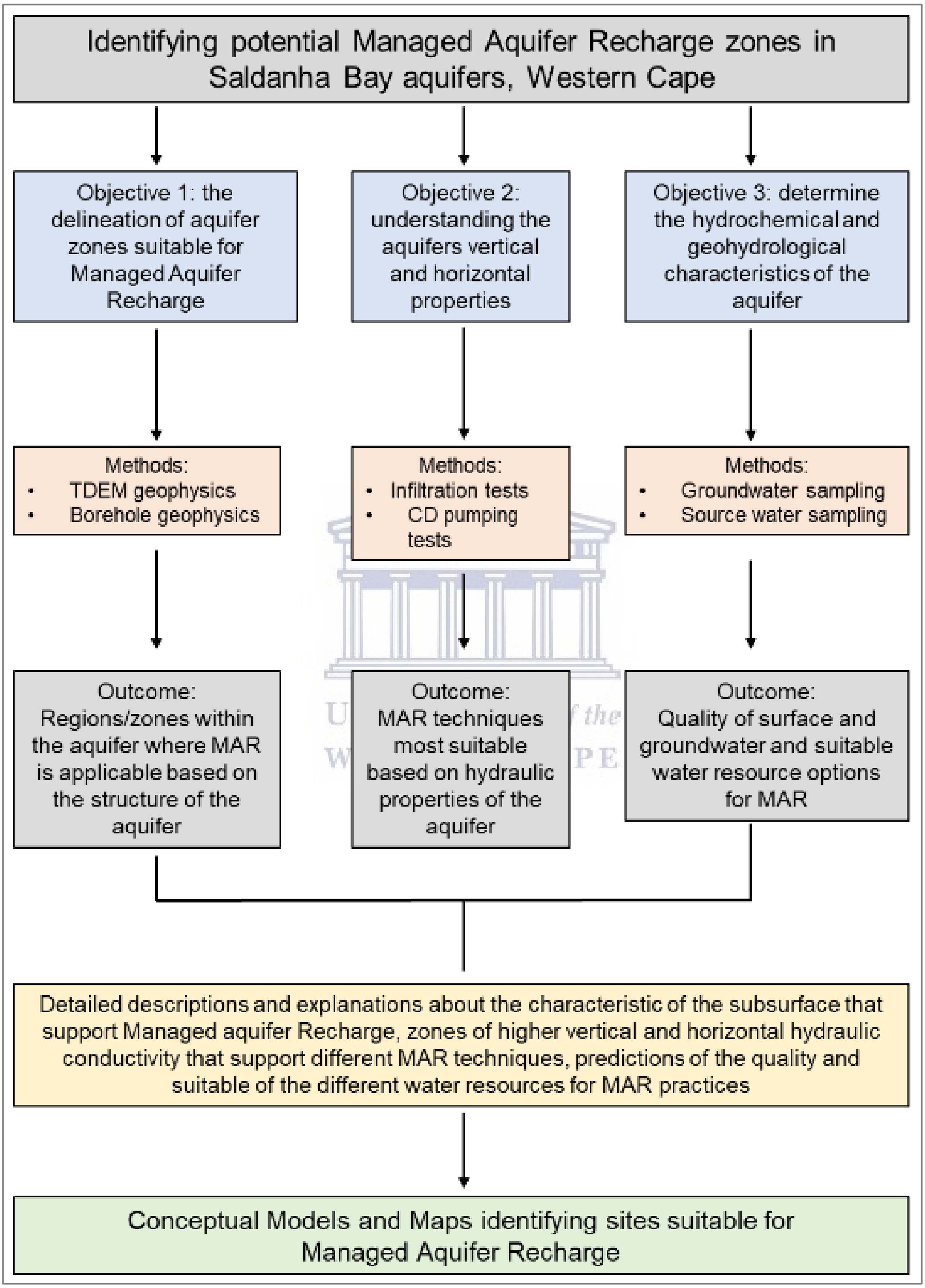


Figure 1-1: Thesis Scope of the Managed Aquifer Recharge Study

1.7.2 Thesis Structure

Chapter 1 forms a general introduction to the study. It includes the significance of the study, the aims of the study and the three objectives outlined to meet the aim of the study. It also includes an overview of the methodology used throughout the study.

Chapter 2 comprises a detailed literature review of what is Managed Aquifer Recharge (MAR), the different types of MAR and what factors are required for MAR. It also looks at the basic underlying hydrogeological principles that relate to this study. It further evaluates the various methods used to characterise an aquifer and the previous work done in the study area to characterise the aquifer.

Chapter 3 provides a detailed description of the study area which includes the location, drainage system, climate, geology and geohydrology of the area.

Chapter 4 focuses on the methodology and data analysis used in achieving the objectives of this study, as set out in Chapter 1. In situ field methods include time-domain electromagnetic (TDEM) airborne, borehole (down-the-hole) geophysics, infiltration tests, constant discharge tests and source water/groundwater sampling. The data analysis focuses on the most practical steps taken to understand and draw conclusions from the field data. Secondary data on static water leaching tests and the Langebaan road and Hopefield wellfield pumping tests were also evaluated as part of this research and supplemented the findings of this research.

Chapter 5 displays the results obtained during this research investigation as well as provides an in-depth discussion of these results. Each of these results speaks directly to the aim of this research study and addresses each objective. A final map and table illustrating which regions within Saldanha Bay Local Municipality support Managed Aquifer Recharge can be found in Chapter 5 along with a general discussion of these findings. The different MAR techniques best suited for these regions will be identified along with the best-suited water resource for MAR within the study area.

Chapter 6 is a conclusion of all the findings and final statements of this study. It highlights the sites selected for Managed Aquifer Recharge and includes the recharge techniques best suited for each site.

Chapter 7 list the recommendations for future Managed Aquifer Recharge studies based on the findings of this study.

2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review of relevant international and local literature assessing the feasibility of Managed Aquifer Recharge (MAR) in a coastal aquifer system. More specifically, it investigates the basic concepts of MAR and identifies the criteria used to evaluate the MAR site selection process. Additionally, this chapter highlights critical hydrological investigations required to carry out a Managed Aquifer Recharge study focusing on important principles behind the hydrogeological investigations used to identify sites suitable for MAR.

2.2 Managed Aquifer Recharge

Managed Aquifer Recharge is another term for Artificial Recharge (Dillon, 2005) and focuses on the replenishment of aquifers within arid and semi-arid regions that have limited surface water supply (Tzoraki et al. 2018). Managed Aquifer Recharge is implemented to provide a large storage capacity of captured excess water, be it seasonally or intermittently, for use while possibly improving the quality of that water. MAR systems are planned systems where surface water is put on or in the ground for infiltration and percolation through an aquifer to augment the groundwater resources. Bouwer (2002) and Daher et al. (2011) found that Managed Aquifer Recharge is also utilized for the purification of water by the cycling process through the subsurface using surface infiltration ponds, the mitigations of the impacts of floods by storing the excess water, and the mitigation of potential saltwater intrusions in coastal areas due to the depletion of coastal aquifers.

Managed Aquifer Recharge can be broadly classified into two main groups, indirect and direct recharge methods. Indirect methods of aquifer recharge require that groundwater abstraction needs to occur as close as practically possible to areas of natural discharge (Murray and Tredoux, 1998). Direct methods of aquifer recharge refer to methods whereby water is conveyed to a site to be placed into the unsaturated zone through mechanisms such as well injection and surface infiltration basins (Murray and Tredoux, 1998). Selecting the most appropriate approach will depend on the characteristics of the aquifer, in particular, whether it is confined or unconfined. There is a range of options for aquifer recharge (**Figure 2-1**), however; this study will focus on direct MAR techniques including infiltration galleries, infiltration ponds/basins and borehole injections.

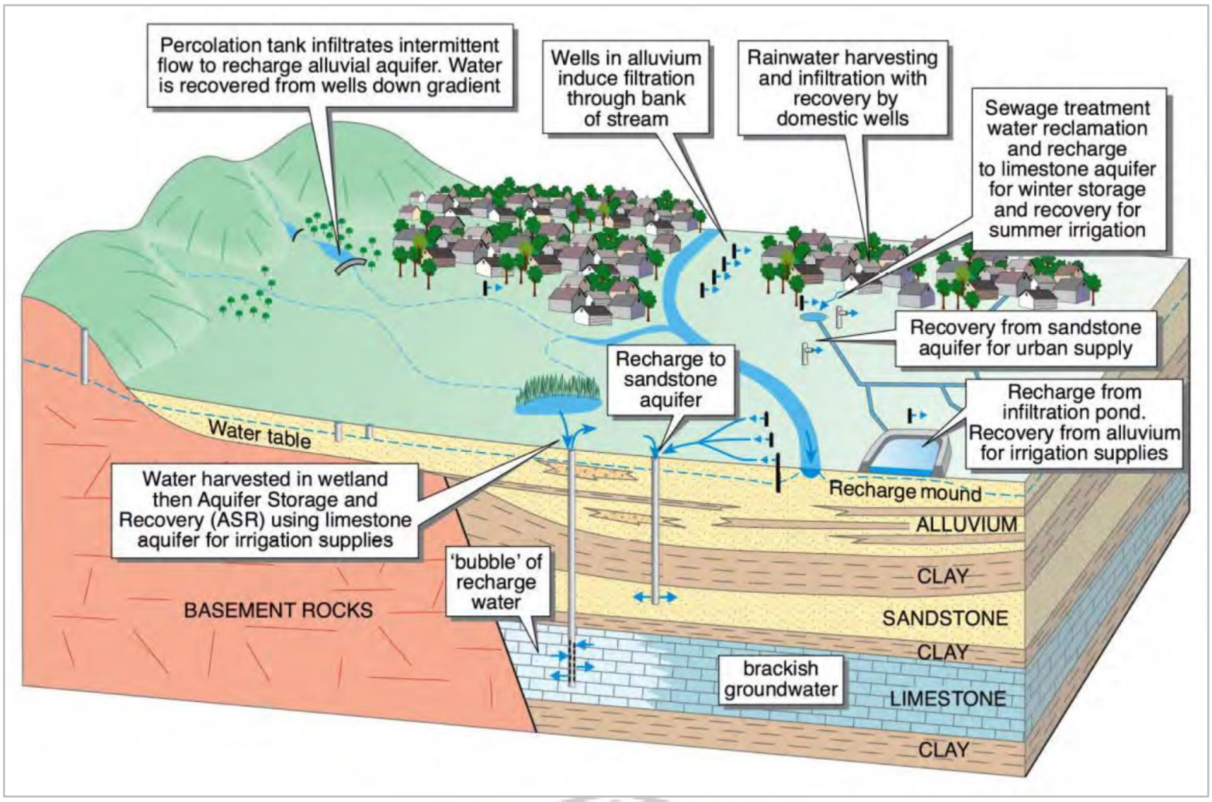


Figure 2-1: Schematic overview of MAR techniques after Dillon et al. (2009).

Managed Aquifer Recharge is not a new concept. Dating back centuries, the nomads of the Kara Kum Plain desert in Turkmenistan have enhanced natural recharge by diverting surface runoff from clay-rich areas to pits dug into porous sandy areas using trenches (Braune and Israel, 2021). At Mt Gambier in Australia, surface runoff has been diverted into limestone pits and wells for over a hundred years. The scheme is still an integral part of the city's water supply system (Braune and Israel, 2021). Although MAR is practised throughout the world, much of the literature is sourced in Europe, the USA and Australia. The successful application of borehole injection MAR in Australia and the USA over the past 40 years has resulted in increased levels of public acceptance. Several applications in Australia have shown that Aquifer Storage and Recovery (ASR) is capable of producing water of drinking quality standards (Dillon et al. 2009).

Countries such as India, Pakistan, Kuwait, Japan, Namibia and many others, have contributed to the international pool of knowledge in varying degrees, usually, but not exclusively, with well-documented case studies. A series of examples from India and Australia was shown in Dillon et al. (2009), which illustrated coupling MAR with demand management to achieve groundwater supplies with aquifer storage. India leads the world in recharge enhancement with unconfined aquifers through infiltration techniques to help sustain groundwater supplies predominantly for agriculture. This volume or recharge does not keep up with groundwater storage depletion in northern India but does help to prolong groundwater resources and allow a window of opportunity for adaptive management (Arshad et al. 2015).

The USA has a long history of both infiltration and injection schemes. The aquifers generally used for storage are confined, have a relatively impermeable layer above them, and the injection boreholes are drilled through the confined layer into the most porous and permeable parts of the lower aquifer. The Kerrville, Texas borehole injection scheme was an effective MAR approach, using treated surface water, that met the seasonal and long-term water security needs of the town. Before the implementation of this scheme, groundwater levels had dropped by 100 m due to over-abstraction from this sandstone and conglomerate aquifer. The hydraulic parameters of the aquifer were comparable with South African sandstone aquifers, although the Kerrville sandstones have primary porosity, whereas most South African sandstones only have secondary (fracture) porosity.

More locally, a pilot MAR investigation was carried out in the semi-arid central highlands of Windhoek, Namibia by Murray and Tredoux (2002). Windhoek's MAR scheme was of interest as it involved large-scale borehole injection and recovery in a highly complex, faulted and fractured quartzite and schist rock aquifer. Before this scheme, MAR had not been practised anywhere in the world at a large scale in complex geological environments, as the risk of losing water was considered too high (Braune and Israel, 2021).

The purpose of Murray and Tredoux's (2002) pilot investigation was to test Managed Aquifer Recharge concepts in secondary aquifers using the city's water supply (pumped from municipal boreholes) as the source water for injection. During these tests, treated surface water was injected via deep boreholes into permeable parts of the aquifer for storage and used when needed. They found that the injection of water had a measurable effect on the water levels in the Windhoek aquifer. This was confirmed by a significant rise in water level several metres from the injection boreholes. They also found that boreholes closer to the main area of natural recharge (Auas Mountains) and further from the area of natural discharge, from the Windhoek aquifer, are more favourable for MAR applications.

By 2011, the success of the pilot scheme led to the expansion of the MAR scheme resulting in a large-scale deep borehole injection and recovery scheme in Windhoek, Namibia to maximize the use of the aquifer's available storage. When fully developed, it is expected that the city's water reserves will be able to provide security for three years as the sole water resource during drought conditions (Murray et al. 2018).

Another example of a successful MAR scheme, as discussed by Murray and Tredoux (2002), is the Kharkams MAR scheme situated in Namaqualand, South Africa. With this scheme, excess river water during flooding events was injected into boreholes as part of the small-scale MAR scheme to replenish the aquifer under immense stress from over-abstraction. A sand filter was used to trap sediments from the river before it entered the borehole, as a way to mitigate the process of clogging. Murray and Tredoux (2002) also found that the effects of MAR allowed for the improvement of the aquifer system as the more water that was injected into the aquifer, the more the salinity of the aquifer decreased and the longer it remained at shallower levels. It did not, however, fully remediate the aquifer as fluoride levels remained above the recommended levels.

2.2.1 Risks associated with Managed Aquifer Recharge

Clogging is the reduction in permeability in porous media and is a technical risk associated with Managed Aquifer Recharge (Martin, 2013). Borehole clogging during MAR activities results in a decrease in the rate of recharge of water. Clogging also negatively impacts the recovery of the recharged water as it increases drawdown during pumping.

The main types and processes responsible for clogging include:

- Physical clogging: the deposition and build-up of suspended solids from the recharged water. These solids build up on the borehole screen, gravel pack or on the wall of the borehole which decreases the rate of recharge (Murray and Tredoux, 1998).
- Mechanical clogging: in infiltration basins, the air within the unsaturated zone has the potential to get trapped during MAR, reducing the infiltration and storage capacity (Martin, 2013). During recharge via injection boreholes, air has the potential to become entrained when water freely flows into the borehole.
- Biological clogging: algal or bacterial (iron or sulphate reducing) growth within the aquifer formation or on the surface and/or down the hole equipment (Martin, 2013) and,
- Chemical clogging: chemical reactions between the recharged water, native groundwater and the aquifer material which lead to the precipitation of certain elements. These oxides then accumulate in the aquifer and on the screen thus reducing the flow of water to and from the borehole, which results in an overall loss in production capacity.

The risk of clogging is common to all operational MAR methods. Solutions to this issue include source water stabilization through settlement ponds, filtration through gravel and sand beds or accepting ongoing maintenance via bottom scraping of silts and clays. In-situ iron removal as a means of preventing iron clogging in production boreholes was investigated in Atlantis, South Africa (Robey et al. 2013). Ozone was generated on-site and was used to disinfect the water before injection back into the aquifer via boreholes. Results of the experiment showed that iron and manganese concentrations in the dissolved phase were reduced considerably, thus mitigating the effects of borehole clogging during the MAR process.

A full monograph on the management of clogging of various MAR systems is available from the International Association of Hydrogeologists (IAH) Commission on the MAR website (http://www.iah.org/recharge). This research study does not go into detail about the clogging process but rather touches on how clogging can be mitigated during certain MAR techniques.

The recovery efficiency of the stored water is another risk associated with MAR. Recovery efficiency is a concern in borehole injection schemes where the quality of the recharge water and the native groundwater differ. In the case of borehole injection systems, recovery efficiency is defined as the percentage of water volume stored that is subsequently recovered while meeting a target water quality criterion (Pyne, 1995). The water quality criteria are typically total dissolved solids (TDS), electrical conductivity (EC) and/or chloride concentration.

Another risk associated with MAR is its potential damage to aquifers. This refers to the negative effects of recharge such as the precipitation of solids, the dissolution of aquifer material and contaminants such as arsenic. Precipitation has been observed in injection boreholes schemes, evident as clogging, but has not been identified as widespread aquifer clogging. The dissolution of arsenic has been observed in several MAR schemes and needs to be assessed in the feasibility stage of most projects. Solutions to these risks would be to ensure the quality of the recharge source water and the native groundwater are similar before injection. Another solution would be the pre-treatment of the source water before injection into the aquifer (Pyne, 1995).

2.2.2 Managed Aquifer Recharge Techniques

Surface infiltration system

Infiltration methods are suitable to recharge shallow unconfined aquifers with minimal treatment. If soils are permeable and the aquifer is unconfined, infiltration basins are generally the method of choice for MAR. Infiltration basins/ponds are flat bottom areas of varying sizes, which are excavated or enclosed by dykes. To promote surface infiltration, these basins require permeable soils that allow for biochemical and microbiological reactions to take place. These reactions allow for the treatment of water as it moves through the soil matrix. Water is diverted into these basins and soaks through the unsaturated zone (**Figure 2-2**) to an underlying aquifer. The shape of these basins can be adjusted to fit the space or the terrain conditions.

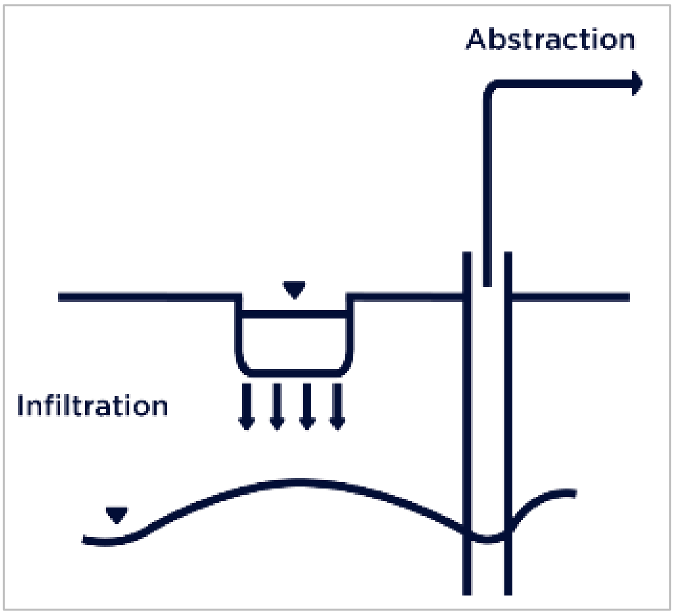


Figure 2-2: Infiltration basin/pond (Dillon, 2005)

The Burdekin Delta scheme is the oldest and largest infiltration scheme in Australia. This scheme has been operating since the mid-1960s and is largely responsible for supporting the Australian sugarcane industry. The MAR scheme consists of natural and artificial channels and recharge pits supplied with water drawn from the Burdekin River. Another example of a successful MAR infiltration basin scheme is seen at Atlantis, South Africa. The Atlantis Water supply scheme has been in operation for over 40 years and supplies (and augments) drinking water to Atlantis. The scheme uses stormwater runoff as well as treated wastewater as the source of water to recharge the aquifer through two massive infiltration basins. After some time, groundwater is abstracted and treated according to the South African drinking water standards. Industrial effluent and excess stormwater are directed to coastal recharge basins, and seep into the ocean via the subsurface, preventing saline intrusion. Rooftop rainwater and urban stormwater have been successfully used for Managed Aquifer Recharge in Australia, Germany, India, Jordan, the USA and in many locations with permeable soils, similar to the Saldanha Bay Lower Berg aquifer systems (Arshad et al. 2015).

Surface infiltration systems require the availability of permeable soils, an unsaturated zone free of undesirable chemicals and restricting layers that produce excessive perched water mounds, as well as an unconfined aquifer of sufficient transmissivity (Dillon et al. 2009). Murray and Tredoux (1998) state that the success of the entire infiltration scheme is largely dependent on the ability of the unsaturated zone to transmit water. When direct recharge is practised, the amount of water that enters the aquifer is controlled by three factors: the infiltration rate, the percolation rate, and the capacity for horizontal water movement (Huisman and Olsthoorn, 1983). The infiltration rate is the rate at which the surface layer allows the water to enter the soil and the percolation rate is the rate at which water moves downward through the soil profile. As such, investigations into the vertical and horizontal hydraulic conductivity of the aquifer are required.

An advantage of surface water infiltration ponds is the potential treatment of recharged water as it infiltrates into the unsaturated zone, thus resulting in better water quality within the aquifer. A limitation to this approach is that the land space needed for these ponds is bigger than it would be for a borehole and the exposed water is subject to evaporation and the attraction of aquatic biota (Bekele et al. 2011).

Subsurface infiltration systems

Borehole recharge methods use injection through boreholes to store water in an aquifer. The injection of treated wastewater, from sewage or stormwater, into an aquifer can also be used to recharge groundwater. Stored water can be recovered either through existing boreholes or through separate newly installed boreholes. According to Pyne (1995), and Maliva and Missimer (2010), boreholes have the advantage of targeting the desired aquifer zone for recharge. Thus, zones of saline water or clay layers (aquitards) can be bypassed.

Direct recharge via injection boreholes is generally used when:

- permeable soils and/or sufficient land area for surface infiltration basins are not available,
- unsaturated zones are not suitable for basins, ponds or trenches and,
- aquifers are deep and/or confined.

Bouwer (2002) found that aquifers under confined conditions can be directly recharged without the fear of pressure building up causing artesian wells. This was because confined aquifers accept and yield water by the expansion and compression of the aquifer itself. He also found, however, that the excessive compression of the aquifer by overpumping can cause irreversible effects. The layers most responsible for this expansion and compression were clay layers. In contrast, Tredoux and Engelbrecht (2009) found that recharging the confined aquifer at the Langebaan Road wellfield, Saldanha Bay, resulted in the formation of an artesian borehole due to high injection pressures into the confined aquifer causing the clay layer to dislodge along the seal between the confined and unconfined aquifer.

Tredoux and Engelbrecht (2009) concluded that the result of this artisan well was due to the infrastructure of the borehole coupled with too high injection pressures under the confining clay layer. As such, it is important to delineate the extent of the clay layers within the aquifer unit. If the aquifer has expanded to the maximum capacity then recharge to the confined zone will result in the loss of stored water through artesian wells. Tredoux and Engelbrecht (2009) also found that when they reduced the injection pressure no further leakages took place. This suggests that MAR to the confined aquifer unit should take place at reduced injection pressures, in areas where the confining clay layer is missing or when the aquifer has been sufficiently depleted.

In 1996, a study to evaluate the use of subsurface injection of water in the lower Floridan aquifer was performed. The study, near Lake Okeechobee, Florida, was designed to determine the recoverability of injected water. Several cycles of injecting water followed by abstraction were performed and as more cycles of the experiment were performed, the percentage of recoverable water increased (Quinones-Aponte et al. 1996). This suggests that as the MAR process takes place, the ability of the aquifer to expand and store water increases.

The different techniques of subsurface infiltration systems include aquifer storage and recovery and, aquifer storage transport and recovery. A basic requirement of injection boreholes is the need to treat recharge water to remove all suspended particles in order to reduce clogging of the pores at the recharge site. Inevitably, clogging will occur and periodic redevelopment will be necessary, and thus, recharge through injection wells is considerably more expensive than with infiltration basins.

Aquifer storage and recovery

Aquifer storage and recovery (ASR) is considered a subset of MAR and is an alternative approach for water storage that applies to a variety of climatic and hydrogeological characteristics (Smith et al. 2017). ASR is the process in which water is injected into a borehole and is recovered from the same borehole (**Figure 2-3**). This technique is useful when the storage of water is the primary goal (Dillon et al. 2009). As water is being injected directly into the aquifer, the quality of the source water is very important before it is injected. Bouwer (2002) explains that in the USA, source water for borehole injection must be treated to meet drinking water quality standards to minimise the clogging of the borehole and protect the quality of the water in the aquifer.

Borehole injection tests conducted at Windhoek, Namibia as part of the Windhoek Artificial Recharge study showed that filtering the recharge water through a carbon filter removed suspended materials in the water, which ensured low turbidity (<< 1 NTU) of the recharged water. Likewise, the addition of chlorine to the water after it had passed through the filter ensured that it was disinfected. This ensured the chemical compatibility of the injected water and the natural groundwater as the injected water was lower in dissolved solids than the groundwater (Murray and Tredoux, 2002).

ASR boreholes are usually used for seasonal storage of finished drinking water and/or where surface water storage is not possible. Very minimal treatment of the water is required (usually just chlorination) is required after recovery. ASR boreholes also typically store good quality raw water supplies when it is in excess to supply for a water treatment plant when the need exists. The raw water might require a bit more treatment than the drinking source water.

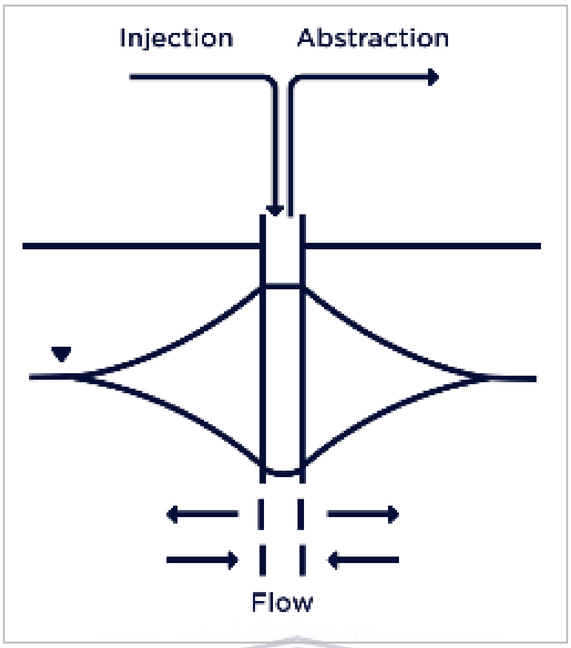


Figure 2-3: Aquifer storage and recovery (Dillon, 2005).

Aquifer storage, transport and recovery

Aquifer storage, transport and recovery (ASTR) is very similar to ASR with the exception of water being removed from a different borehole (**Figure 2-4**). This is useful when the treatment of water within the aquifer is required as this process allows for water to remain in the aquifer system for an extended residence time (Dillon et al. 2009).

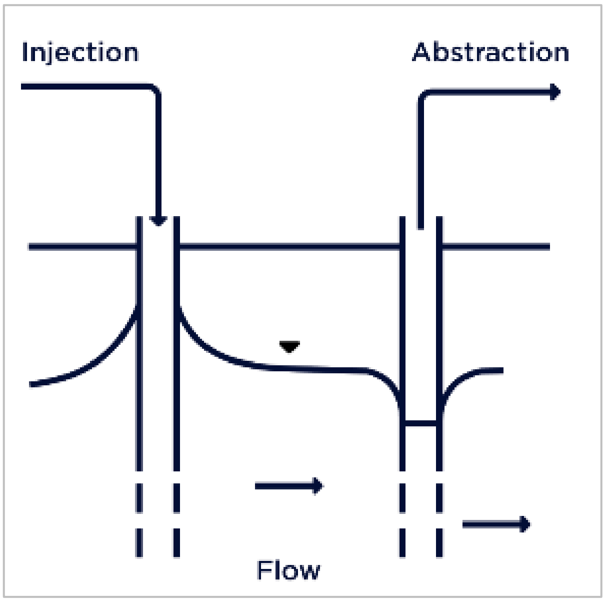


Figure 2-4: Aquifer storage transport and recovery (Dillon, 2005)

Borehole injections as an approach to MAR have advantages and limitations. The advantages of borehole injection include no loss of recharged water through evaporation, no loss of large areas of land and no attraction of mosquitoes and algae to a water body (Tzoraki et al. 2018). The limitations to this approach are that the sediment or particles within the recharged water could lead to clogging issues that reduce the soil porosity of the aquifer and, recharged water loses the potential added treatment of infiltrated water by the unsaturated zone. The main drawback to borehole injections as stated by Murray and Tredoux (1998) is that water quality requirements are usually high for borehole injections. This places emphasis on the type of water being used as the source water for the MAR scheme.

Infiltration galleries

Whenever possible, surface infiltration systems are preferred, because they offer the best opportunity for clogging control and the best soil-aquifer treatment, however, it is not always possible under certain conditions. If permeable sediments/soils occur at the ground surface or within an excavatable depth, the water can directly move into the coarse soils. However, where deeper fine-textured soil layers or clay restrict the downward movement of the water to the aquifer, a combination of injection and infiltration systems can be used.

Infiltration galleries are subsurface trenches that contain a structure and/or pipe (**Figure 2-5**). This structure is surrounded by a gravel filter layer that allows for infiltration through the vadose zone to an unconfined aquifer (Bekele et al. 2018). This approach is suitable when the treatment of water through the infiltration process is necessary but the effects of evaporation and land excavation need to be at a minimum.

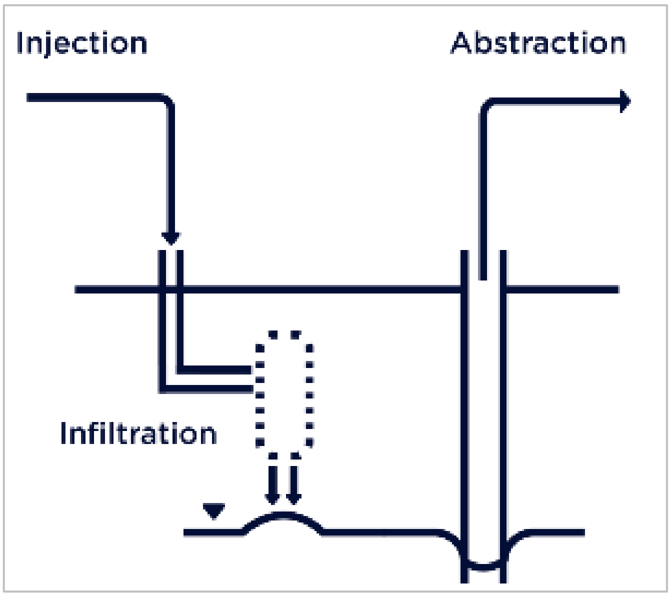


Figure 2-5: Infiltration gallery (Dillon, 2005)

Bekele et al. (2013) investigated the changes in the quality of recycled water after infiltration through a 9-metre-thick vadose zone and moving laterally through 2.3 metres of an unconfined aquifer, using infiltration galleries as the MAR method. The focus of this work was on calcareous sands and limestones and the results of this work were particular to the MAR conditions of the study. The impact of a thicker unsaturated zone, anoxic conditions, different flow rates and contact times were not investigated and could not allow for a different percentage of removal rates of each constituent.

Nonetheless, Bekele et al. (2013) found that there were water quality benefits to infiltrating secondary treated wastewater through calcareous sands and limestone of the unsaturated zone using infiltration galleries. Reductions in the average concentrations of constituents in the recycled water before and after MAR were observed, except for nitrates in the water, due to the aerobic conditions of the unsaturated zone. This means that if the removal of nitrate concentrations in the water is essential, recharged via infiltration cannot rely entirely upon processes in the vadose zone for nitrate removal.

Dillon et al. (2005, 2009), Bhattacharya (2010) and Bekele et al. (2011) all discuss other specific surface and subsurface infiltration systems which include flooding, ridge and furrows, stream channel modifications, recharge pits and seepage trenches. All these methods of MAR have some sort of infiltration mechanism that allows for the treatment of water whilst storing the water. The maintenance associated with surface and subsurface infiltration systems varies according to the techniques used. Generally, the areas in which water accumulates for surface infiltration require periodic cleaning, known as wetting and drying cycles, to reduce the clogging of suspended material.

2.3 Managed Aquifer Recharge Site Selection Criteria

The operation of a Managed Aquifer Recharge system requires a good knowledge of the involved hydrological processes. The local geological and hydrogeological settings decide if a MAR implementation can be feasible or not. The implementation of a successful MAR scheme takes into consideration many factors. These include the quality and quantity of the source water available for recharge, the aquifer structure surrounding formations; hydraulic properties of the aquifer and vadose zone, the groundwater level and unsaturated zone thickness, and the quality of both the recharged water and the native groundwater (Gale, 2005).

According to Daher et al. (2011), confined and unconfined aquifers will behave differently when being recharged. In an unconfined aquifer, the unsaturated zone needs to be thick to promote a rise in the saturated zone when being recharged. In a confined aquifer, the system's boundary conditions need to allow for the addition of water into the system by displacing the native water in the system (Daher et al. 2011). Aquifer characterisation forms a big part of this study and therefore the different approaches to aquifer characterisation, based on the criteria set out in 1.5 for the determination of suitable sites for Managed Aquifer Recharge will be looked at in more detail.

2.3.1 Water Resources Suitable for Managed Aquifer Recharge

Murray and Tredoux (1998) state that the water being used for recharge must be suitable for use after it has been abstracted from the aquifer. The source of the water being used to recharge the aquifer is important when determining where and what type of MAR scheme should be implemented. Source water for MAR purposes needs to have a consistently high quality and a predictable quality over time. Generally poorer quality source waters will need a higher level of treatment before recharge.

Sources that are usually considered for MAR include:

- municipal wastewaters;
- perennial or intermittent river flows that might/might not be regulated with dams;
- water purposely released from dams and;
- stormwater runoff, including from urban areas

Municipal wastewaters are usually of predictable quantity and quality but require significant chemical treatment before they can be considered for MAR. Wastewater is usually treated in wastewater treatment plants and then used for recharge. Since the water after treatment is in most cases still not of potable water quality, it is directed to spreading basins for further treatment. Reclaimed municipal wastewater is seen as an alternative source of water, especially for applications other than drinking, however, the main problem with this source of water is its perception by the general public. Treated wastewater has successfully been used to augment and secure groundwater supplies in Australia, Belgium, Germany, Israel, Italy, Mexico, Namibia, South Africa, Spain, and the USA (Arshad et al. 2015).

Rivers are more consistent in terms of quantity than storm runoff; however, the climate of the area will determine how continuous this source of water is. In arid areas, river flows are more variable than flows in more humid areas (Murray and Tredoux, 1998). Rivers can carry considerable quantities of suspended load which can result in clogging. Therefore, settling ponds are used before the water is led into infiltration ponds. The quality of the recharge water has to be considered when rivers or lakes are used as a potential MAR water resource as they are at risk of pollution from waste discharge.

Stormwater is a natural asset and should be regarded as an essential part of the recharge water supplies of a city (Haskins, 2012). Stormwater can vary in quantity, largely depending on the rainfall in the area. The quality can change, especially in urban areas, where stormwater can be contaminated with various sources from surface materials. If untreated water from dams or storm runoff is used as a source to recharge the aquifer, then types of MAR that have a component of infiltration should be considered.

2.3.2 Geophysical characterisation techniques

The characterization of geology within an aquifer is important in determining aquifer layers suitable for MAR (Bhattacharya, 2010) as the geological properties control the ability of groundwater to move through an aquifer system, and ultimately which formations will be most suitable to capture and store water. This information is required when implementing surface infiltration ponds, borehole injection and infiltration gallery type Managed Aquifer Recharge schemes.

Most sampling techniques for characterizing the subsurface occur by means of drilling a borehole and acquiring borehole logs. This is extremely useful in situ information as it describes geological material directly around the borehole. When the study area is large, however, or when the hydrogeology is very complex, data obtained at a point location may not be enough to characterise the whole area. The integration of both direct borehole measurements, as well as spatially extensive data, is a way to improve the subsurface characterisation of an area.

Geophysics is an application used in many earth exploration systems, with a particular focus on the investigation of groundwater resources. The purpose of undergoing a geophysical survey is to assess the physical and chemical properties of the subsurface from measurements made at the surface of the earth (Weight, 2008). Geophysical methods can be used for geological characterisation in terms of the thickness of strata or the presence of palaeo structures (USEPA, 1993). Geophysical methods are used in conjunction with descriptions of geological formations as well as borehole logs as a means of 'ground-truthing' when interpreting the geophysics data to delineate the various geological materials that make up an aquifer unit.

A lack of contrast between different subsurface properties, such as the density of earth materials, is one limitation when doing a geophysical survey as it limits the distinction between different properties/ zones of interest in the subsurface. Similarly, when two separate features are close in proximity, it would require a specific resolution to distinguish the two (Weight, 2008). Therefore, the desired resolution needed for a specific parameter could be a limitation due to the chosen method not being able to provide that detailed resolution. Another limitation to geophysical surveys is the 'noise' or the disturbances from unwanted signals that are not a representation of a specific source (Weight, 2008). This could lead to an inaccurate reading of data.

The advantages of geophysical techniques are that they allow for an alternative approach to the widely used sample/ interpolation approach. Another advantage is that larger areas can be surveyed over a given period (Weight, 2008). USEPA (1993) also makes note of the fact that geophysical methods are typically non-destructive. The most common methods used for hydrogeological characterisation include electromagnetic, electrical resistivity and borehole logging techniques (Hubbard and Rubin, 2017).

Time Domain Electromagnetic (TDEM) soundings

Time Domain Electromagnetic (TDEM) is a geophysical sounding method based on the investigation of the electrical resistivity of rocks. Resistivity is a well-known parameter in hydro geophysics. For this research study, electrical resistivity is a well-adapted parameter because the objective is to discriminate permeable formations from more clayey formations. Hubbard and Rubin (2017) found that generally, electrical conductance is affected by moisture content where electrical conductivity is higher for saturated sediments and lower for unsaturated sediments. This means that clay-like materials will have higher electrical conductivities than sandy like materials and even more so, gravels.

In TDEM surveying, low-frequency alternating current is passed by a transmitter through a wire loop or dipole to produce a local electromagnetic field, referred to as the primary electromagnetic field, on the earth's surface. Once the primary magnetic field is established, the current is abruptly turned off creating a decreasing flux with time (Flores Avilés et al. 2020). Due to the induction principle, eddy currents then create a secondary magnetic field (with the same polarity as the primary magnetic field) also decreasing with time in the soil that is measured by a receiver coil, refer to **Figure 2-6**.

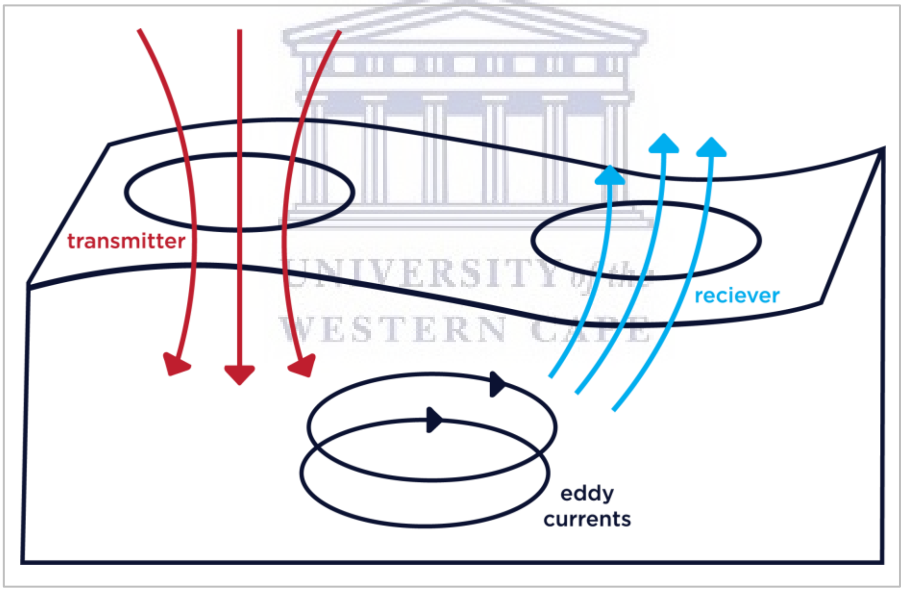


Figure 2-6: Electromagnetic surveying conceptual model (Adapted from Hubbard and Rubin, 2017)

These fields vary in amplitude, orientation and phase shift (Weight, 2008). The result (the decreasing voltage with time) is then analysed to derive the basic information given by TDEM (the variation of apparent resistivity with time). That is, earlier time measurements produce data about the shallow subsurface (<100m) (USEPA, 1993) while later time measurements give data on the deeper subsurface. The resolution of this information is governed by the coil configuration. Larger coil separations pick up electrical properties from deeper depths (Hubbard and Rubin, 2017).

TDEM surveys are being increasingly used in environmental studies for hydro geophysical applications about the investigation of the subsurface deposits in terms of their types, thicknesses and extensions (Rey et al. 2020; Basheer et al. 2014). Al-Amoush et al. (2015) successfully used TDEM geophysical investigations to identify a potential aquifer suitable for Managed Aquifer Recharge applications. He found that TDEM results produced well-resolved geological layers illustrating subsurface hydrogeological conditions as well as noted that it was possible to locate lateral changes in rock properties due to water saturation and or facies changes even at a small horizontal scale.

Similarly, Flores Avilés et al. (2020) conducted TDEM surveys investigating the different outcropping formations and groundwater flow dynamics of the Katari-Lago Menor Basin aquifer, Lake Titicaca – Bolivia. He combined in situ groundwater measurements with the results of TDEM surveying to identify hydraulic head contours and general flow paths within the groundwater system. Concerning Managed Aquifer Recharge, recharged water will enter the groundwater system and follow the natural groundwater flow of that aquifer system. As such, it is advisable to understand the natural flow path of this recharge water.

Electrical resistivity (ER) soundings

Resistivity is a measure of the ability of electrical current to move through a material. With ER, a current is injected into the subsurface using a pair of electrodes (USEPA, 1993). Currents flow from the positive to the negative electrode and how these current flow within the subsurface reflect the resistivity of the subsurface. The principle behind ER is these patterns of current flow can be deduced by measuring the variations in the potential difference (voltage) at the surface, using another pair of electrodes. Any variations in current density at the surface will lead to variations in the measured potential difference (Weight, 2008).

Similar to electromagnetic conductivity, resistivity is sensitive to moisture content. It is the inverse, however, so unsaturated sediments usually have higher resistivities than saturated sediments (Hubbard and Rubin, 2017). This suggests that sandy materials will have a higher resistivity than clay-like materials, and bedrock should have the highest resistivity.

Smith (1982) carried out a resistivity study over the coastal plain southeast of Saldanha, South Africa. His most notable find was the presence of a paleo valley that extended throughout the Langebaan Road, Hopefield and Elandsfontein area (**Figure 2-7**). The trough of sand highlighted was said to be an indication that a paleo valley was present within the Langebaan Road region. The lack of calibration boreholes drilled to bedrock was a limitation in Smith's study. Without calibration points, there could be a misinterpretation of his resistivity profiles. Smith was also unable to correctly see below the muddy, clayey layers so his interpretations of the bedrock topography need further investigation. This finding, however, suggests that the thick sands and gravels extending throughout the study area could be targeted as suitable zones for Managed Aquifer Recharge zones granted investigations into the spatial extent of the bedrock topography were carried out.

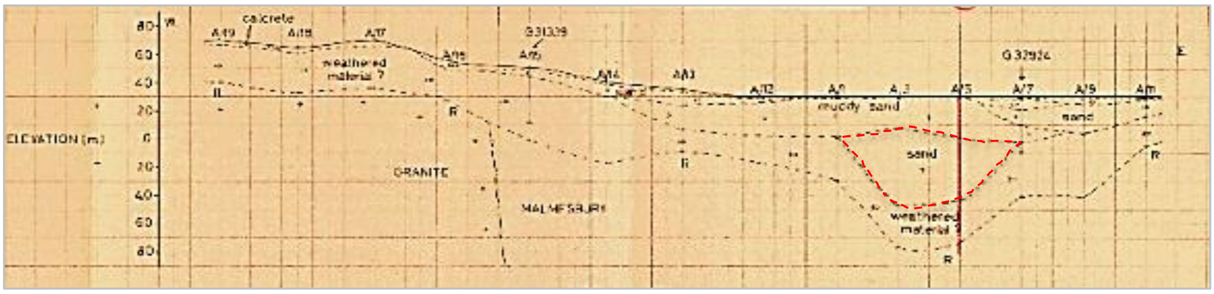


Figure 2-7: Resistivity profile line A indicates the presence of a palaeo valley in the study area, represented by a trough of sand (Smith, 1982)

Nel (2019b) carried out a resistivity survey within the Saldanha Bay Local Municipality, South Africa, that identified no lower confined aquifer unit within the aquifer system at Hopefield, rather the presence of a clay layer at the base (**Figure 2-8**). Additionally, according to drilling logs obtained from Nel (2019a) boreholes were drilled into the Hopefield wellfield through sand layers followed by a confining clay layer. HPF2-3M was drilled 150m deep into shale bedrock below the confining clay layer interbedded with fine sands and peat. Similarity HPF 2-1M and HPF 2-5M was drilled about 140m deep with no evidence of a lower aquifer below the fine sands, peaty clay layer. This leads to the assumption that there is no lower confined aquifer at Hopefield, but rather a shallow aquifer unit consisting of thick sediments from the Witzand, Langebaan, Velddrif and Varswater formation overlying shale bedrock. These findings suggested that infiltration type Managed Aquifer Recharge should be evaluated within these thick sandy sediments at Hopefield.

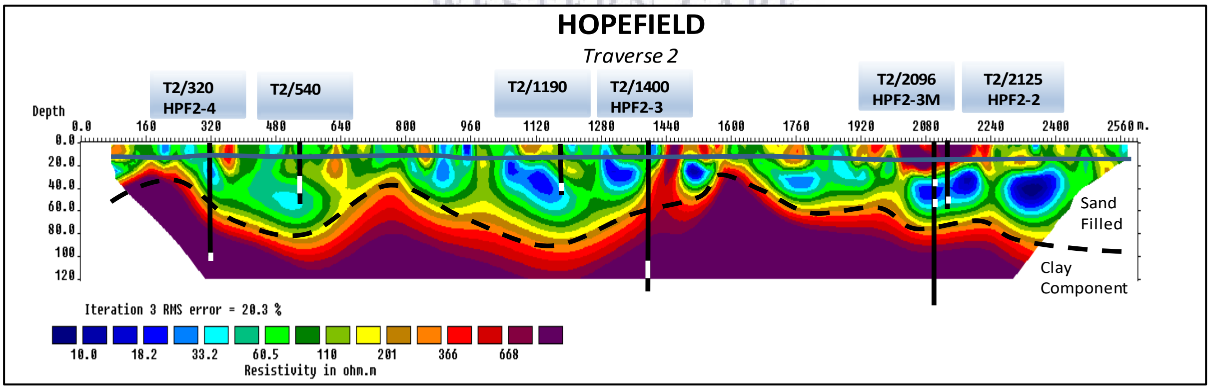


Figure 2-8: Electrical resistivity survey at Hopefield wellfield (Nel, 2019) showing thick clay layers at basement depths

Borehole geophysical methods

Borehole geophysics refers to the recording and analyzing of geophysical parameters collected within a borehole. This information can be used alone to obtain site-specific conditions of the subsurface, i.e. geophysical parameters of the subsurface, or it can be used with surface/airborne geophysical data, as mentioned above, to obtain hydrogeological information extrapolated over an entire area. Borehole measurements are taken by lowering a sonde into the borehole. A sonde is a probe which contains sensors and electronics necessary for transmitting and recording signals. The types of probes within the sonde determine the data received from the borehole. Fluid conductivity measurements are used to measure variations in salinity with a probe that records only the electrical conductivity of the borehole fluids by placing electrodes inside a protective housing. Similarly, a sonde can be equipped to measure fluid temperature with a temperature probe that records temperature or the rate of change in temperature with depth (USEPA, 1993).

Both Baumgarten et al. (2014) and Coianiz et al. (2019) used downhole logs to identify lithological units and their borders, as well as interpret the lithological properties and their links to sediment characteristics. Baumgarten et al. (2014) used an array of downhole log data such as spectral gamma rays, including the spectral components, magnetic susceptibility, resistivity, borehole diameter, seismic velocity and the temperature and salinity of the drill mud. He used a cluster analysis to identify a set of log responses to characterise a continuous lithological unit and allow classification from other lithological units. He found he was able to distinguish different lithological units by grouping them based on similarities in their physical and chemical properties.

Similarly, Coianiz et al. (2019) successfully used downhole logs to infer different depositional sequences related to changing lake levels and the related processes controlling their formation at the Dead Sea basin, Jordan. She found that it was possible to identify key lithological boundaries and discern between three sedimentary stacking patterns within the lake.

Geophysical logging is advantageous as it can record subsurface data beyond the disturbed drilled area (Keys, 1990). Both Baumgarten et al. (2014) and Coianiz et al. (2019) found that downhole logs need to be used in conjunction with drilling logs to determine the most accurate representation of the subsurface in a given area.

2.3.3 Aquifer hydraulic properties

Aquifer hydraulic properties are used to explain the ability of geological formations to store and transmit groundwater. Three objectives commonly defined for Managed Aquifer Recharge are to maximize the amount of water infiltrated, maximize the amount of water recovered, and maximize the improvement in the quality of recovered water (Arshad et al. 2015). Attaining each of the above three objectives for optimal MAR operations relies largely on how quickly water moves into and through the vadose zone (i.e. operation depends on infiltration and unsaturated flow rates).

Darcy's Law states that a volume of water that passes through a bed of sand per unit of time is dependent on the area of the bed, the thickness of the bed, the depth of ponded water on top of the bed and the hydraulic conductivity of the bed (Tindall et al. 1999), and is expressed mathematically as:

$$Q = K\frac{A\Delta H}{L}$$

Where Q = volume of water that passes through the bed or column (m^3) per unit time; K = hydraulic conductivity (m/day); A = cross-sectional area of the column (m^2); H = the difference between the head at the inlet boundary and the head at the outlet boundary (m); and L= distance (m). On a macro scale, unsaturated flow is derived from Darcy's equation which equates the flux density (the rate of water through a medium, q,) to the driving forces of flow (gravity and matric pressure).

Hydraulic conductivity (K) is a function of geological parameters and refers to the ease at which water moves through pore spaces. It is a physical parameter that has varied orders of magnitude with both Lewis et al. (2013) and Boonstra and Soppe (2017) finding it commonly ranging from 10^3 m/d in coarse gravel to 10^{-8} m/d in clay deposits. The media through which water is being transmitted must be permeable enough to allow for a greater rate of water entry into the system. Fine-grained sand to coarse-grained gravel ranging from 0.2 – 0.6 mm in thickness is the recommended soil size for recharging an aquifer (Murray and Tredoux, 1998). Therefore, the hydraulic conductivity of the aquifer system must be linked to the geological layers.

Any type of infiltration system, such as infiltration ponds or galleries, requires permeable soils in the unsaturated zone to get water into the ground to the aquifer. Freeze and Cherry (1979), Bouwer (2002), and Boonstra and Soppe (2017) listed the typical hydraulic conductivity values of various soils as clay soils (<0.1 m/day), loams (0.2 m/day), sandy loams (0.3 m/day), loamy sands (0.5 m/day), fine sands (1 m/day), medium sands (5 m/day), coarse sands >10 m/day.

Hydraulic conductivity is important for Managed Aquifer Recharge as it determines whether the water being injected into an aquifer will be accepted by the aquifer, can be stored until needed and can be extracted from the aquifer (Smith et al. 2017). According to Dillon et al. (2009) and Murray and Tredoux (1998), the grain size of soils used for MAR should typically range from fine sands to fine gravels, which relates to any hydraulic conductivity value above 1 m/day. In general, aquifers with higher hydraulic conductivities and higher storage capacity are favourable for MAR schemes compared with those of lower hydraulic conductivities and storage capacities (Murray and Tredoux, 1998).

To assess the hydraulic properties of geological formations for subsurface investigations, the permeability of the aquifer needs to be investigated. The parameters used to quantify aquifer permeabilities are transmissivity and hydraulic conductivity. Aquifer hydraulic testing is an effective way to obtain these values (Kruseman and de Ridder, 2000). Hydraulic testing includes pumping tests, recovery tests, infiltration tests and slug tests (Freeze and Cherry, 1979). The main differences between these methods are the scales at which the data is represented. Pumping tests and recovery tests allow for the investigation of aquifer properties at a larger scale compared to infiltration tests and slug test borehole point estimates of aquifer properties.

Pumping Tests

Pumping tests, also known as constant discharge tests, estimate the hydraulic properties of an aquifer by stressing the aquifer for a set amount of time and then observing the changes in the hydraulic head. Pumping tests are based on the principle that if water is being pumped from a borehole and the discharge and drawdown of the borehole are measured, these measurements can be used to determine the hydraulic properties of the aquifer using the appropriate flow equations (Kruseman and de Ridder, 2000). Pumping tests can be both constant rate and multi-rate discharge tests in which the pumping rates are controlled (Tse and Amadi, 2008). Constant rate tests are used for determining hydraulic properties, while multi-rate discharge tests are used for establishing sustainable rates at which to pump the borehole.

For both confined and unconfined aquifers, there are a certain set of conditions that are assumed when analysing constant discharge (CD) rate tests. According to Kruseman and de Ridder (2000), the methods used to interpret pump test data for confined aquifers are under the assumption that:

- the aquifer is confined,
- the aquifer has a seemingly infinite areal extent;
- the aquifer is homogeneous, isotropic, and of uniform thickness over the area;
- prior to pumping, the piezometric surface is horizontal (or nearly so) over the area;
- the aquifer is pumped at a constant discharge rate and;
- the well penetrates the entire thickness of the aquifer and thus receives water via horizontal flow.

The methods discussed to interpret pumping test data for confined aquifers include Thiems' method, Thesis's method and the Cooper Jacob method. The Thiem method (equation) follows all the assumptions set out by Kruseman and de Ridder (2000) for confined aquifers with the addition that the flow to the borehole is in a steady state. The Theis method factors in time and storativity into an equation under unsteady state flow conditions. Theis's curve fitting model is based on the assumptions set out by Kruseman and de Ridder (2000) for confined aquifers with the addition that the flow to the borehole is in an unsteady state (drawdown differences with time are not negligible and the hydraulic gradient is not constant with time). The Cooper Jacob straight-line method is based on the Theis curve fitting formula and assumes that the flow to the borehole is in an unsteady state. This method has been found suitable where the abstraction borehole itself serves as the observation borehole (Tse and Amadi, 2008).

Anomohanran and Iserhien-emekeme (2015) successfully used pumping tests using the Cooper-Jacob method to determine the properties of the aquifer in Erho, Nigeria. They found that the hydraulic properties obtained from this method were similar to hydraulic properties obtained by other researchers using other methods in the same area, which deemed the method appropriate to use in confined systems.

Similarly, the methods used to interpret pump test data for unconfined aquifers are under the assumptions that:

- the aquifer is unconfined;
- the aquifer has a seemingly infinite areal extent;
- the aquifer is homogeneous and of uniform thickness over the area that will be influenced
- before pumping, the water table is horizontal over the area that will be influenced
- the aquifer is pumped at a constant discharge rate and;
- the well penetrates the entire aquifer and thus receives water from the entire saturated thickness of the aquifer

The methods discussed to interpret pumping test data for unconfined aquifers include Neuman's curve fitting method and the Thiem-Dupuit method. Neuman's curve fitting method can be applied following the assumptions set out by Kruseman and de Ridder (2000) for unconfined aquifers with the addition that the aquifer is isotropic or anisotropic, the flow to the borehole is in an unsteady state, there is no influence on the drawdown in the aquifer by the unsaturated zone, the monitoring borehole is screened over the entire length penetrating the full thickness of the aquifer and both the pumping and monitoring boreholes are small in diameter.

The Thiem-Dupuit can be applied following the assumptions set out by Kruseman and de Ridder (2000) for unconfined aquifers with the addition that the aquifer is isotropic and flow to the borehole is of steady state and the drawdown induced by pumping activities are significantly smaller than the saturated thickness of the aquifer. Recent pumping test data analytical software, such as AQTESOLV, apply the Cooper-Jacob method to both confined and unconfined aquifers following their respective set of assumptions.

Weaver and Fraser (1998) conducted four aquifer tests on the production boreholes drilled into the lower aquifer at Langebaan Road, South Africa, which according to Roberts et al. (2011), coincides with the Elandsfontyn medium to coarse sand and gravel formation. These consisted of a series of step drawdown, constant discharge rate and recovery tests. The data was interpreted using the Jacob and Theis recovery method to determine a range of transmissivities and subsequent hydraulic conductivities.

Weaver and Fraser (1998) found that the transmissivities in the aquifer in the region ranged between 700 and 1100 m2/day. With the assumed aquifer thickness being approximately 40m the hydraulic conductivity of the sands and gravels would range around 14 to 33 m/day. This is typical for the medium to coarse sands and is considered high hydraulic conductivity.

Similarly, Nel (2018) conducted aquifer tests on the newly drilled production boreholes drilled into the lower aquifer at Langebaan Road. These also consisted of a series of step drawdown, constant discharge rate (72 hours) and recovery tests. Using Cooper-Jacob and Theis curve fitting methods the hydraulic conductivity values for the sand and gravel layers range from 12 – 62 m/day (**Table 2-1**). This is typical for the medium to coarse sand and is considered high hydraulic conductivity.

Table 2-1: Hydraulic parameters of the Langebaan Road new production holes

Pumping borehole	Transmissivity (m²/d)		Saturated thickness (b)	Hydraulic conductivity (K) (m/day)	
	Cooper-Jacob	**Theis**		**Cooper-Jacob**	**Theis**
LRA 1B1	1583.4	2501.8	40	39.59	62.55
LRA 1B2	712.5	374.4	30	23.75	12.48
LRA 1B3	26.39	24.43	40	0.66	0.61
LRA 1B4	601.3	601.3	45	13.36	13.36

In addition to Langebaan Road wellfield, Nel (2019) conducted aquifer tests on the production boreholes drilled into the shallow unconfined aquifer at Hopefield wellfield, South Africa, which according to Roberts et al. (2011), coincides with the Varswater rounded fine to medium quartzes sand member formation. These consisted of a series of step drawdown, constant discharge rate (72 hours) and recovery tests. Using Cooper and Jacob and Theis curve fitting methods the hydraulic conductivity values for Hopefield wellfield ranged from 0 – 3 m/day (**Table 2-2**). This is typical for this type of sedimentology (fine sands).

Table 2-2: Hydraulic parameters of Hopefield wellfield

Pumping borehole	Transmissivity (m²/d)	Saturated thickness (b)	Hydraulic conductivity (K) (m/day)
HPF2-2	33.25	63	0.53
HPF2-5	120.7	60	2.01
HPF2-6	142.9	55	2.60
HPF2-7	50.25	72	0.70

Pumping borehole	Transmissivity (m^2/d)	Saturated thickness (b)	Hydraulic conductivity (K) (m/day)
T2-540	80.31	53	1.52
T2-1190	38.39	48	0.80
T3W-1510	52.78	55	0.96
T4-2240	194.5	60	3.24
TB-2150	36.42	55	0.66
TA-1850	29.06	48	0.61

Timmerman (1985) did constant rate and recovery tests within the coarse sands and gravels of the Elandsfontyn formation and one borehole in the sands of the Varswater formation within Saldanha Bay Local Municipality, Western Cape. From this, he concluded that the Elandsfontyn formation has a wide range of hydraulic conductivities (2- 69 m/day) depending on the sedimentology. That is, the finer the sediment the lower the hydraulic conductivity. The storativity values he obtained from these pumping tests were considered high for the confined conditions of the Elandsfontyn formation.

Timmerman's (1985) test done within the Varswater quartzose sands showed that this formation has a lower hydraulic conductivity of 2.24 m/day due to the local fineness of the sediments. His constant discharge test data shows that a relatively high yield could be maintained from this zone because of the great saturated thickness of the aquifer section.

Infiltration Tests

Infiltration is the process of the downward flow of water as it moves into the soil (Horton, 1933). Johnson (1963) found that the amount of water that can infiltrate the soil is dependent on various characteristics such as soil type and structure, soil moisture distribution, and the creation of macropores from vegetation and wildlife. He also found that the infiltration rate is most often controlled by the least permeable zone. Field methods used to determine infiltration, or infiltration rate include flooding basins, ring infiltrometers, or sprinkling/rain simulation (Johnson, 1963). In addition to these infiltration instruments, tension infiltrometers and near-surface infiltration instruments such as mink disk infiltrometers and the Guelph Permeameter may be used to determine field saturated hydraulic conductivity and infiltration rates. This research focuses on measuring soil hydraulic conductivity using a mini disk infiltrometer.

A mini disk infiltrometer is a tension infiltrometer that measures the unsaturated hydraulic conductivity of the medium it is placed on at different applied tensions using the Mariotte principle. Tension disc infiltrometers allow measurements of infiltration with a constant and small negative pressure head at the soil surface and have been extensively used to measure the near-saturated hydraulic conductivity and sorptivity. If the level of water remains constant and the amount required to maintain that level is measured, it is a constant head test. If the head pressure is not constant it is a falling head test and the variable head pressure of the water column allows for error in the measurements. Research has shown that infiltration rates for different types of soil differ under these two methods (Wu et al. 1997). Infiltration rates are reportedly underestimated on coarse-textured soils using the falling head test. However, not much difference was observed on fine-textured soils using both falling and constant head tests (Wu et al. 1997). As such, constant head tests are suitable to determine infiltration on sandy soils.

A number of methods are available for measuring soil hydraulic conductivity with a disk infiltrometer. Xue et al. (2004) along with Decagon Devices (2016) suggest using the method proposed by Zhang (1997) to determine the hydraulic conductivity of the unsaturated soil. The method requires measuring cumulative infiltration vs. time and fitting the results to compute the hydraulic conductivity of the soil.

Hu et al. (2008) investigated the structure of spatial variability of soil surface hydraulic properties on steep slopes in the Loess Plateau of China using the Mini Disk Infiltrometer under multiple pressure heads. Hydraulic conductivities were found to be moderately variable under different pressure heads yet decreased variability was seen when pressure heads decreased. Soil structure and texture were the main factors that controlled the variation of hydraulic conductivities. He also found that in the direction of the slope, hydraulic conductivities under all pressure heads overall decreased.

2.3.4 Water quality

Information on the geochemistry of the groundwater and the aquifer rock is important for successful Managed Aquifer Recharge schemes dealing with surface infiltration ponds and borehole injections (Daher et al. 2011). Risks associated with many Managed Aquifer Recharge systems primarily originate from the quality of the source water. Predicting and managing MAR water quality can be challenging as the recharged water may interact with both the native groundwater and the aquifer rock via physical, chemical and biological processes. Contrasting water quality between injected source water and native groundwater gives prospects for geochemical reactions that result in precipitation and dissolution of minerals, and changes in the quality of the recovered water (Dillon et al. 2006; Murray and Tredoux, 1998). This suggests that investigations into the mixing of recharged water and native groundwater need to take place when trying to understand how the aquifer will respond to particular MAR applications.

For assessing the water quality aspects of a MAR scheme, three types of risks associated with the aquifer, need to be evaluated (Arshad et al. 2015):

- quality of the recharge water (evaluated in section 2.3.1);
- interaction of recharge water with aquifer rock; and
- quality of the native groundwater and its influence while mixing the two waters

Ruiz-Pico et al. (2019) conducted a hydrological characterization of groundwater in the Loja Basin, Ecuador, to determine the hydrochemical characteristics of the groundwater in the region, and to understand the state of the groundwater. He collected in situ information on the pH, temperature and conductivity of the groundwater as well as collected samples for further analysis with accredited labs. Ruiz-Pico et al. (2019) found that the chemical composition of groundwater is controlled by factors such as the lithology, the weathering and dissolution of minerals, the precipitation of minerals, residence time in the aquifer and/or ion exchange. Additionally, he found that the presence of highly soluble rocks and minerals such as evaporites and carbonates can generate variations in the concentrations of ions such as sodium (Na^{+}), magnesium (Mg^{2+}) and calcium (Ca^{2}). His interpretations of data using bivariate diagrams of the major ions or elementary ratios provided clear evidence of the relationship between the chemical composition of groundwater and the lithology of the basin.

Jeelani et al. (2014) carried out a similar study in the Kashmir Valley in India and found that lithology was a dominant factor in controlling groundwater chemistry. Jeelani et al. (2014) further noted that most of the major ions were high in shallow groundwater aquifers (except Mg, HCO_3 and Fe) and attributed this to lithogenic and anthropogenic activities as the shallow groundwater is more prone and vulnerable to contamination. The lower concentration of major ions in the deeper aquifer indicated that the source of major ions is solely lithogenic in deeper aquifers, which are naturally more protected from contamination by anthropogenic activities. Several other studies (Belkhiri et al. 2012; Pazand et al. 2018; Qu et al. 2019) on the hydrochemical processes and assessment of groundwater show similar results.

Murray and Tredoux (2002) used treated municipal water as the source water for their Managed Aquifer Recharge pilot study in Windhoek, Namibia. They found that the municipal source water was highly compatible with the groundwater as the injected water was lower in total dissolved solids (TDS) than the groundwater, particularly in the case of calcium. The injection water diluted the natural groundwater and, therefore, shifted the calcium carbonate equilibrium, reducing the precipitation potential thus mitigating the effects of chemical borehole clogging.

Geochemical modelling code PHREEQC has been widely applied in many hydrogeological investigations and has proven to be reliable in simulating the outcome of mixing different sources of water and determining the possible hydrogeochemical processes that are likely to be influencing the groundwater chemistry of different environments. PHREEQC is designed to determine the possible final speciation of solutions in batch mode when mixed. The mixing proportions of the initial solutions are calculated in the modelling process in combination with phase mole transfers. The Saturation Indices (SI) are estimated for each mineral as:

$$SI = logIAP - logK(T)$$

Where IAP is the Ionic Activity Product and K is the equilibrium constant of the reaction at temperature T. An uncertainty limit must be specified by the user for each component (Tzoraki et al. 2018).

Manoj et al. (2019) used PHREEQC to model the temporal changes in the interaction between surface water and the groundwater in a uranium mineralised region within the Bhima Basin, India. Webster (2019) effectively used PHREEQC to model the chemical composition of groundwater in the brackish-water zone as mixtures of end-member solutions, comparing his results with samples from the monitoring wells located across the brackish-water zone. Webster (2019) also took into consideration that geochemical reactions between groundwater and host rock took place.

Johnson et al. (2019) successfully used PHREEQC to simulate the mixing of tailings leachate from the Elandsfontein Phosphate Mine, South Africa, with the native groundwater downstream of the mine. He simulated mixing scenarios whereby 2% - 20% of tailings leachate recharged the groundwater (i.e. 2% recharge from tailing with 98% groundwater). This study will adopt the above-mentioned method to simulate the interaction between recharge source water and native groundwater at different recharge percentages during the Managed Aquifer Recharge process, taking into consideration the influence of lithology on the final chemical composition of groundwater.

3 DESCRIPTION OF STUDY AREA

3.1 Introduction

This chapter describes the physiographic attributes of the study area and focuses on the locality, topography, climate, geology and geohydrology at the Langebaan Road wellfield, Hopefield wellfield and surrounding regions. These factors control the conditions needed for Managed Aquifer Recharge such as whether the geology in a certain area will allow for the movement and storing of water. In this way, physiographic, geological and geohydrological information will play an important role in forming a conceptual model of the study area.

3.2 Managed Aquifer Recharge Study Locality and Physiography

The study area falls within the boundaries of the West Coast District Municipality. The major towns focused on in the local area are Vredenburg, Saldanha, Hopefield, Langebaan and Langebaan Road. This study focuses on the Langebaan Road and Hopefield wellfield and surrounding areas and is situated within quaternary catchment G10M.

The Langebaan Road and Hopefield wellfields are situated between Vredenburg, Hopefield and Langebaan. They are bordered by Saldanha Bay to the west, the Elandsfontein Phosphate Mine to the south and the Berg River to the northeast. The Langebaan Road wellfield is situated next to the Langebaan Road Air Force base and the Hopefield wellfield is situated just west of Hopefield (**Figure 3-1**). The West Coast District Municipality has various pipelines that transport municipal drinking water throughout the area.

According to the national land use mapping classification (NLC 2000, cited in DWAF, 2008), scrublands, fynbos and cultivated land for farming dominate the land use in the study area, along with the industrial areas found in Saldanha, Langebaan, Velddrif and Hopefield. Most of the agricultural activities had been limited to dryland farming, with a lack of large-scale irrigation. Groundwater abstraction in the Langebaan Road aquifer is limited to domestic use and stock watering purposes. An open-pit Phosphate Mine known as the Elandsfontein Phosphate Mine is also located within the study area (**Figure 3-1**), just southwest of the Hopefield wellfield.

The topography of the study area is variable and encompasses a variety of landscape zones, i.e., floodplains, coastline, lagoon, etc. The highest parts of the area are in the east around Hopefield with a height of about 100 m, with a levelling off towards the Berg River in the north and the coast in the west. Otherwise, the regional topography is generally flat to slightly undulating, with a lack of relief features (Timmerman, 1985).

The Atlantic Ocean encircles the study area to the north and west side. The perennial Berg River, with its tributaries, the Sout, Groen, Brak and Kuilders Rivers, is the most significant river within the region and is located along the north-eastern boundary of the study area. Its flow is derived from the Drakenstein and Franschoek Mountains and drains northwards into the Atlantic Ocean at St Helena Bay as well as towards Velddrif and Laaiplek. The lower course of the Berg River around the study area is situated at an altitude of approximately 4m above sea level and is subjected to tidal influence.

The Groen and Sout non-perennial rivers and their tributaries are situated towards the eastern border of the study area and drain northwards into the Berg River (Timmerman, 1985).

Groundwater in the study area is said to move from an area of higher elevation west of Hopefield in a semi radial direction towards Langebaan Road. The groundwater then splits into paths flowing northwest discharging into Saldanha Bay, southwest towards Langebaan lagoon and north towards the Berg River (Timmerman, 1985). The flow in the Langebaan Road deeper aquifer unit is controlled by the basement topography and where the gravels of the Elandsfontyn formation are deposited allowing for flow towards the coastline.

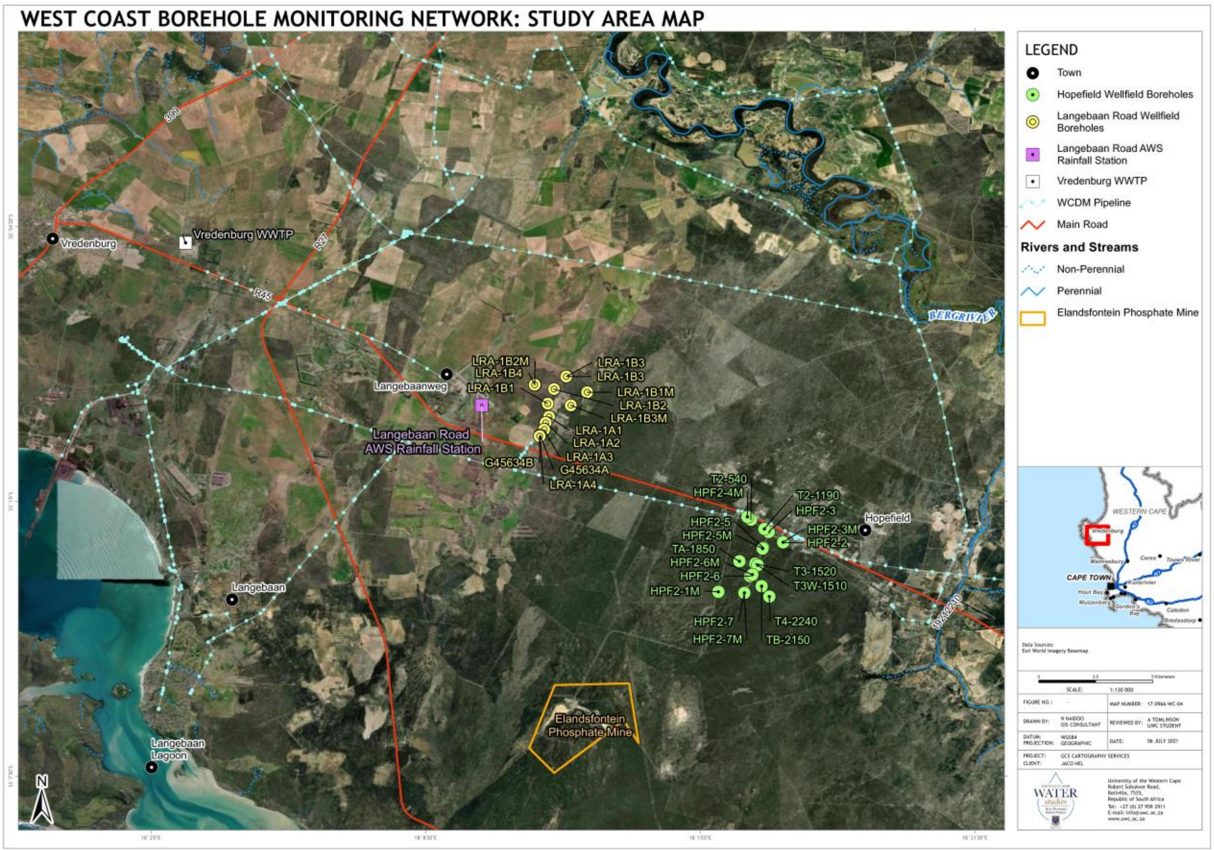


Figure 3-1: Managed Aquifer Recharge site selection study area.

3.3 Climate

The study area experiences a semi-arid Mediterranean climate, with rainfall occurring predominantly in winter (May to August). It is considered semi-arid as evaporation exceeds rainfall, with June being the wettest month in 2019 and August being the wettest month in 2020 (**Figure 3-2**). Rainfall over the West Coast is cyclonic extending over a few days with significant periods of clear weather in between rainfall periods. This frontal, cyclonic weather system is responsible for the characteristic cold wet winters and hot dry summers associated with the Cape (Timmerman, 1985).

Precipitation in the study area is in the form of coastal fog and low rainfall coming from the Atlantic Ocean. The Langebaanweg Automatic Weather Station (AWS) rain station is situated within the Langebaan Air Force base. According to Timmerman (1985), rainfall decreases inland from south to north and from east to west. Rainfall significantly decreased in the summer months (October – February) with the lowest recorded rainfall being 0mm in February 2020.

The temperatures of the study area are usually moderate because of its proximity to the Atlantic Ocean and the cold Benguela current. The maximum temperatures within the study area range between 20ºC and 30ºC, whilst the minimum temperatures range between 10ºC and 15ºC (**Figure 3-2**). Higher temperatures promote higher rates of evaporation. This, coupled with the significant decrease in rainfall in the summer months reiterates the need for Managed Aquifer Recharge in the dry season.

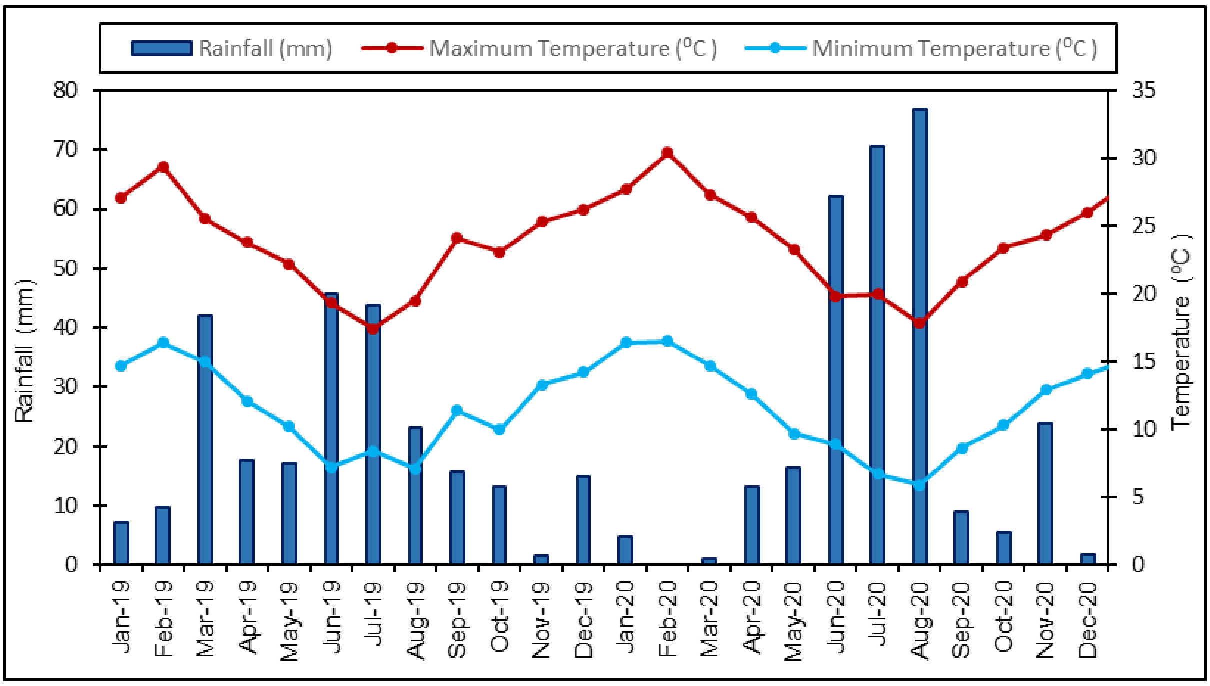


Figure 3-2: Total rainfall and temperature received at the Langebaanweg AWS rain station from January 2019 – December 2020 (SAWS)

3.4 Geology

The West Coast is underlain by discontinuous layers of late Cenozoic aeolian and marine deposits with some situated in the Precambrian basement (Roberts et al. 2011). The basement rock is dominated by Malmesbury rock, with Cape Granite intrusions occurring in certain parts along the coast. The granites form the hills and exposed rock on the coastal areas around Langebaan. The southern region of the study area is underlain by the erodible shales of the Malmesbury Group. The Berg River flows approximately parallel to and east of the regional contact between Malmesbury Group and the Cape Granite suit.

The Sandveld Group overlies the Cape Granite Suite and the Malmesbury Group basement rock in the study area. It consists of, from oldest to youngest, the Elandsfontyn Formation, the Varswater Formation, the Velddrif Formation, the Langebaan Formation, the Springfontyn Formation and the Witzand Formation. The regional geology underlying both Langebaan Road and Hopefield consists mainly of Quartzose sand, interbedded with gravels, silt, clay and peat (**Figure 3-3**).

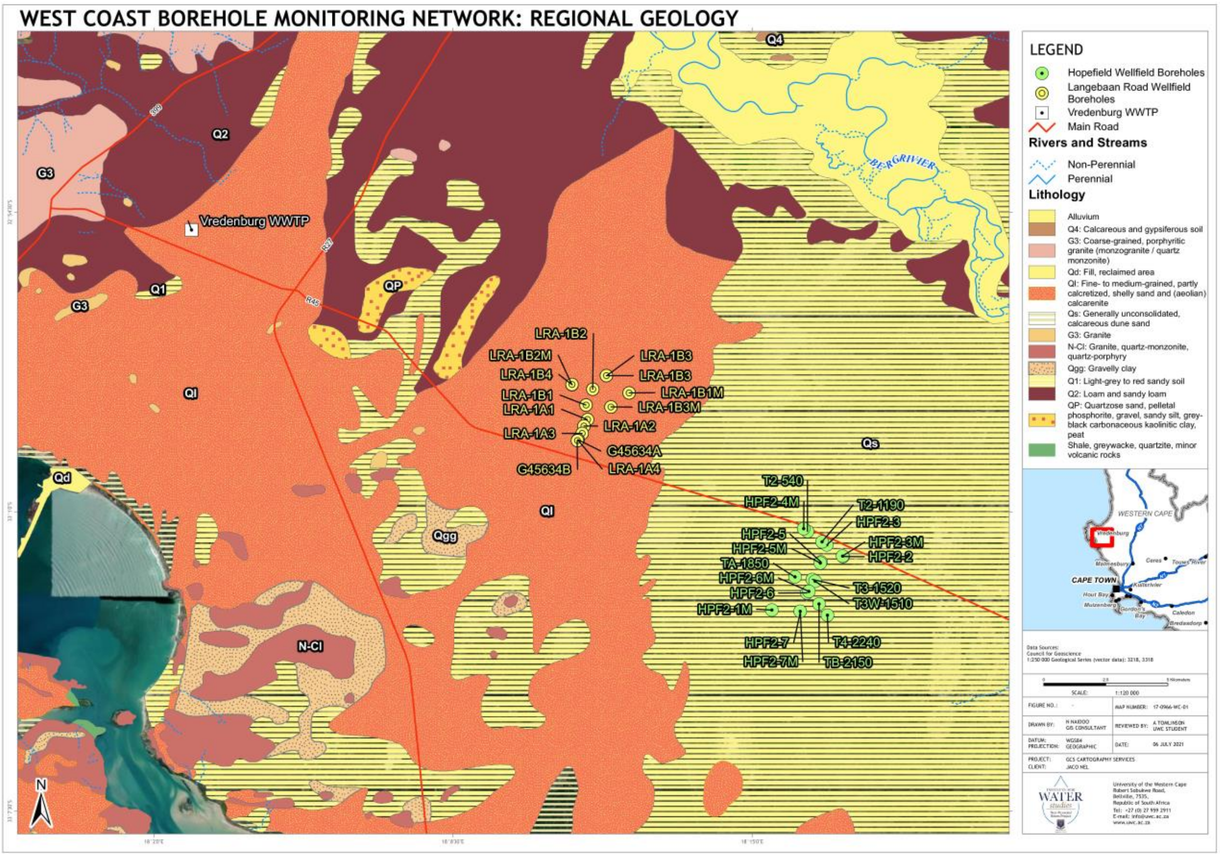


Figure 3-3: West Coast Regional Geology

The Elandsfontyn Formation comprises poorly sorted, angular, fine to coarse-grained quartzose sand and gravels, alternating with very fine-grained sand and silts. Thicknesses of up to 70m below mean sea level has been reported east of Langebaan Lagoon and between the Berg River and Elands Bay. The Elandsfontyn Formation occupies palaeo depressions, or palaeo channels, in the bedrock and conformably to unconformably overlain by the Varswater Formation (Roberts et al. 2006).

Palaeo channels are identified based on the geophysical and borehole investigations and represent the palaeo-courses where rivers used to flow. Due to the limitation of data availability, there are various opinions on certain key features of the palaeo-topography. Woodford and Fortuin (2003) described a southern palaeo channel (the Elandsfontein palaeo channel) that was continuous towards the Langebaan

Lagoon, and a northern palaeo channel (the Langebaan palaeo channel) beneath the WCDM wellfield, which was not continuous towards the Saldanha Bay. However, DWAF (2008) argued that if the palaeo channels were palaeo-courses of where rivers used to flow, they would be continuous rather than isolated depressions, and the southern and northern palaeo channels both extended to the south-west coastline. The area of the palaeo channels coincides with the thick water-bearing sedimentary sequences of Elandsfontyn Formation of Sandveld Group

The marine/ estuarine Varswater Formation attains a thickness of up to 60m (Timmerman, 1985) resting on either the Elandsfontyn Formation or the bedrock. At Langebaan Road, the Varswater Formation is informally divided up into four Members, namely the Langeenheid clayey sand Member, the Konings Vlei gravel Member, the Langeberg quartz sand Member and the Muishond Fontein pelletal phosphorite Member. The Varswater Formation is unconformably overlain by the Velddrif, Langebaan and Springfontyn Formation. The Velddrif Formation is most commonly found north of the Berg River near Velddrif. It is characterised by coarse to fine-grained shelly and pebbly sands as well as shallow marine gravels that occur along the coast in a narrow ridge.

The Langebaan Formation mainly comprises of coastal aeolianites consisting of quartzose sand and calcrete (Roberts et al. 2011). According to Johnson et al. (2006), the strata of the Langebaan Formation is well exposed on the western shores of Langebaan Lagoon. In most regions, the Langebaan Formation is commonly overlain by the Witzand Formation, but can also be unconformably overlain by the Springfontyn Formation. The Springfontyn Formation is generally classified as an informal category that accommodates the non-calcareous windblown sands and dunes. It consists of reddish to grey unconsolidated quartzose sand, which is interbedded by muddy and peaty layers (Roberts et al. 2011).

The Witzand Formation is the uppermost Formation seen over some parts of the area. It comprises aeolian fine-grained to medium-grained sand that is whitish-grey to slightly reddish in colour. This Formation is mobile and can be vegetated in certain areas. A summary of the Formations expected in the Langebaan Road and Hopefield region is displayed in **Table 3-1** below.

Table 3-1: Lithological units within the West Coast (DWAF, 2008 adapted from Roberts et al. 2006)

GROUP	FORMATION	ORIGIN		DESCRIPTION
Sandveld	Witzand	Aeolian	Shallow Aquifer	Semi consolidated fine to medium-grained calcareous, cross stratified dune sand
	Springfontyn/ Noordhoek	Aeolian		Fine to medium-grained reddish quarzitic sands, decalcified dune sand. Dominates in the coastal zone. The Noordhoek Formation consists of more peaty sands.
	Langebaan	Aeolian		Cross bedded, fine to medium-grained calcareous sandstone with calcrete (limestone) layers
	Velddrif	Marine		Shallow marine gravel and pebbly sand. Associated with the last interglacial sea-level rise with 6-7 m above the present level.
	Varswater	Marine		Deposits include a coarse basal beach gravel member, peat layers, clay beds, rounded fine to medium quartzes sand member and palatal phosphate-rich deposits. Varswater sediments do not extend further than 15 km inland of Saldanha Bay (reaching halfway to the Berg River) (Timmerman, 1985b).
	Elandsfontyn	Fluvial	Deeper Aquifer	The oldest Cenozoic deposits are the lower fluvial Elandsfontyn gravels, which occur within the deeper basement areas of the palaeo channels in the area. Coarse angular fluvial sands and gravels, deposited in several palaeo channels filling depressions. The deposits were subsequently covered by clays and peat. It is situated approximately 40m below sea level with a thickness of 40-60m (Roberts et al. 2011). The thickness of the sediments varies between 0 and 120m, with the greatest thicknesses occurring between Langebaan Lagoon and Hopefield (Timmerman, 1985).
MAJOR UNCONFORMITY				
Cape granite Suite				Bedrock Granites
Malmesbury Group				Bedrock Metamorphosed Shales

4 RESEARCH METHODOLOGY, MATERIALS AND DATA ANALYSIS

4.1 Introduction

This chapter presents materials, field methods, secondary data collection methods and data analysis methods used for the research study outputs. The MAR field investigations selected target the main objectives of this research study and include geophysical, hydrogeological and water quality investigations.

The research study field methods include down-the-hole borehole logging, time-domain electromagnetic geophysics surveys, infiltration tests, constant discharge tests and groundwater/surface water sampling. The secondary data used for this study included constant discharge tests from previous tests done in the area by Nel (2018, 2019b), as well as, the static water leaching tests done at the Elandsfontein Mine (Nel and Nel, 2020). Data analysis for all water quality investigated was carried out by accredited labs: VinLab$_{H20}$ and Aquatico Laboratory.

4.2 Managed Aquifer Recharge Study Field Investigations

A field program was piloted from November 2019 to November 2020 for 12 months. Due to the uncertainty of the construction of the boreholes in the study area, the first step in the investigation was to carry out down-the-hole logging of several DWS boreholes in the Langebaan Road and Hopefield vicinity to access whether the boreholes were well connected to the aquifer. The final selection of DWS boreholes used in this MAR study was based on whether they were connected to the main aquifer, and their position relative to the deepest parts of the aquifer within the Saldanha Bay municipal area as well as the practical access to the boreholes.

The field work required to meet the research objections included, geophysical investigations, hydrogeological investigations and water quality investigations across the study area, refer to **Figure 4-1**. As part of the geophysical investigations, SkyTEM was appointed by Saldanha Bay Local Municipality (SBLM) to conduct an airborne geophysical 3D aquifer mapping survey. The survey was done from May 2020 to June 2020 to obtain geophysical data that provided information on the physical properties of the subsurface geology and the groundwater resources contained within the Lower Berg aquifer system.

Infiltration tests were carried out around several boreholes throughout the study area to investigate the vertical hydraulic properties of top soils. Similarly, pumping tests were conducted at two boreholes in the Langebaan Road and Hopefield areas to supplement previous pumping tests done in the area to understand the horizontal hydraulic properties of the aquifer. In addition, monthly monitoring took place to obtain water levels at the Langebaan Road and Hopefield Wellfields, refer to **Figure 4-2**. This was done to examine which areas had physical space to recharge the aquifer as well as to see how the aquifer responded to the wet and dry season.

Bi-annual water quality sampling took place in February/March 2020 and July/August 2020 as part of the water quality investigations needed to obtain and assess surface water and groundwater samples representative of the study area in the dry and wet season. Groundwater samples were taken from various boreholes spread throughout the study area. The Berg River sample was taken directly from the Misverstrand Dam Weir, about 45kms west of the wellfields. The WWPT sample was taken at the Vredenburg Wastewater Treatment plant approximately 20 km northwest of the wellfields. The WCDM pipeline was taken from a tap at the Hopefield wellfield.

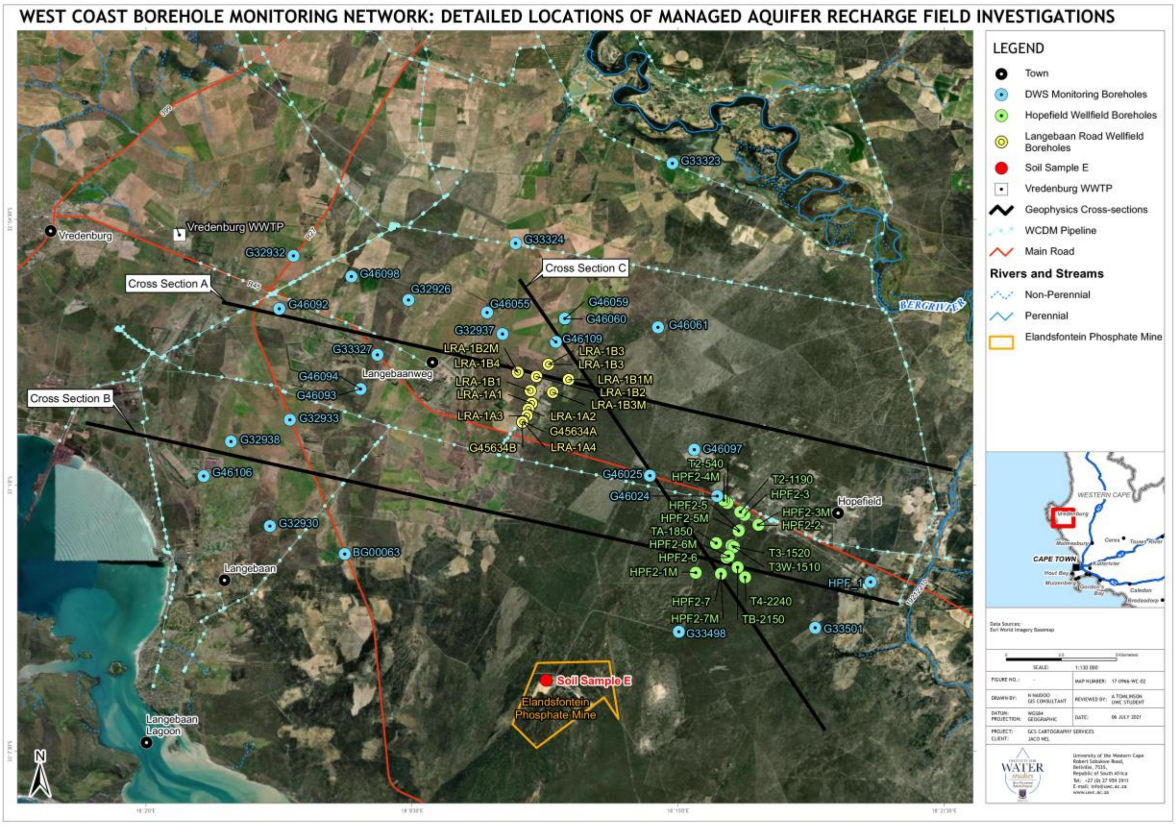


Figure 4-1: Detailed Locations of Managed Aquifer Recharge Field Investigations

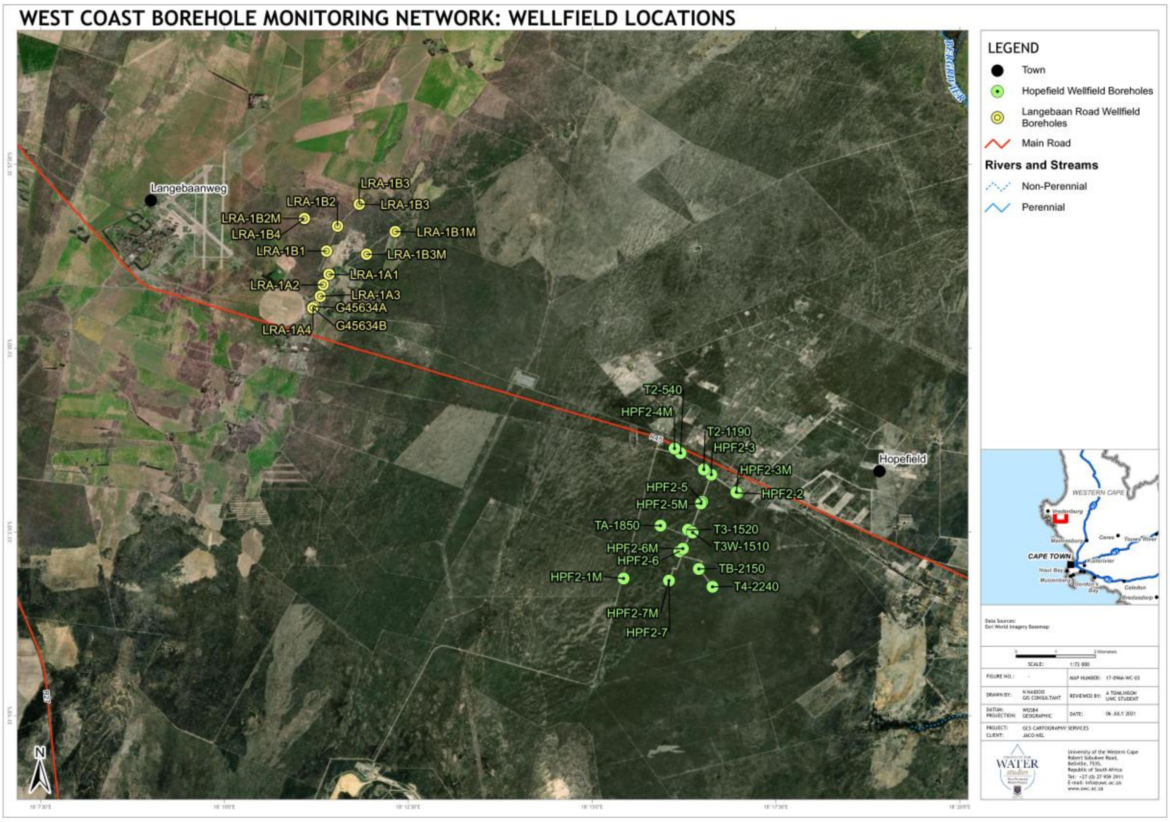


Figure 4-2: The Langebaan Road and Hopefield wellfield

4.3 Research design

4.3.1 Geophysical Investigations

When deciding on sites suitable for MAR within the Langebaan Road and Hopefield region, the delineation of the aquifer material within the study area is important. This includes knowing the spatial extent of the sands and gravels that make up the supposed Langebaan Road and Elandsfontein palaeo channels, as well as delineating the confining clay separating the shallow and deeper aquifers in the region. The size and position of the palaeo channels play an important role in determining where to recharge an aquifer as paleochannels house the coarser aquifer material that is more likely to store water. The spatial extent of the clay layers over the area is important to note. Regions, where the clay layer is absent, will be the target for Managed Aquifer Recharge. This is because the confined aquifer can only receive recharge in areas where the overlying clay aquitard is missing or where water can flow around the edge of the confining layer.

The airborne electromagnetic (AEM) geophysics was chosen above other geophysical techniques as the study area is large and some areas where information is required may be inaccessible by foot. Airborne electromagnetic surveying allows for the delineation of the different aquifer materials (clay, unsaturated sand, saturated sand and bedrock) within the study area. Time Domain Electromagnetic (TDEM) operations were chosen for its resolution capabilities in the shallow (>100m) subsurface as most of the boreholes in the area are drilled to less than 100 m. Also, using any type of surface electrodes that need to be in direct contact with the ground would be difficult in the dry sand or bedrock outcrop environments.

Airborne electromagnetic methods have an advantage over ground-based methods as they capture electromagnetic data on a large scale over a greater distance to the surface, therefore reducing the noise from unwanted man-made sources. A limitation to AEM methods is that if the helicopter flies too high there can be a loss of valuable data. Another limitation is that electromagnetic methods are at risk of disturbance from not only a conductive subsurface, but also man-made conductors at the surface of the earth. Therefore there needs to be an equilibrium between the height of the aircraft and the quality of data received (Siemon et al. 2011).

Descriptions of the lithologies of the subsurface were used alongside the geophysics data to delineate layers within the aquifer unit that would support the injection or infiltration and storage of water for MAR. The geophysics surveys done over the study area are moisture dependent. This means that water levels can also be used in conjunction with geophysics to determine areas of saturated and unsaturated sands with similar electrical properties. The different moisture contents of the soils will have different electrical properties (i.e. dry soils have lower resistivities than dry soils and so areas of high resistivity could be interpreted as the saturated soils of an aquifer) therefore allowing for interpretations of the geophysical data. Water levels also indicate which direction water is most likely to move through the aquifer following the theory that water moves from a high hydraulic gradient to a low hydraulic gradient.

The helicopter system used was SkyTEM as it provided the sufficient accuracy needed for groundwater investigations. The limitations for airborne TDEM geophysical surveying in this study are therefore related to the SkyTEM methods used, and according to BurVAl Working Group (2006), this includes the calibration of the instruments, the altitude and the flight speed of the helicopter. A detailed description of the SkyTEM operation can be found in BurVAl Working Group (2006).

4.3.2 Hydrogeological Investigations

Aquifer testing allows for the determination of the hydraulic parameters of the various aquifer layers. This will give an indication of which layers are most suitable for collecting and storing water and whether this water will be able to infiltrate into the aquifer or whether it needs to be injected. In this study, aquifer characteristics that will be focused on are vertical and horizontal hydraulic conductivity and water levels. Pump tests and infiltration tests will be chosen as the methods for determining aquifer permeability due to there being previous pump test wellfield data in the area to compare results, as well as to ensure the most accurate representations of the hydraulic parameters of the aquifer.

The limitations of pumping tests are that the test can be costly, require a lot of equipment and there could be regulatory issues related to the discharge of contaminated water generated from the pumping (Weight, 2008).

Pumping tests were done at boreholes at a distance from the wellfields to supplement previous tests done at the Langebaan Road and Hopefield wellfields. The objective was to see if similar horizontal hydraulic conductivities were observed over the entire study area. Infiltration tests were done as a means to collect hydraulic properties of the shallow/top soils within the area. With this information, a decision on the type of MAR technique best suited for the Langebaan Road and Hopefield area can be made.

The formations in the respective areas were determined using Roberts et al. (2006) descriptions of the formations. The geology suggests that Langebaan Road lower aquifer and the Hopefield shallow aquifer are the targeted aquifers for aquifer hydraulic investigations. Based on this, the pumping tests will be focused on the Langebaan Road wellfield region and infiltration tests will be targeted around the Hopefield wellfield region.

Additionally, monthly water level monitoring done at Langebaan road and Hopefield provided an understanding of how the aquifer responds to pumping events as well as indicates how 'full' the aquifer is in certain regions. As reviewed in previous literature, if an aquifer has no space for recharge, any addition of water to the aquifer results in the formation of artesian wells downgradient of the recharge site. Managed Aquifer Recharge is only viable in aquifers with space to store water and/or during seasons when the water levels in the aquifer have dropped.

4.3.3 Water Quality Investigations

This study is intended to provide site specific information on the water quality of the Langebaan Road and Hopefield aquifer system as well as the possible water resources within the region. This is useful information as part of this study includes determining areas suitable for MAR based on the quality of the groundwater as well as evaluating suitable water resources available for MAR. The groundwater sample collection was focused on privately owned, departmental and public boreholes. The boreholes chosen for sampling were dependent on whether a pump could physically fit down the borehole as well as boreholes that had sufficient reliable data about the depth of the screen for sample collection.

As part of this research, 15 boreholes in the vicinity of the Langebaan Road and Hopefield wellfield were sampled, three water resources were sampled (the Berg River, the Vredenburg Wastewater treatment plant and the west coast district municipal pipeline), as well as the 10 boreholes that make up the Langebaan Road wellfield and the 7 monitoring boreholes of the Hopefield wellfield for a total of 35 boreholes sampled. This sampling was done over two sampling runs, in February/March 2020 and July/August 2020, to obtain water samples from various boreholes representative of the Langebaan Road aquifer and Hopefield aquifer, during both the wet and dry seasons.

Traditional purging was chosen as the type of groundwater sampling technique for water quality investigations because according to WRC (2017), it is a suitable sampling method for the assessment of the groundwater quality for drinking as this method allows boreholes to operate under stressed conditions. Sampling was carried out according to the WRC (2017) sampling technique guide. Samples of both the source water and groundwater were needed to determine the outcome quality of water when these solutions mix. The water quality parameters that will be specifically looked at are the recommended inorganic parameters for geochemical investigations of MAR, as set out by Murray and Tredoux (2002). Microbiology, Turbidity and Dissolved oxygen will not be looked at in this study and are recommended for future MAR water quality investigations.

Contrasting water quality between injected source water, aquifer material and native groundwater can cause geochemical reactions that result in precipitation and dissolution of minerals, influencing the quality of the recovered water (Dillon et al. 2006; Murray and Tredoux, 1998). This suggests that investigations into the mixing of recharged water, aquifer material and native groundwater need to take place when trying to understand how the water quality within the aquifer will respond to particular MAR applications.

Managed Aquifer Recharge will initially be focused on areas of good groundwater quality (meets SANS 242- 2015 drinking water standards). The criteria used to determine whether the groundwater in a zone is suitable for MAR include:

- native groundwater meets drinking water standards
- groundwater meets drinking water standards after mixing with source water
- groundwater quality does not deteriorate after interacting with aquifer material.

4.4 Limitations to study

The February/March sampling run experienced some setbacks due to pump equipment breakdowns and/or malfunctioning in the field causing a decrease in the number of boreholes that could be pumped during that period. The pump was repaired for the next field trip. Additionally, due to the Covid-19 pandemic, the field trip in March 2020 had to be cut short due to lockdown regulations which meant that fewer infiltration and pumping tests were done throughout the study area.

4.5 Data collection

4.5.1 Down-the-hole Borehole logging

Down-the-hole profiling was conducted using the YSI multiparameter Sonde. The multiparameter Sonde is an instrument with several probes (EC, pH, temperature and salt) attached to it. As it was lowered down the borehole, these probes took measurements. The unattended sampling times are likely to be quite long (minutes or hours) and readings were logged to a single file.

The Sonde was connected to the YSI handheld PC and was programmed to take readings at 0.2 second intervals. The probe was then detached from the computer and attached to a tag line that was lowered into the borehole by 30 cm at the chosen time interval until the bottom of the borehole was reached (**Figure 4-3**). As the probe was lowered, it captured the pre-pumping EC, pH and temperature readings.

Once the Sonde reached the bottom of the borehole, the probe was pulled out of the borehole by winding the tag line back onto the holder and the Sonde was reattached to the computer and the logging was stopped. The Sonde was then cleaned and/or decontaminated accordingly before it was used at the next borehole. These steps were repeated at each borehole before and after pumping took place.

This data was used to generate pre and post pumping down-the-hole profiles that provided information on the construction of the borehole in terms of screen depths within the borehole and indicate where water was flowing through the borehole. This data was then used in the selection of the final boreholes for this research study.

Figure 4-3: D-T-H logging using a YSI attached to a tagline to measure depth specific EC and temperature

4.5.2 Time Domain Electromagnetic (TDEM) Airborne Geophysics data acquisition

From the 18th of May to the 14th of June 2020, TDEM data was acquired from Saldanha Bay using the SkyTEM system. The airborne geophysical survey was conducted over the Saldanha Bay Local Municipal (SBLM) jurisdiction area and the flight lines are depicted in **Figure 4-4** below. The yellow lines indicate trial lines and the red lines are the flight lines from the main survey. The trial lines were conducted over the existing SBLM water supply wellfields (Langebaan Road and Hopefield). These sites were chosen due to the availability of borehole data and ground geophysics data which could be used to confirm the quality of the airborne geophysical trial lines data.

After the data from the trial survey was analyzed and confirmed to be representative of the known conditions along the trail lines, the main survey commenced. The vertical lines of the main survey were flown 1 kilometer apart with horizontal lines 10 km apart over the greater survey area. At the wellfields, the survey lines were flown 100 m apart to obtain more detailed data. 200 m line spacing along the Elandsfontein aquifer towards Geelbek was flown.

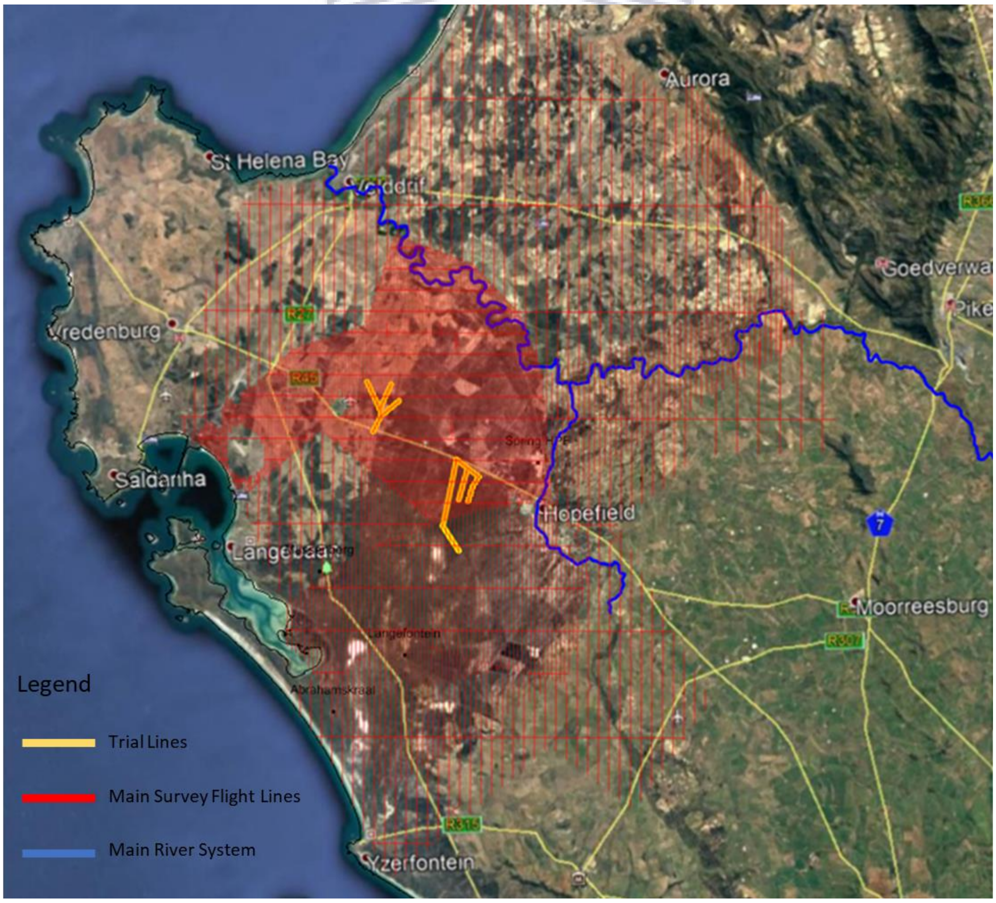


Figure 4-4: Flight lines from the main airborne geophysical survey.

The SkyTEM helicopter flew at approximately 20-40 km per hour and maintained an altitude of 15-20 m for the carrier frame and 50 m for the helicopter (**Figure 4-5**). The SkyTEM system was calibrated before it was used and as part of the standard field procedure for data quality check, repeated datasets were measured.

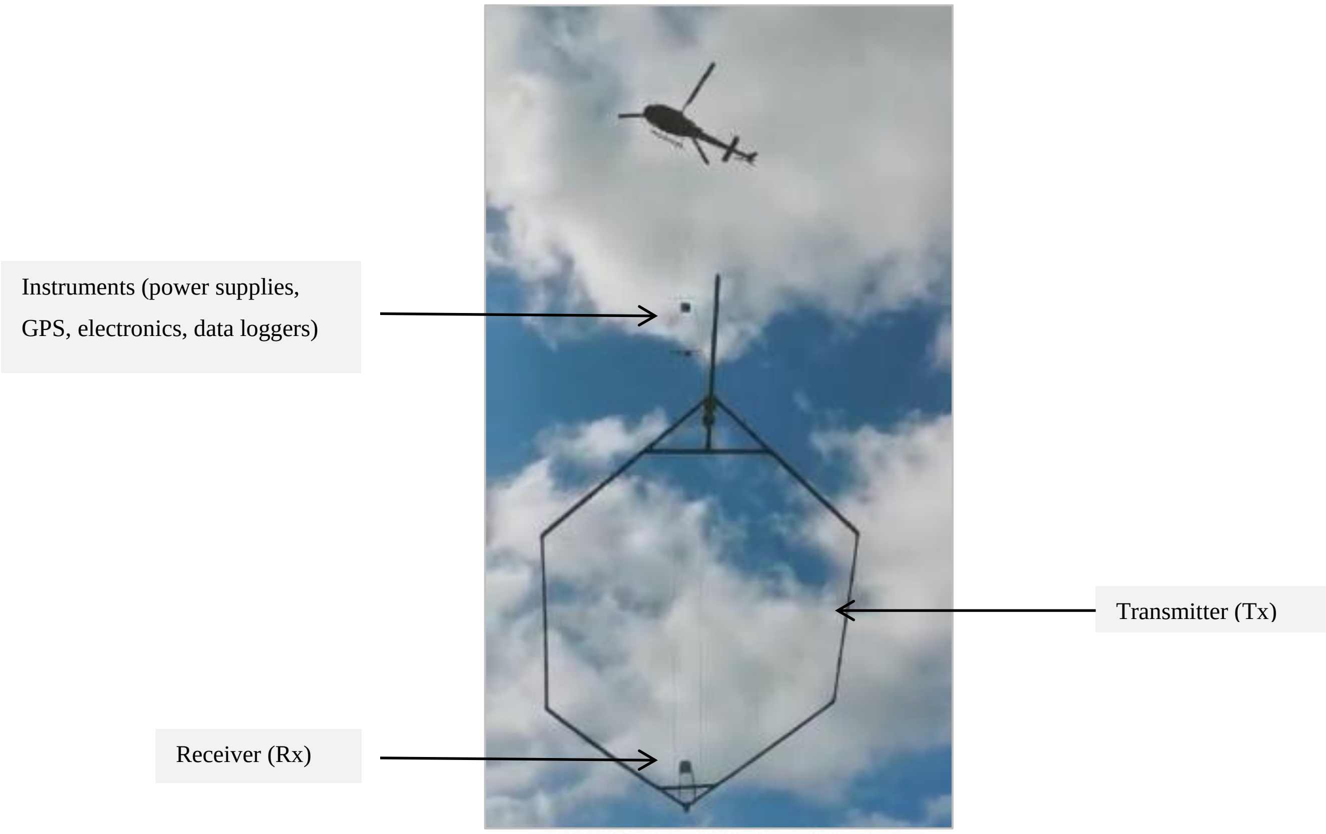


Figure 4-5: SkyTEM TDEM helicopter surveying in operation

4.5.3 Water Level standard procedure

Monthly water levels, both static water level and data logger readings were taken around the Langebaan Road and Hopefield region, as set out by the WRC (2017) groundwater level measurement field procedure. Static water level readings were measured using an electrical conductivity meter (dip meter) (**Figure 4-6**). The instrument typically consists of a sensor attached to the end of a double connector wire.

When the sensor came into contact with water, there was a spike in mV on the metre reader, or the dip meter made a sound. The depths to water levels were then taken directly from the tape/wire at the top of the borehole casing. The sensor was pulled up and the measurements were repeated to verify the correct reading and the readings were recorded onto a field sheet. These steps were repeated at every borehole.

Data logger readings were obtained after depth to water levels measurements were taken. The logger cable was connected from the level sensors in the borehole to a field laptop and the data was downloaded using the Solinst level logger software. Thereafter, the data was compensated using the barometric logger data and depth to water measurements on the Solinst software to obtain a static water level at each borehole.

Figure 4-6: Measuring water levels at Langebaan Road wellfield using a dip meter

4.5.4 Infiltration Test field procedures

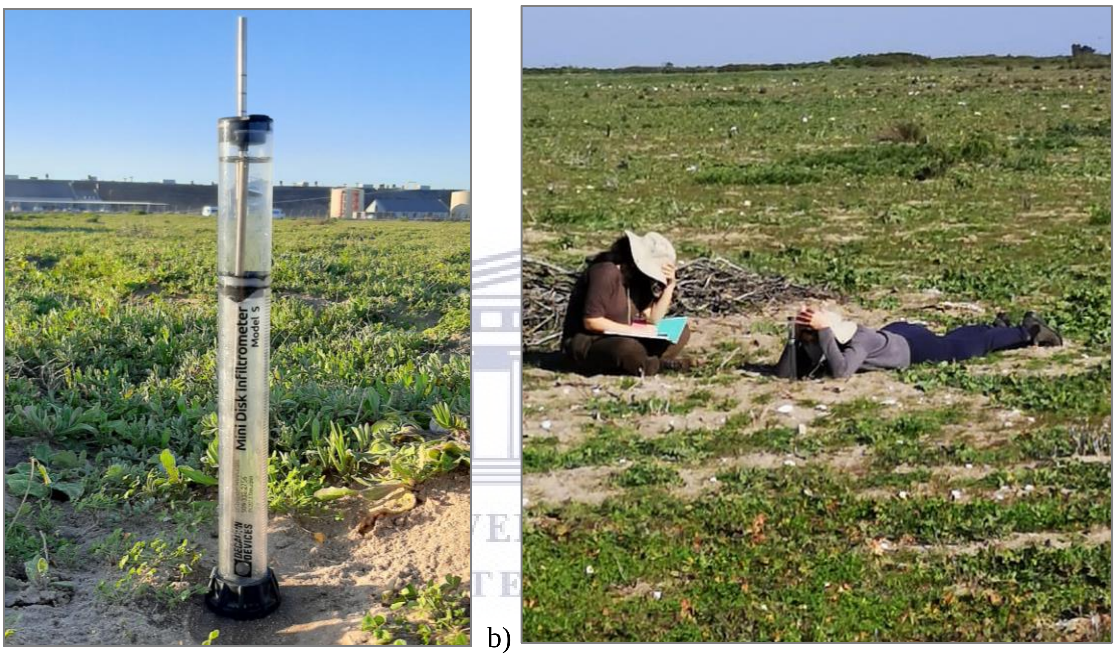
Infiltration tests were conducted at the Langebaan Road and Hopefield sites to determine the vertical hydraulic conductivity (rate of infiltration) within the saturated and unsaturated zone. Ideally, the infiltration tests should have been conducted 2 to 3 meters below the surface to simulate real-life infiltration galleries. Digging 2 to 3 meter deep trenches in the field was not possible and therefore the assumption is made that the dry top soils should have similar characteristics as the deeper unsaturated soils. This technique was used to indicate whether both Langebaan Road and Hopefield regions had the potential to support infiltration galleries or basins as a type of Managed Aquifer Recharge.

Unsaturated infiltration tests

Unsaturated zone infiltration tests were carried out using a Decagon mini disk infiltrometer. The mini disk infiltrometer was prepared according to the Decagon Devices Mini Disk Infiltrometer guide (‘Mini

Disk Infiltrometer Manuel', 2016). A suction rate of 2 was chosen to accommodate measuring the infiltration rate of the soils. The starting water volume in the mini disk infiltrometer chamber was recorded at time zero.

The infiltrometer was placed on a smooth spot on the soil surface, ensuring that it made solid contact with the soil surface (**Figure 4-7**). Once contact was made, the suction tube was pulled up to 2 and the volumes were recorded at regular time intervals as the water infiltrated into the soil. This was done until all the water had left the mini disk infiltrometer chamber. These tests were repeated three or four times at each site.



a) b)

Figure 4-7: (a) Minidisk infiltrometer placed on soil surface while (b) readings are taken at regular time intervals

Saturated infiltration tests (falling head hydraulic tests)

The saturated zone infiltration test was carried out using a falling head hydraulic test. Shallow holes were augured into the soils at Langebaan Road and Hopefield. A 1-metre long piezometer with a 0.3-meter perforated screen was placed into each hole to prevent the holes from collapsing. A water level logger (Solinst Levelogger, model 3000) was installed into the piezometer at the 1-metre depth making sure to not let the logger lie on the ground. Water was then injected into each hole (**Figure 4-8**) at least three times to ensure saturated conditions.

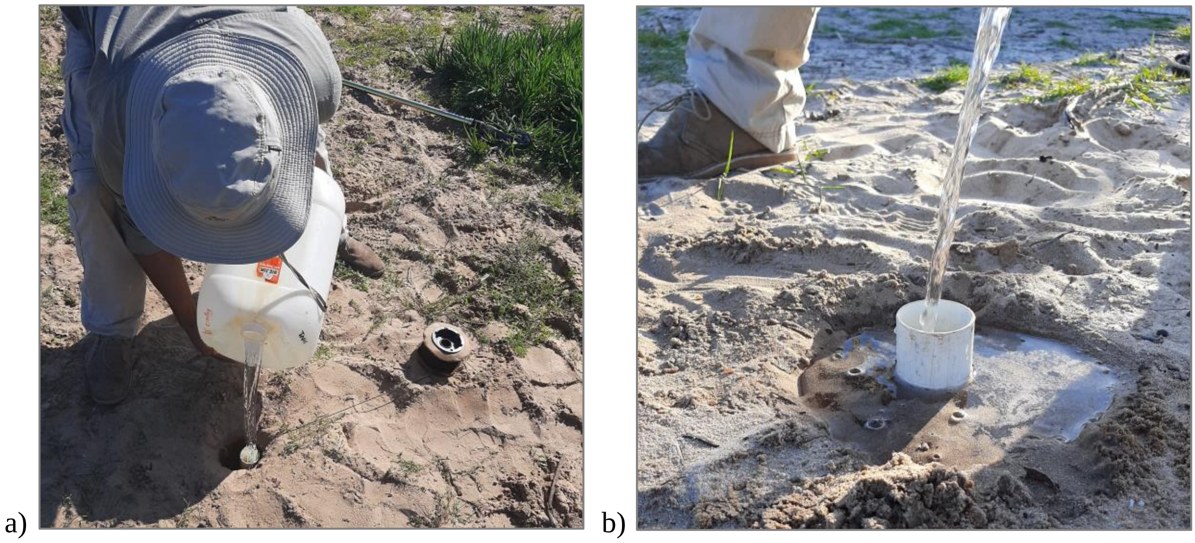


Figure 4-8: (a) water being injected into 1m long PVC pipe until (b) subsurface has reached saturated conditions

The holes were injected instantaneously with water and allowed to infiltrate into the soil while measurements of head were recorded with the data logger. The rate of infiltration is related to the hydraulic conductivity of the soils. The data was downloaded and used to determine the hydraulic conductivity of the saturated aquifer zone.

4.5.5 Constant Discharge Test (CD) procedure

Short term single-well pumping tests of three (3) boreholes surrounding the Langebaan Road and Hopefield wellfields were done following the principles set out by Kruseman and de Ridder (2000) and improved the understanding of hydraulic characteristics of the Langebaan Road and Hopefield aquifer system.

A pump was lowered into the borehole at a specific depth below ground level (mbgl) using a rope. The depth the pump was lowered varied for different boreholes. The pump was connected to a generator which supplied the pump power in the field. The initial static water level was measured before the pump was switched on.

Individuals were located at the pumping point to measure water levels as pumping began. Individuals were also located at the discharge point, several metres from the pumping point to measure the rate of discharge and obtain field chemistry parameters (**Figure 4-9**). The pump tests as well as the collection of groundwater samples occurred simultaneously. A detailed description of how the groundwater samples were collected is found in section 4.4.7.

The pump was switched on and the change in water levels from the initial static water level was recorded, first in 1-minute intervals for the 1st 10 minutes, then in 5-minute intervals for 20 minutes and then at every hour for the duration of the pumping test. These tests were conducted on a single pumping hole.

An irrigation pipe was used as the discharge outlet and placed downgradient of the pumping borehole. A bucket and a stop watch were used to determine the discharge rate during pumping using the following equation:

$$\text{Rate (L/s)} = \frac{Volume\ of\ bucket\ (L)}{Time\ to\ fill\ bucket\ (s)}$$

Once the pump was turned off, recovery water levels were recorded in the pumping borehole following the same time intervals as the drawdown was recorded. The data derived from these holes was interpreted using the Cooper-Jacob method.

Figure 4-9: Pumping test done at G46094

4.5.6 Static Water Leaching: U.S.EPA Method 1314

The quality of the constituents leached from soil sample E was determined using the percolation column method (1314) as set out by U.S.EPA. This method was intended to be used as part of an environmental leaching assessment for the Elandsfontein Phosphate Mine which shares the same geology as the Hopefield region. In situ soil samples from the mine and deionized water were used in a 1:4 ratio. In situ soil samples were collected from the Elandsfontein Phosphate Mine and passed through a 2.83 mm sieve. Oven drying was not recommended for the preparation of test samples due to the potential for mineral alteration.

The soil samples of acceptable particle size (<2.83mm) were weighed and then moderately packed into a percolation column. The column was packed with the soil material surrounded by layers of quartz sand at the top and bottom of the column that provided a flow pattern regulation and coarse filtration. Deionized water, four times the volume of soil, was introduced to the column, thus wetting the column package.

The infiltrating water moved through the porous soil material and leaching occurred at the solid-liquid interface between the water and soil. Once the column packing was completely wetted, it was allowed to equilibrate for 24 hours. After 24 hours, a tap located at the bottom of the column was opened and the eluate was collected in a Teflon sample bottle (**Figure 4-10**). The eluate was then filtered and chemically analysed for inorganic compounds.

Figure 4-10: Aquatico's static water leaching column setup following the USEPA 1314 percolation column method.

4.5.7 *Groundwater and surface water sampling field procedure*

Traditional pumping was done at boreholes to purge the borehole of any stagnant water, for the determination of high or low yielding boreholes and to measure field parameters of the aquifer water. The static water level (SWL) was measured at the borehole following the standard procedure stated in 4.5.3. The depth of the borehole was measured and the height of the water column in the borehole was determined by the following equation:

$$Water\ column\ in\ borehole\ =\ borehole\ depth -\ depth\ to\ water\ level$$

The standing volume of water in the borehole was then calculated in litres using the following equation:

$$V = (лd\text{^}2\ h)/4000$$

Where, V= volume of standing water in litres, d= diameter of the borehole in mm and h= height of water column in metres.

A rope and hose pipe of sufficient length was attached to the pump. Thereafter the pump was lowered into the borehole at the desired depth or just above where the borehole screen is. The YSI handheld multi parameter probe measuring EC, pH and DO was set up to obtain field measurements of parameters. Once the pump was lowered, the pump electricity cable was plugged into the generator and the generator was switched on.

Using the calculated borehole volume, the amount of time needed to remove 3 volumes of water in the column was calculated and the borehole was pumped for that recommended time. After approximately three volumes of water were removed, the pump was lowered about 0.5m and samples were collected. This was done so that contamination from the stagnant water above the pump inlet did not occur.

Continuous field readings of desired parameters (EC, pH, DO) were taken using a handheld YSI multiparameter probe, by placing the probe into the discharge bucket until the parameters were stable. Stabilized parameter readings mean that the water discharged was aquifer water. Following Weaver's (1998) recommendation the temperature, EC and pH were measured in the field because EC and pH are temperature-dependent variables and are influenced by the precipitation of salts out of solution. These parameters can also provide a check on laboratory data.

At the Langebaan Road and Hopefield Wellfield, water samples were collected from a sampling tap attached to the production boreholes (**Figure 4-11**). The tap was opened and allowed to run for a few minutes before the groundwater sample was collected. This was done to ensure that any stagnant water in the tap was removed before the sampling occurred.

For general water quality, a 500 ml Teflon bottle was rinsed thrice with the aquifer water. The bottle was then filled and sealed tightly before being placed onto ice blocks in a cooler box. The samples were then transported and stored in a fridge (as per storage guidelines) until analysis took place. For quality control, a duplicate sample was taken at selected boreholes.

Sampling using a bailer was done at boreholes where the pump needed for purging the borehole could not fit into the borehole, or where the borehole was previously stated too low yielding. A Teflon flow through bailer was attached to the tag line and lowered into the borehole at a specific depth. This depth was chosen based on where the borehole screen was identified. Once full, the bailer was then pulled to the surface and the water sample was collected following the same procedure stated above.

The Berg River sample was taken directly from the Misverstrand Dam weir (**Figure 4-12**). The Teflon bottle was rinsed thrice before the sample was taken. The pipeline water was collected at a tap at the Hopefield wellfield in a 500 ml Teflon bottle. The treated wastewater was collected at the Vredenburg wastewater treatment plant. These samples were stored in the same manner as the groundwater samples and sent to the Vinlab lab for analysis.

Figure 4-11: Collection of water sample T3W-1510 at Hopefield wellfield

Figure 4-12: The collection of a water sample from the Misverstrand Dam Weir

4.6 Data Analysis

4.6.1 Time Domain Electromagnetic (TDEM) Airborne Geophysics Data Analysis

Time Domain data processing

The conductivity data of the geological formations that were obtained from the airborne geophysics survey, was interpreted by reducing resolutions with depth. The top layers were interpreted at about 2m intervals to 10m and ultimately to 20m resolution layers at a 150m total depth (**Figure 4-13**). The conductivity layers were overlaid with the surface topography of the area to incorporate features such as bedrock highs, clay layer depth and paleochannel depths. Incorporating the surface topography of the area gives a true measure of the actual depth that which the different geological formations can be found.

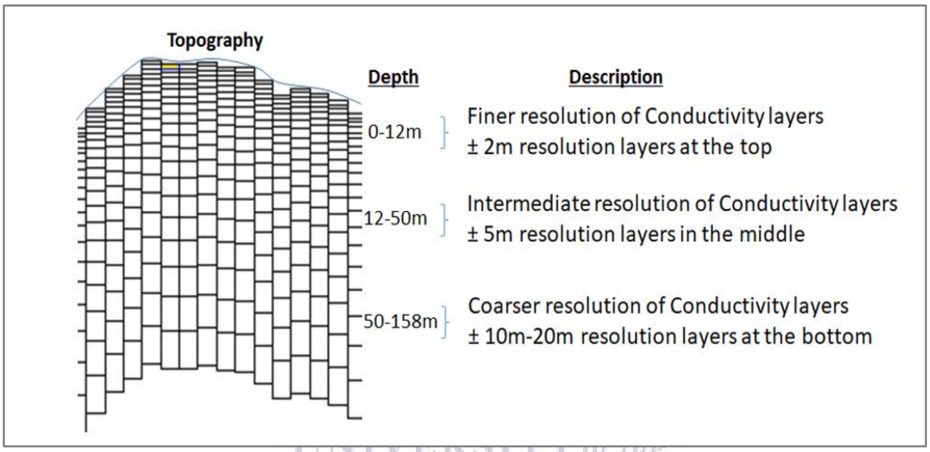


Figure 4-13: Conceptualization of conductance layers at depth correlated with the surface topography

The TDEM geophysics survey obtained from SkyTEM showed varying conductivities at different depths within the subsurface. These conductivities each represented a change in geological material, with the lower conductivities coinciding with bedrock formations and the higher conductivities coinciding with clay and salt lenses. The ranges of conductivities representing a certain geological formation were grouped and colour coded to generate maps and cross-sections in the Surfer 2D and 3D mapping, modelling and analysis software (Golden software). The bedrock topography was interpreted from the contact between the sand and the bedrock in each layer and then combined to form a single data set. The bedrock depth was then combined with the topography to provide a bedrock elevation map. The TDEM properties that represent clay, unsaturated sands, saturated sands and bedrock were overlaid on top of each other to generate maps indicating the extent of these geological units.

4.6.2 Unsaturated infiltration Analysis

Decagon Inc created a Microsoft Excel spreadsheet to calculate the slope of the curve of the cumulative infiltration versus the square root of time based on the data gathered in the above steps. The field data was manually input into the Excel spreadsheet and the hydraulic conductivity of the soil was determined. The geometric mean of the three unsaturated hydraulic conductivities calculated at each site was identified as the hydraulic conductivity representative of the subsurface at that site. The unsaturated infiltration test data can be found in Appendix A.

Decagon Inc used the method proposed by Zhang (1997) to determine the infiltration rates into dry soil. Zhang's (1997) method requires measuring cumulative infiltration versus time and fitting the results with the function:

$$I = C_1 t + C_2\sqrt{t}$$

Where C_1 (m.s^{-1}) and C_2 (m.s$^{-1/2}$) are parameters. C_1 is related to hydraulic conductivity (k) (m/day), and C_2 is soil sorptivity. The hydraulic conductivity is then computed from:

$$k = \frac{C_1}{A}$$

Where C_1 is the slope of the curve of the cumulative infiltration versus the square root of time, and A is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the Infiltrometer disk. A is computed from the following equations:

$$A = \frac{11.65\ (n^{0.1} - 1)\exp\ [2.92(n - 1{,}9)\alpha h_o]}{\alpha {r_0}^{0.91}}$$

$$A = \frac{11.65\ (n^{0.1} - 1)\exp\ [7.5(n - 1{,}9)\alpha h_o]}{\alpha {r_0}^{0.91}}$$

Where n and a are the van Genuchten parameters for the soil, r_o is the disk radius, and h_o is the suction at the disk surface. The Mini Disk Infiltrometer infiltrates water at a suction of -0.5 to -6 cm and has a radius of 2.25 cm. The van Genuchten parameters for the 12 texture classes were obtained from Carsel and Parrish (1988) and are shown in **Table 4-1** below.

Table 4-1: van Genuchten parameters for the 12 soil texture classes.

			h_o						
			-0.5	-1	-2	-3	-4	-5	-6
Texture			A						
Sand	0.145	2.68	2.84	2.40	1.73	1.24	0.89	0.64	0.46
Loamy Sand	0.124	2.28	2.99	2.79	2.43	2.12	1.84	1.61	1.40
Sandy Loam	0.075	1.89	3.88	3.89	3.91	3.93	3.95	3.98	4.00
Loam	0.036	1.56	5.46	5.72	6.27	6.87	7.53	8.25	9.05
Silt	0.016	1.37	7.92	8.18	8.71	9.29	9.90	10.55	11.24
Silt Loam	0.020	1.41	7.10	7.37	7.93	8.53	9.19	9.89	10.64
Sandy Clay Loam	0.059	1.48	3.21	3.52	4.24	5.11	6.15	7.41	8.92
Clay Loam	0.019	1.31	5.86	6.11	6.64	7.23	7.86	8.55	9.30
Silty Clay Loam	0.010	1.23	7.89	8.09	8.51	8.95	9.41	9.90	10.41
Sandy Clay	0.027	1.23	3.34	3.57	4.09	4.68	5.36	6.14	7.04
Silty Clay	0.005	1.09	6.08	6.17	6.36	6.56	6.76	6.97	7.18
Clay	0.008	1.09	4.00	4.10	4.30	4.51	4.74	4.98	5.22

4.6.3 *Saturated infiltration Analysis*

Logger data derived from the falling head hydraulic tests was interpreted with the Bouwer and Rice Equation 1 (Kruseman and de Ridder, 2000) using the AQTESOLVE PRO version 4.0 software **(Figure** 4-14). All the falling head test data analysed using the AQTESOLVE PRO software can be found in Appendix A.

The Bouwer- Rice equation:

$$K = \frac{r_C^2 \ln\left(\frac{R_e}{r_w}\right) 1}{2d} \frac{1}{t} - ln \frac{h_o}{h_t}$$

Where K = Hydraulic conductivity (m/d); r_c = radius of the casing where the rise of the water level is measured (m); R_e = radial distance over which the difference in head is dissipated (m); h_o = Head in piezometer at t_o = 0 (m); h_t = Head in piezometer at t > t_o (m); r_w = effective radius of piezometers (m); d = length of open section of piezometer through which water can enter (m) and; t = the time since H = H_0 (s)

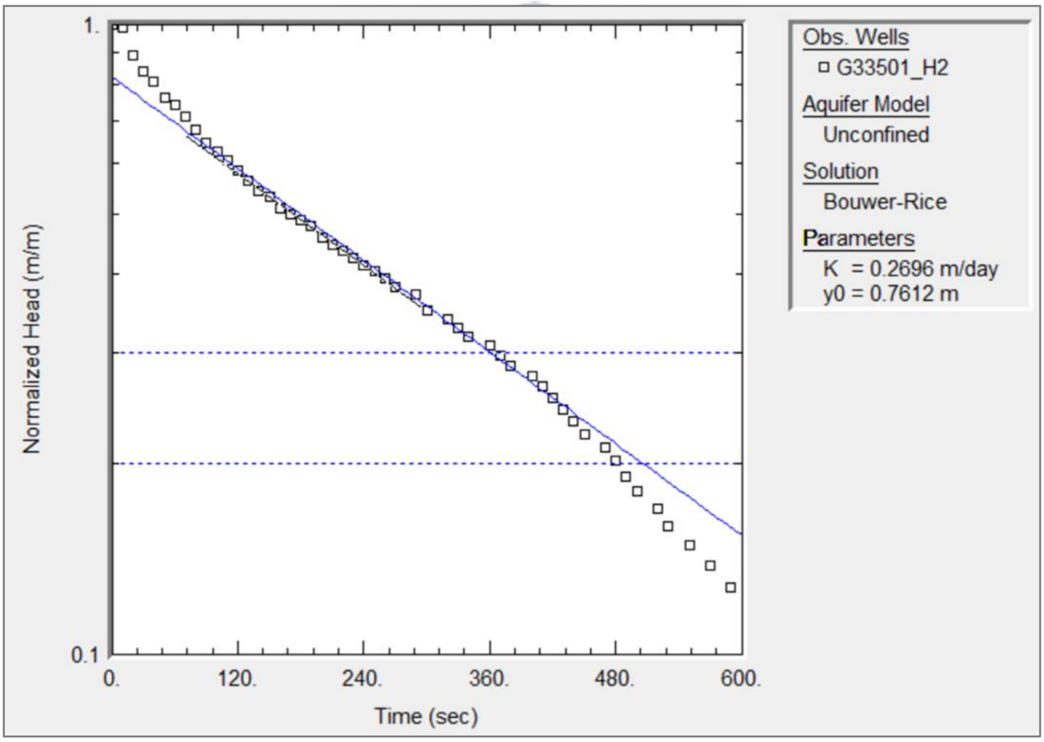


Figure 4-14: Analysis of falling head slug test using Bouwer and Rice (1976) method and recommended normalized head range at G33501

4.6.4 *Constant Discharge Test Analysis*

The constant Discharge test data was analysed using the AQTESOLVE PRO version 4.0 software interpreted with the Cooper-Jacob curve fitting method (**Figure 4-15**). This method was chosen as the abstraction borehole itself serves as the observation borehole. Both of the constant Discharge test data analysed using the AQTESOLVE PRO version 4.0 software can be found in Appendix A. Cooper and

Jacob (1946) derived a modified form of the Theis (1935) solution for transient flow to a well discharging at a constant rate from a homogeneous and isotropic nonleaky confined aquifer of infinite extent and uniform thickness. As such, the Cooper- Jacob equation for drawdown is as follows:

$$s = \frac{Q}{4\pi T}\log\left(\frac{2.25Tt}{r^2 S}\right)$$

Where Q = pumping rate (L^3/T); r = radial distance from pumping borehole to observation borehole (L); s = drawdown (L); S = storativity; t = elapsed time since the start of pumping (s); T is transmissivity (L^2/T)

To apply the Cooper and Jacob solution to the equation, S is plotted as a function of log t on a semi-logarithmic axis and a straight line is drawn through the data. T is calculated as:

$$T = \frac{2.303Q}{4\pi\Delta s}$$

Where Δs = slope of the fitted line. With the estimate of T obtained, S is calculated as:

$$S = \frac{2.25Tt_0}{r^2}$$

Where t_o = the intercept of the line on the x-axis (T).

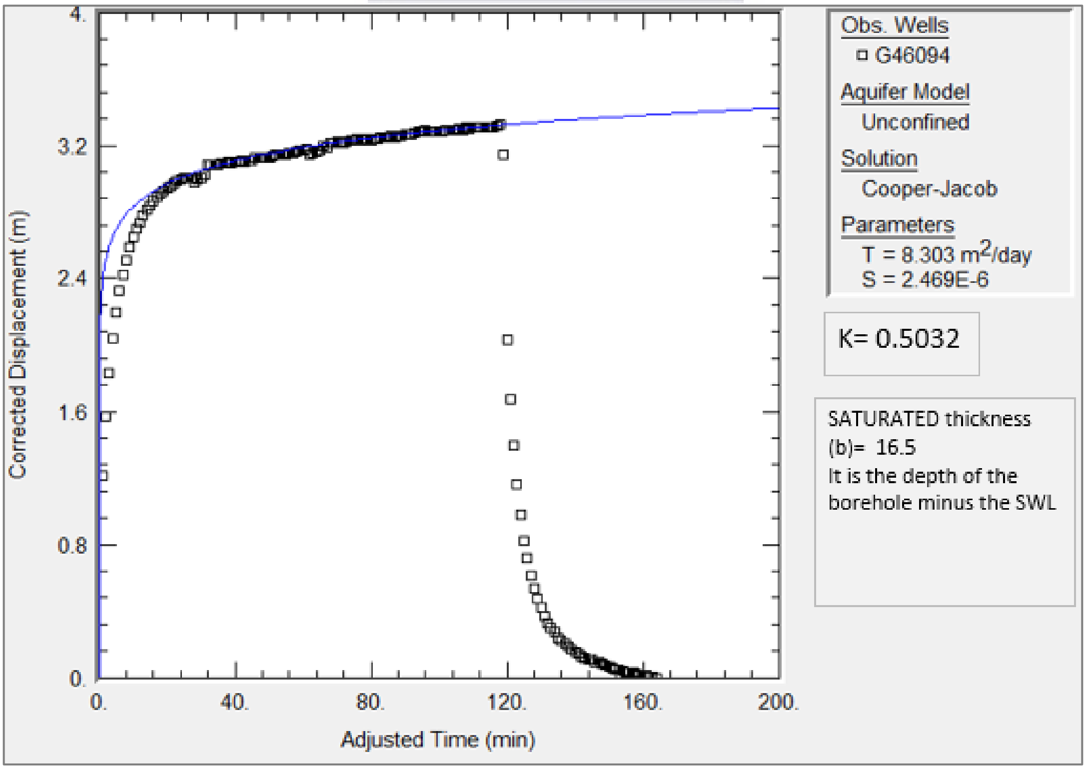


Figure 4-15: Estimation of aquifer properties at G46094 by matching Cooper-Jacob (1946) type-curve solution to discharge data from a constant-drawdown test in an unconfined aquifer.

4.6.5 Hydrochemistry Analysis

Static Water Leaching Analysis

The chemical analysis of the leachate sample was done by Aquatico Laboratory services. The parameters sent out for analysis were determined by the Elandsfontein Phosphate Mine hydrological assessment team and included mostly inorganic compounds. Aquatico used the Elements Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) method to analyse total metals.

Water quality analysis received from the lab was set up using Excel to identify leachate water chemistry representative of the Elandsfontein and Hopefield region. This eluate was then used as an input in the geochemical mixing model simulating the reaction between the source water and the soil aquifer material at Hopefield.

Water Chemistry Laboratory Analysis

The chemical analysis of all the groundwater and surface water samples was done at $VinLab_{h2o}$. The samplers were kept refrigerated in the laboratory between analyses. $VinLab_{h2o}$ used two different types of methods to analyse the chemical parameters in the water samples, namely the Colormetric method and the Inductively Coupled Plasma (ICP) method. Additionally, pH was determined using the titration method electrical conductivity was determined using a conductivity sensor, both at a temperature of 25°C.

Water quality analysis received from the lab was set up using Excel to identify water chemistry that was similar in type. The hypothesis behind this is that several boreholes with the same type of water will behave the same when mixed with the different sources of water. Therefore, one water sample from the Langebaan Road region and one water sample from the Hopefield region can be used to simulate various mixing scenarios with the different water resources in the area.

Geochemical Mixing

A geochemical mixing model was achieved using the PHREEQC software code to simulate various mixing scenarios. According to Parkhurst and Appelo (1999), the model works by converting the chemical concentrations to moles and then solving a series of simultaneous non-linear algebraic equations (chemical reaction, charge balance and mass balance equations) to determine the activity-concentration relationship for all the chemical species in the specified system. The model usually requires electrical balance and will force charge balance with one of the components (that can be designated), as they solve the matrix of non-linear equations. The non-linear algebraic equations are solved using an iterative approach by the Newton-Raphson method.

Several mixing scenarios were run in the model to predict the chemical concentrations of elements if the raw river water, pipeline water and treated wastewater were to mix with groundwater and/or aquifer material. The model output for these mixed reactions described the elemental concentrations that are expected in the groundwater once the water samples are mixed. The scenarios focused on included mixing between the source water and groundwater to simulate MAR borehole injection conditions, as well as the mixing between the source water, aquifer material and the groundwater to simulate MAR infiltration conditions (**Figure 4-16**).

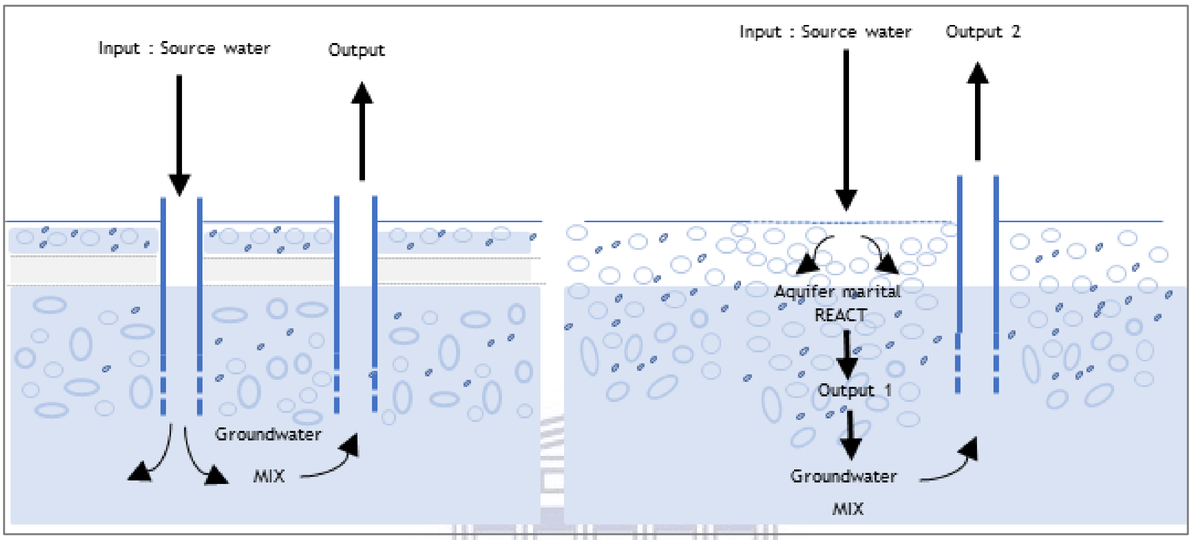


Figure 4-16: Conceptual model simulating borehole injection and infiltration Managed Aquifer Recharge techniques to simulate 'real world' mixing scenarios

The chemical composition of the groundwater at Langebaan Road and Hopefield did not significantly change between the wet and the dry season. Due to this, a single sample was used to represent the mixing of the groundwater and source water in the two areas. Similarly, the West Coast District Municipality pipeline water stays constant all year round, therefore, a sample of this water source was used for the mixing model. The Misverstrand Dam water was expected to change from wet season to dry season, however, an insignificant change in the water quality between the season was observed. As such, the dam water in the wet season was used in the model as it is representative of both seasons. It is also likely that the excess water from the river, stored at the dam, is more likely to be used as a potential water resource for MAR. Surprisingly, the wastewater treatment plant, which was thought to remain fairly constant all year round, had changes in the water quality so a model representing both the wet and dry seasons was run.

5 RESEARCH RESULTS AND DISCUSSION

5.1 Geophysical Investigations

5.1.1 Selection of boreholes for MAR study using down-the-hole (D-T-H) profiling

Figure 5-1 and **Figure 5-2** below represent D-T-H logs of G46093 and G46055 respectively. G46093 is a well-constructed borehole and is connected to the deeper aquifer at Langebaan Road. According to data obtained from the NGA, G46093 is screened in the deeper Langebaan Road aquifer system at a depth of 95 m – 101 m. The main flow of groundwater into the borehole occurs at the screen, up towards the pump during the borehole purging process. This is observed by the change in electrical conductivity (EC) and temperature at screen depth.

There are minor changes in EC between the pre and post pumping logs which suggests that this is a high yielding borehole being continuously flushed. Additionally, the slight change in EC at screen depth suggests that G46093 is well connected to the coarse sands that make up the deeper Langebaan Road aquifer system. There is no evidence of groundwater entering the borehole through the top zone. The casing of the borehole has remained intact which infers that a sample from this borehole is not a mixed sample and represents the deeper Langebaan Road aquifer.

Some of the construction of the borehole G46055 is unknown (i.e. the gravel packs) and there is a clear lack of data from 98 m – 160 m suggesting that this borehole has collapsed. This was observed in the field as the logger would not pass 98 m.

According to data obtained from the NGA, G46055 is screened in the Langebaan Road aquifer system at a depth of 25 m – 34 m. Looking at the geological formation that coincides with the screen depth, this borehole is screened between the confining clay layers that separated the upper and lower Langebaan Road aquifer. The groundwater sample representative of this confining clay layer is not representative of either the shallow or the deeper Langebaan Road aquifer. Furthermore, there is evidence of inflows of water from the shallow and deep zone indicted by deviations in temperature and electrical conductivity, suggesting a possible mix of groundwater in this borehole. As such, a sample from screen depth is not representative of the aquifer targeted for Managed Aquifer Recharge.

Down-the-hole logs provided insight into the construction of the boreholes, the boreholes' connectivity to the aquifer as well as characterized the aquifer formation at screen depth, in terms of temperature and electrical conductivity. Boreholes that gave good data were used to continue this research. Boreholes where data was missing, the hole could not be logged or where the borehole seemed to be disconnected from the aquifer were excluded from this research.

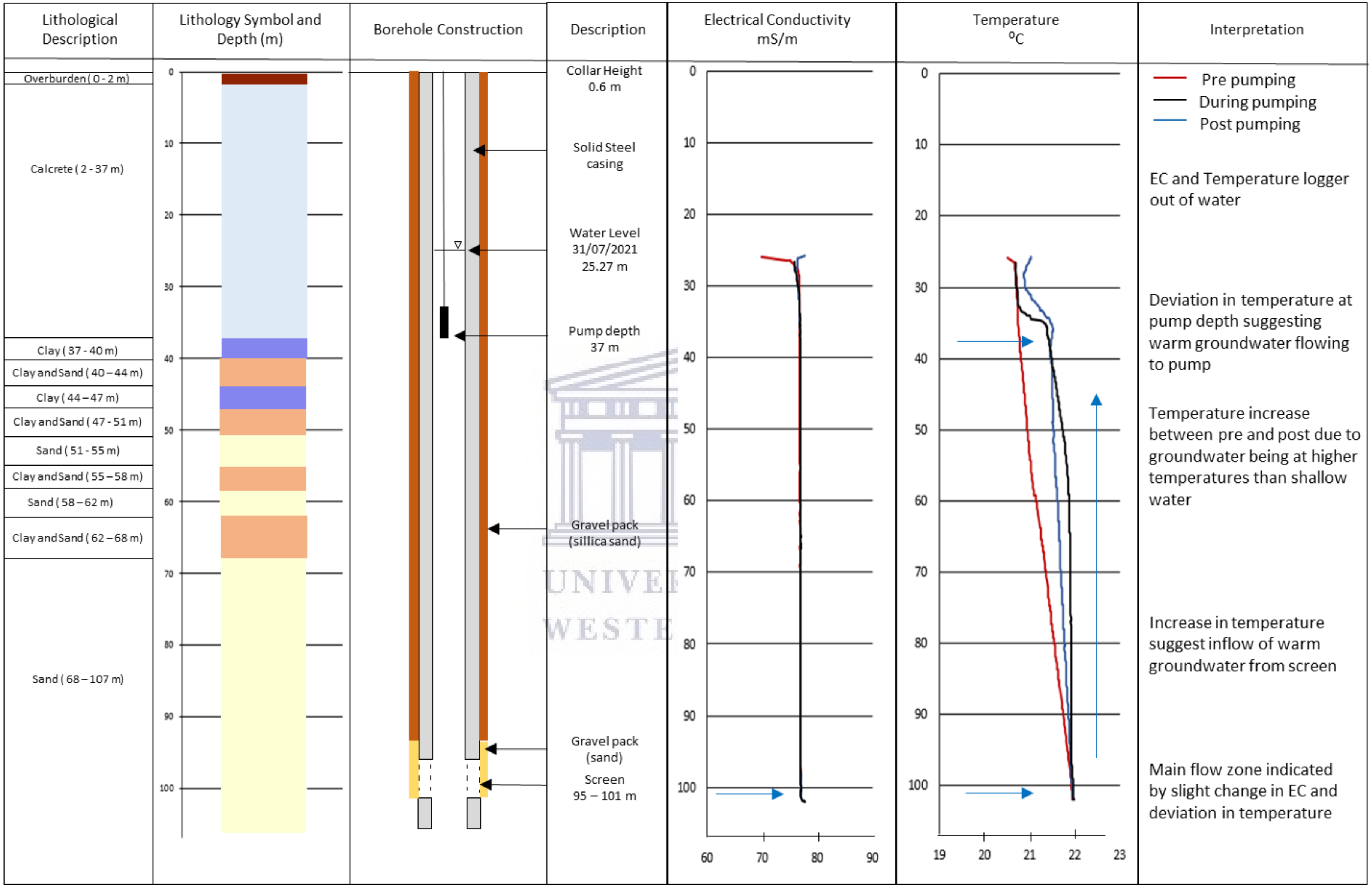


Figure 5-1: Down-the-hole electrical conductivity and temperature log for G46093, a lower aquifer borehole at Langebaan Road.

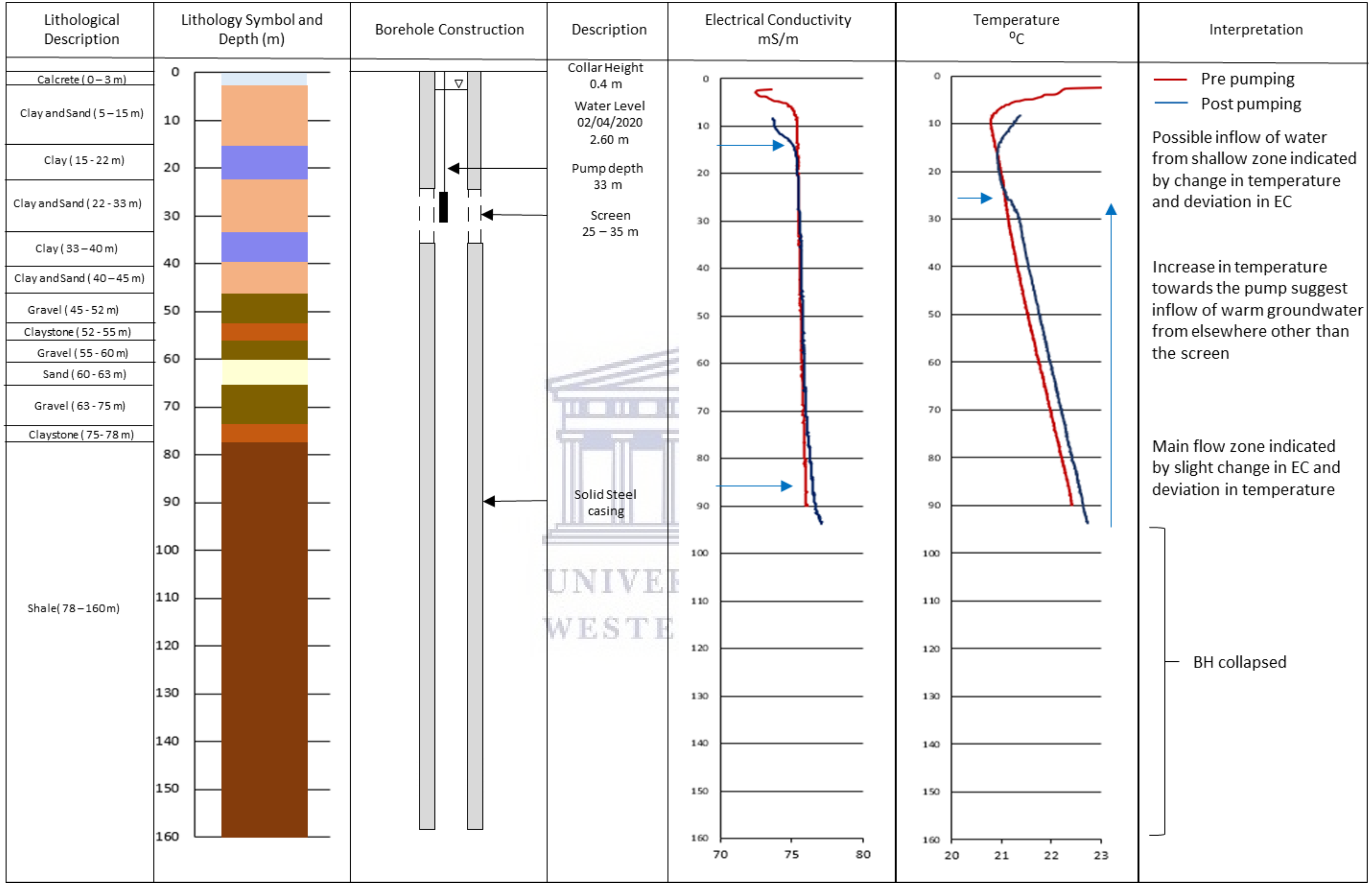


Figure 5-2: Down-the-hole electrical conductivity and temperature log for G46055, a borehole at Langebaan Road.

Table 5-1 summarizes the results of the D-T-H logging of boreholes sited for the MAR study in terms of their construction. Most of the boreholes used in this study were well constructed and well connected to the main aquifer units in the respective areas. These boreholes were used throughout the study. Bedrock boreholes, such as BG000063 and G46060 were removed from the study as they were not connected to the deeper aquifer unit at Langebaan Road. Similarly, boreholes lacking any information about their construction, or collapsed boreholes, were also removed from the MAR study. Both the Langebaan Road and Hopefield wellfields were used in the study, despite not being logged, however, their construction is confirmed through drilling logs (Nel, 2019a).

Table 5-1: Borehole construction based on D-T-H logs.

Borehole ID	Latitude	Longitude	Sample depth (m)	Shallow/ Deep/ Bedrock	Borehole Construction
G33327	-32.9635	18.1276	30	D	Borehole construction intact
G32926	-32.9412	18.1403	32	D	Borehole construction intact
G32937	-32.95495	18.17850	23	D	Borehole construction intact
G33323	-32.8855	18.24770	18	D	Borehole construction intact
G46059	-32.94872	18.20387	9	D	Borehole construction intact
G46092	-32.94473	18.08762	21	D	Borehole construction intact
G32938	-32.99873	18.06793	23	D	Borehole construction intact
G46030	-32.94886	18.20377	37	B	Borehole construction intact
G32933	-32.9899	18.09195	24	D	Borehole construction intact
BG00063	-33.04454	18.11430	33	B	Borehole construction intact
G46061	-32.95227	18.24188	13	D	Borehole construction intact
G46097	-33.00208	18.25657	33	D	Borehole collapsed
G46109	-32.95819	18.20031	12	D	Borehole construction intact
G46055	-32.94622	18.17727	33	-	Borehole collapsed
G32932	-32.92317	18.09342	19	S	Borehole construction intact
G46093	-32.97735	18.12070	33	D	Borehole construction intact
G46094	-32.9773	18.12074	33	S	Borehole construction intact
G46098	-32.93156	18.117	33	D	Borehole construction intact
BG00168	-33.05622	18.32653	24	-	Open borehole
G33497	-33.03743	18.26098	-	-	No information on construction
G46024	-33.02105	18.26588	13	-	No information on construction
G33501	-33.0746	18.3058	12	S	Borehole construction intact
G33324	-32.9181	18.1839	28	D	Borehole construction intact

5.1.2 Managed Aquifer Recharge potential at the Langebaan Road and Hopefield wellfields using trial line TDEM Geophysics survey

Langebaan Road wellfield

The Time Domain Electrical Magnetic (TDEM) geophysical investigations at the Langebaan Road wellfield identified an extensive clay subsurface layer separating the upper and lower aquifer unit at the wellfield, with sand being the dominant aquifer lithology (**Figure 5-3**). This is supported by the lithological logs from the boreholes that were drilled by GEOSS (2018). Similarly, Roberts et al. (2011) lithological descriptions also identify sand as the dominant aquifer lithology at Langebaan Road. The clay layers (blue) in the TDEM surveys seem to thin out in a north-easterly direction towards the Berg River and appear to be missing in the north-easterly region, just after the Langebaan Road monitoring boreholes LRA 1B1M and LRA 1B3M.

Currently, there are four active monitoring boreholes within this north-easterly area, namely LRA 1B1M, LRA 1B3M, G46109 and G46061 that are being used in the recent study. Drilling logs obtained from Nel (2018) show that the peaty clay layer at LRA 1B1M and LRA 1B3M is around 12 to 20 metres thick. Drilling logs obtained from the NGA show that boreholes G46109 and G46061 have only three metres of clay separating the upper and lower Langebaan Road aquifer. This suggests that the clay layer seems to thin out towards the northeast region of the Langebaan Road wellfield, supporting data received from the TDEM geophysical survey (**Figure 5-4**).

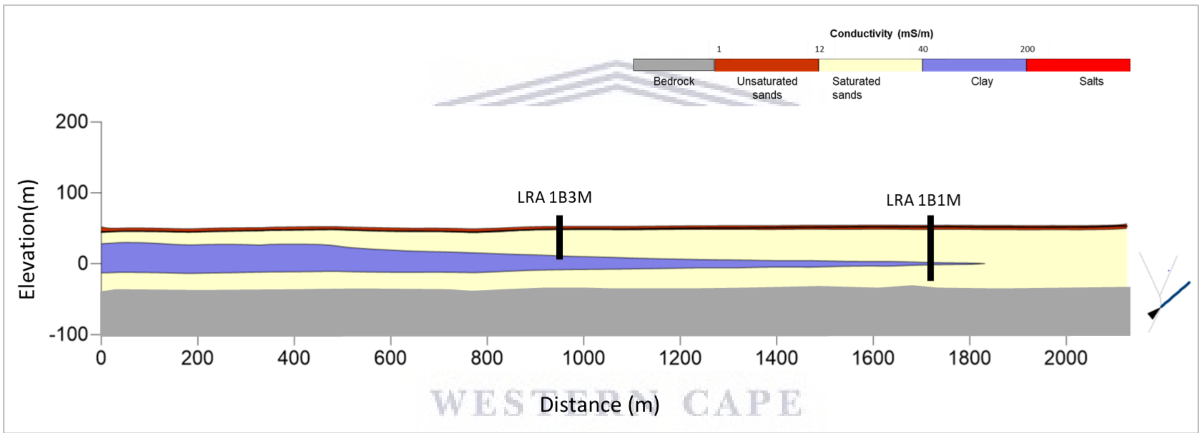


Figure 5-3: TDEM Airborne geophysical trial line 900061 at Langebaan Road wellfield indicating clay aquitard at Langebaan Road wellfield thinning out at LRA 1B1M

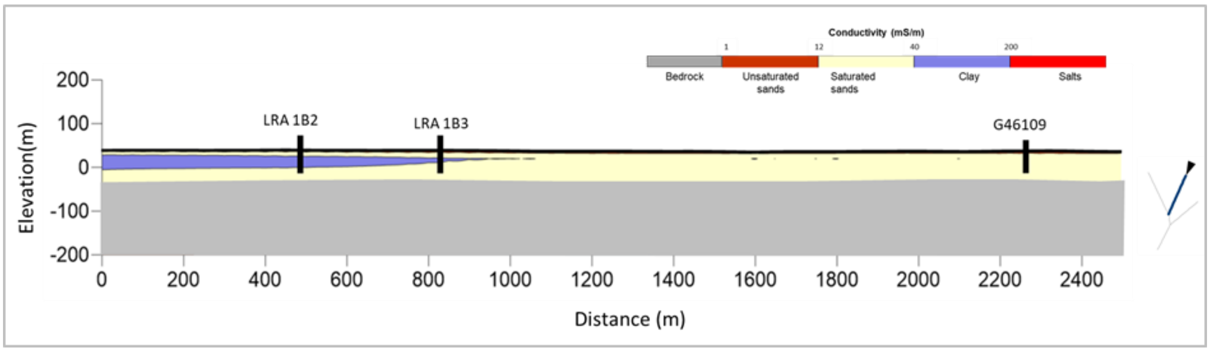


Figure 5-4: TDEM Airborne geophysical trial line 900070 at Langebaan Road wellfield indicating 'missing clay window' north east of the wellfield

When evaluating the potential of Managed Aquifer Recharge at Langebaan Road, the presence of the clay layer infers recharge into the lower aquifer would not be possible by MAR applications in the upper aquifer. Instead, the system could only support borehole injections as the type of Managed Aquifer Recharge application.

Tredoux and Engelbrecht (2009) used MODFLOW to simulate aquifer systems in which saturated flow conditions existed. From the spatial analysis of the aquifer, they found that the clay aquitard is the thickest in the southern part of the Langebaan Road region, and thins out towards the north. This supports the findings of the TDEM geophysical lines conducted at the Langebaan Road.

Additionally, Timmerman (1985) makes mention of older boreholes in his hydrological assessment of the Lower Berg aquifers and four of those boreholes (G29820, G29810, G29769 and G29770) are situated within the area where the clay layer is seen to be missing at Langebaan Road wellfield. Unfortunately, there is very little information on those boreholes and no evidence of their drilling logs, so additional drilled boreholes in this region are recommended to support these claims.

Hopefield wellfield

The TDEM geophysical investigations at Hopefield wellfield revealed that Hopefield has low variability in subsurface layers with sand being the dominant lithology (**Figure 5-5** and **Figure 5-6**). The data from these trial lines confirmed the findings of the wellfield ground resistivity (RES) geophysical survey lines. These are also supported by the lithological logs from the boreholes that were drilled by Nel (2019b).

There is an indication of deep saturated sand layers below the intermittent peaty clay layers at Hopefield wellfield in the airborne geophysics that was not seen with ground RES geophysics. Furthermore, there is a thin layer of light clay content observed in the drilling logs at a depth of ~ 100 m at HPF 2-6M that is not observed with the TDEM geophysics data. The clay layer at Hopefield is not continuous, suggesting that the aquifer system underlying Hopefield would act as one aquifer unit. This supports findings by Tredoux and Engelbrecht (2009) who stated that there are localised areas where the clay is absent.

The thick saturated sands of this aquifer will be the targeted geology for Managed Aquifer Recharge at the Hopefield wellfield. The absence of a confining clay suggests that Managed Aquifer Recharge techniques that focus on infiltration are supported at the Hopefield wellfield.

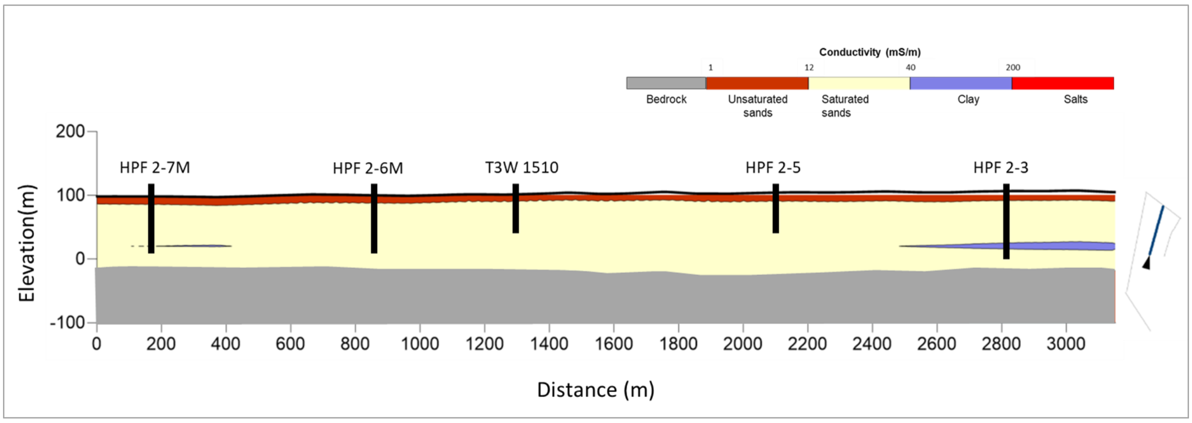


Figure 5-5: TDEM Airborne geophysical trial line 900040 indicating intermitted clay layers at Hopefield wellfield

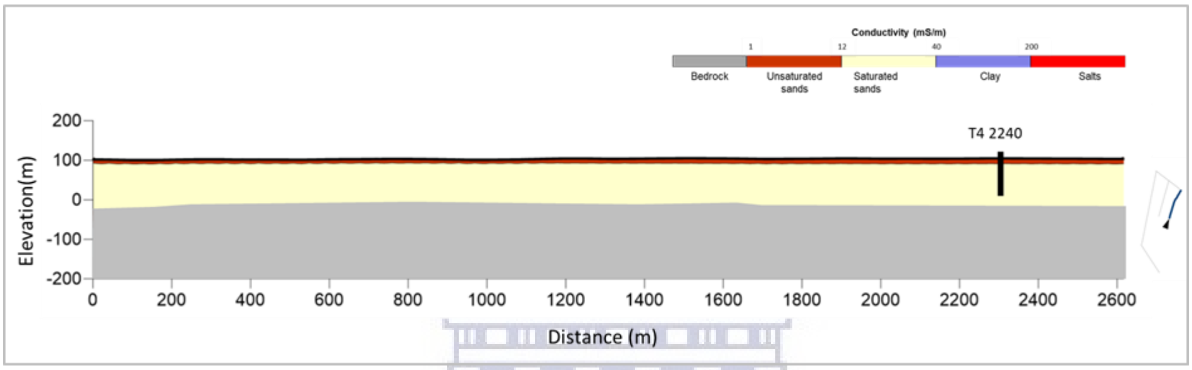


Figure 5-6: TDEM Airborne geophysical trial line 900050 at Hopefield wellfield identifying Hopefield as an unconfined single aquifer unit

5.1.3 Delineation of Lower Berg Aquifer System using TDEM Airborne Geophysics Data

Figure 5-7 identifies the different bedrock elevations that make up the Lower Berg aquifer system, focusing on the Saldanha Bay Local Municipal region. The yellow colour on the map situated just south of Langebaan Road and west of Hopefield depicts higher elevated areas such as the granite hills along the western part of the Saldanha Bay Municipality area. In terms of bedrock elevation, groundwater should flow from higher elevations (yellow) to lower elevations (blue), i.e. from the granite hills towards the south of the Langebaan Road wellfields towards the wellfield.

The blue colour represents the deeper parts of the bedrock and the deepest bedrock elevations (dark blue). These bedrock depths are approximately 100m below sea level. These deeper bedrock zones are where sands were deposited over time and make up the Lower Berg aquifer systems. There are also some deep bedrock patches found in the Langebaan Road wellfield vicinity towards the Berg with depths up to 60m below sea level. The positions of the deeper bedrock correlate with Smith's (1982) geophysics interpretations at Langebaan Road.

Similarly, The department of Water and Sanitation (DWS), formerly known as The Department of Water and Forestry (DWAF), appointed Umvoto to assess the groundwater components in the assessment of water availability in the Berg Catchment (WMA 19) by means of water-related models (DWS, 2008). Their paleo topography map identifying bedrock elevations (mamsl) within the West Coast shows that around Langebaan, bedrock elevations each a maximum of 90 mamsl and correlated with the granite hills found in the area. Similarity, at Hopefield, bedrock elevation reaches a maximum of 60 mamsl and decreases to approximately – 3 mamsl west towards the Hopefield wellfield and – 50 mamsl south-west towards the Langebaan Lagoon. This trend was also seen with the TDEM geophysics bedrock data in the study area. Moving north of the granite hills, towards the Berg River, bedrock elevation decreases.

Various descriptions of the basement topography have been generated by Timmerman (1985a). Depths are recorded in the northern palaeo channel of -55 mamsl in the vicinity of Saldanha, to - 25 mamsl near the Berg River, with its widest point just north of Langebaan Road. The southern channel slopes from -40 mamsl at Langebaan Lagoon to +10 mamsl near Hopefield. The TDEM geophysics data show the bedrock depths at the Hopefield wellfield range between 10 m and 30 m below sea level. This slightly higher bedrock elevation suggests local groundwater flow from the Hopefield wellfield towards the Lagoon in the southwest and also the Langebaan Road wellfield towards the northwest, which is similar to Timmerman's (1985) findings.

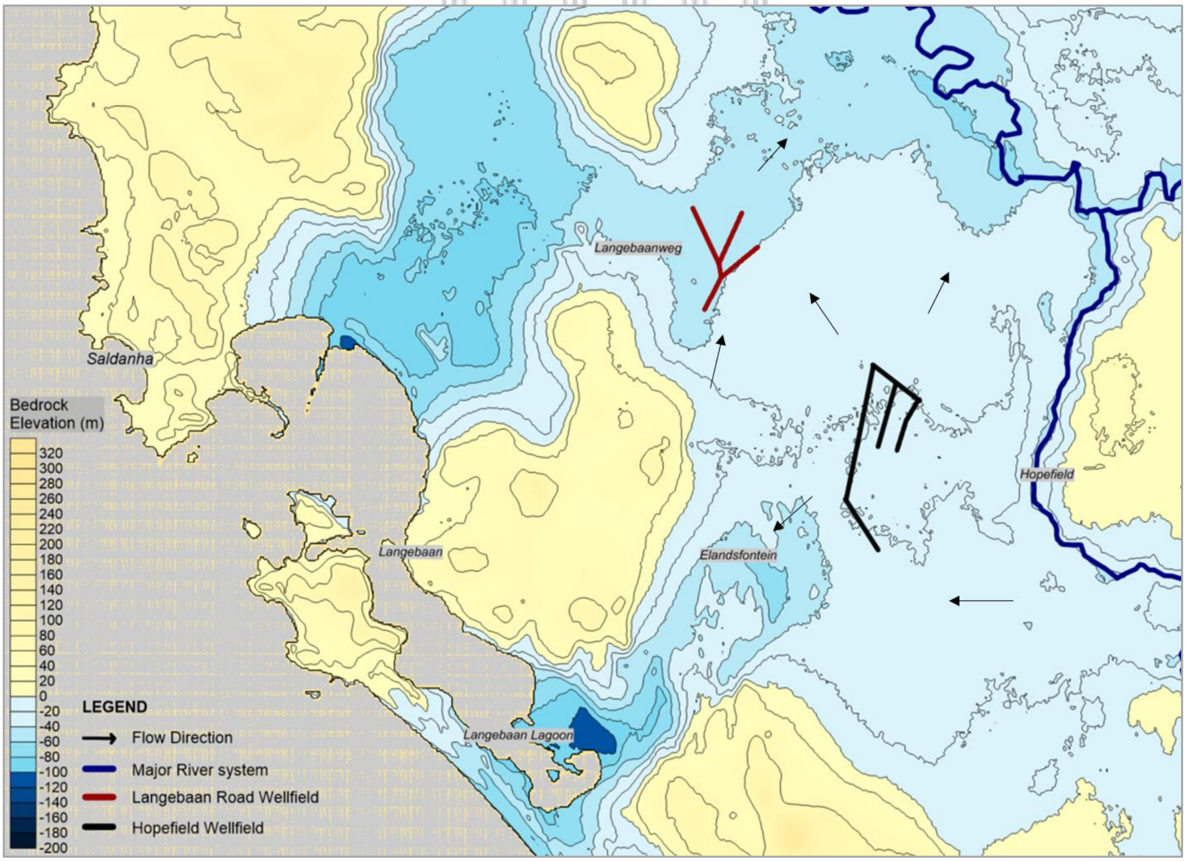


Figure 5-7: Bedrock topography map of the Saldanha Bay Local Municipality area delineating the extent of the underlying aquifer unit.

5.1.4 Delineation of subsurface layers within the Managed Aquifer Recharge study area from TDEM Airborne Geophysics Data

There are extensive clay layers observed within the Langebaan Road and Hopefield region (**Figure 5-8**). As these clay-filled zones were superimposed, the darker blue regions represent the areas with the thickest clay subsurface layers. To the northeast of the Langebaan Road wellfield, identified as 'Region A', there is an area in which there is no confining clay layer up to 80m below the surface. Similarly, at Hopefield, there are areas of missing clay layers to the west and east of the Hopefield wellfield, identified as 'Region B' and 'Region C' respectively.

The extent and distribution of the clay aquitard across the study area are similar to what Zhang (2019) found at Langebaan whereby thick clay layers (25 -30 m) underlaid the Langebaan Road wellfield and thinned out to < 5m towards the Berg River as well as towards the granite koppies to the south of the wellfield. Zhang's (2019) study differs, however, in Hopefield. Zhang (2019) identified Hopefield as having a very thick clay aquitard of up to 35 m and in contracts, the results from the TDEM geophysics identify that Hopefield has 'missing clay windows' to the east and west of the Hopefield wellfield.

Similarly, through the spatial analysis of the Langebaan Road/Hopefield aquifer units, Tredoux and Engelbrecht (2009) found that the clay aquitard is absent southwest of Hopefield. This supports the finding of the TDEM airborne geophysics conducted across the study area. This suggests that in these regions, recharge from the shallow aquifer to the deeper aquifer is possible. Regions A, B and C along with both the Langebaan Road and Hopefield wellfield are identified as potential sites for Managed Aquifer Recharge.

Cross sections A, B and C were generated to intercept the regions of missing clay layers around the Langebaan Road and Hopefield wellfield. Areas along these cross sections that coincide with missing clay layers and are situated within the deep parts of the Saldanha Bay aquifer system will be identified as Managed Aquifer Recharge sites.

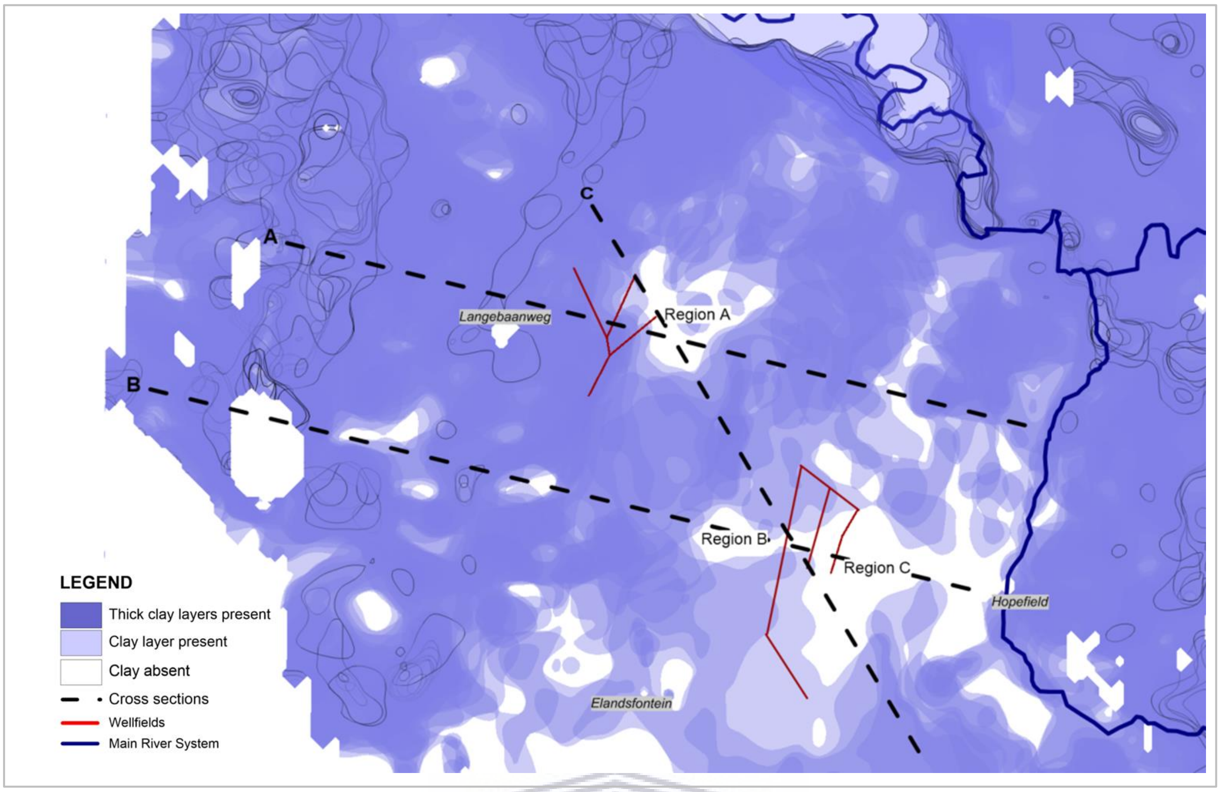


Figure 5-8: Spatial extent of the clay layers within the Managed Aquifer Recharge study area indicating potential MAR sites.

Three cross sections running through the Langebaan Road and Hopefield (**Figure 5-9**) show the depth and thickness of the different aquifer materials within the region. The bedrock is characterized by any conductivity lower than 1 mS/m. Zones of lower conductivity (1-12 mS/m) are identified as dry unsaturated sands. As conductivity increases, the saturated sands (12- 40 mS/m) and the clay lenses (40 – 200 mS/m) become distinguishable. The zones of highest conductivity (200+ mS/m) are identified as the regions within the aquifer that have a high salt content.

This is similar to what Al-Amoush et al. (2015) saw with their MAR study using geophysics applications. The study slightly differs, however, as the TDEM application was not able to distinguish between the clay and peat layers at Langebaan Road and Hopefield, on such a small scale.

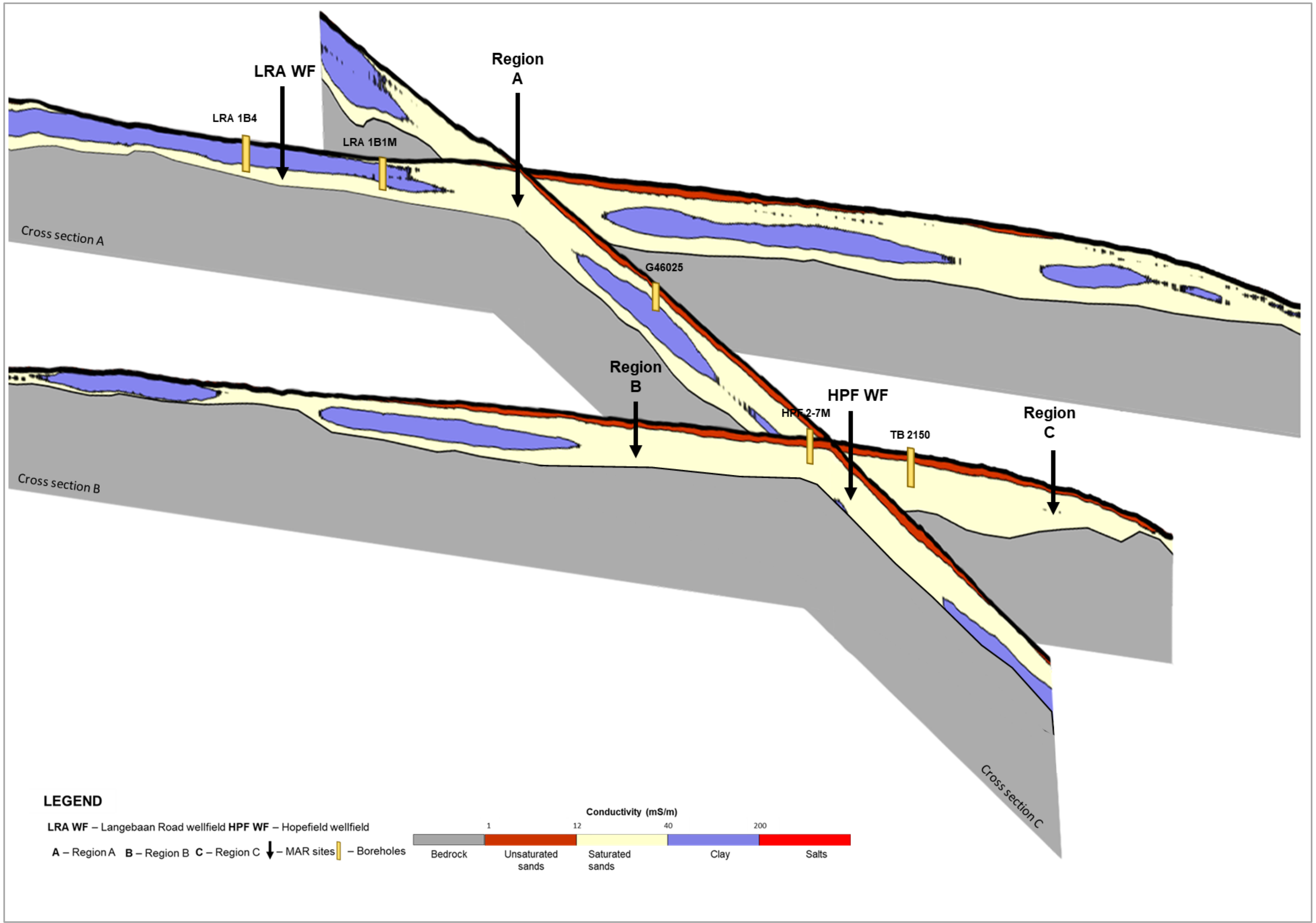


Figure 5-9:Conceptual model identifying the target Managed Aquifer Recharge sites based on the geophysics done within the Saldanha Bay Local Municipal region.

A conceptual model identifying the areas suitable for Managed Aquifer Recharge within the Lower Berg aquifer system was generated using the delineated aquifer material within this region (**Figure 5-9**). The conceptual model identifies five regions in the study area that have the potential to support Managed Aquifer Recharge, namely, the Langebaan Road wellfield, the Hopefield wellfield, Region A, Region B and Region C.

Zhang (2019) assessed Managed Aquifer Recharge using a GIS-based modelling approach in the West Coast, South Africa. He generated several maps indicating suitable sites for MAR in the West Coast based on source water availability, infiltration capacity and storage capacity. The outputs of his MAR site suitably maps at Langebaan Road and Hopefield correlate well with the 5 regions identified as potential sites for MAR in this study. Additionally, Zhang (2019) outlined one area west of the Hopefield wellfield identified as a "clay-missing window area'. This area correlates well with "Region B".

Based on **Figure 5-9**, at the Langebaan Road wellfield, the main aquifer system is situated below a thick clay layer. Therefore, borehole injections would be the only possible Managed Aquifer Recharge technique in this area. The lack of unsaturated sands (due to the aquifer being a confined system) suggests that the aquifer itself would need to expand to recharge the system. MAR can only take place once the piezometric levels in the aquifer have dropped by displacing some of the pressure of the aquifer.

As seen by Tredoux and Engelbrecht (2009), two borehole injection tests at Langebaan Road wellfield resulted in the formation of artesian wells due to the high pressure with which the source water was injected as well as the lack of sufficient space to recharge the aquifer. As such, Zhang (2019) proposed that the Langebaan Road lower aquifer is only suitable for MAR on the condition that water levels have significantly dropped.

In Region A, the absence of the clay layer means that recharge to the shallow aquifer would result in the recharge of the main deeper aquifer. Additionally, there is evidence of thicker unsaturated sands underlying Region A. This infers that more space is available to recharge the aquifer than compared with the Langebaan Road wellfield. There are also fewer pressures acting on the system where there is no confining clay layer. The presence of the unsaturated sands means that the formation of artesian wells is less likely to occur during the MAR processes. Additionally, the absence of clay means that infiltration-type MAR techniques are suitable for this region, which has the advantage of an added treatment as it infiltrates and percolates through the aquifer. Lastly, as Region A falls directly within the natural groundwater flow path of the local area, any recharge to this area suggests that water can be stored and later abstracted from the Langebaan Road wellfield when needed.

At the Hopefield wellfield, clay is present sporadically throughout the area. In the far northern and southern regions of the wellfield, thick clay layers are observed. In the middle of the wellfield and towards the west and east of the wellfield, the clay is absent. This suggests that recharge to the deeper aquifer at the Hopefield wellfield is possible through the unsaturated zone using infiltration-type techniques. Borehole logs of the Hopefield wellfield drilled by Nel (2018) confirm the distribution of clay zones within the aquifer system underlying Hopefield. Additionally, there is evidence of thicker unsaturated sands at the Hopefield wellfield. Similar to Region A, this suggests that space is available to recharge the aquifer. Additionally, the local movement of groundwater within the Hopefield region suggests that the aquifer can be recharged at the Hopefield wellfield, stored, and abstracted from either the Region B or the Langebaan Road wellfield.

In Regions B and C there is a layer of unsaturated sands overlying the thick saturated sands of the aquifer underlying Hopefield. The unsaturated and saturated sand seems to be thicker in Region B than compared to Region C. The presence of the unsaturated sands, however, suggests that there is space to recharge the aquifer in these regions. The absence of clay infers that Managed Aquifer Recharge is possible to the deeper main aquifer through infiltration-type techniques that aid in the treatment of water as it moves through the aquifer. Groundwater flow in Region B has the potential to flow towards Langebaan Road (area of lower elevation) or towards the Elandsfontein aquifer unit where it can be abstracted. Groundwater flow at Region C has the potential to flow towards the Hopefield wellfield from a south-westerly direction, where it can be abstracted.

All potential Managed Aquifer Recharge sites need to be further evaluated in terms of their hydraulic properties before sites are confirmed. Likewise, the evidence of the unsaturated zone observed with the TDEM geophysics needs to be compared with actual water levels (mbgl) across the study area to determine which areas have the space to store water before final MAR sites are selected.

5.2 Hydrogeological Investigations

5.2.1 Availability of Space for Water Storage based on water levels at Langebaan Road and Hopefield.

Water levels at Langebaan Road and Hopefield identified space for the physical addition of water to the aquifer in the specified regions with the assumption that unsaturated sands, observed with the geophysics, have the potential to become saturated during the MAR process. This will indicate whether the Managed Aquifer Recharge scheme is required immediately or whether the municipality needs to use its water reserves before the recharging of the aquifer is required.

Short term monitoring took place at the Langebaan Road wellfield and surrounding boreholes between 2019 – 2021. Water levels suggest that the deeper aquifer at Langebaan Road wellfield is currently full (water level close to the surface) as the piezometric level at Langebaan Road ranges from about 2 -10 metres below ground level (**Figure 5-10**). These levels are very similar to the water levels observed by Weaver and Fraser (1998) during the drilling of the Langebaan Road wellfield. Water levels close to the surface could limit the space for recharging the aquifer , as seen in previous studies (Tredoux and Engelbrecht, 2009; CSIR, 2008), where water injection at the Langebaan Road wellfield resulted in the formation of artesian wells. If the Langebaan Road aquifer were to be used for Managed Aquifer Recharge, it would be most feasible once the piezometric levels in the aquifer have dropped. Groundwater abstraction will lower the pressure in the confined system, therefore, allowing for efficient MAR.

LRA 1B1M and G46061 are an exception as they have piezometric levels of around 10 - 23 metres below ground level. LRA 1B1M is situated to the northwest of the Langebaan Road at the same elevation as the wellfield. According to the TDEM geophysics data (**Figure 5-3**), the clay aquitard thins out in this direction resulting in a lower piezometric head at this borehole. As a result, water levels are lower in this region. Similarly, G46061 is located in the "missing clay window" at Langebaan Road and as such has a lower water level. It is also possible that the difference in surface elevation of about 2 m has resulted in this water level being lower.

Water levels in and around the Hopefield wellfield between 2019 – 2021 generally range between 10 – 15 metres below ground level (mbgl) (**Figure 5-11**). Water levels are slighter lower at Hopefield when compared to Langebaan Road as Hopefield is at a higher elevation. Similarly, G33498 and G33498A are situated on a dune at an elevation of about 101 m just south of the Hopefield wellfield. As a result, water levels in this region are the lowest below ground level (between 20 – 30 mbgl).

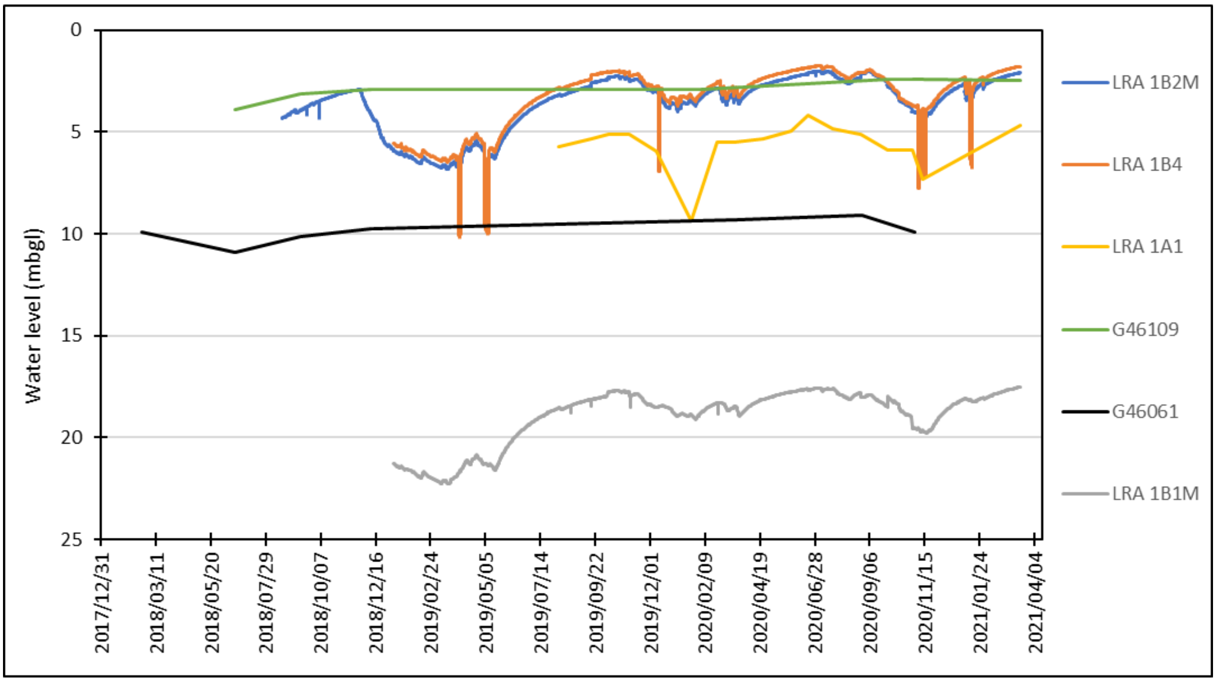


Figure 5-10: Water levels at Langebaan Road indicate the majority of water levels ranging from 2 -10 m.

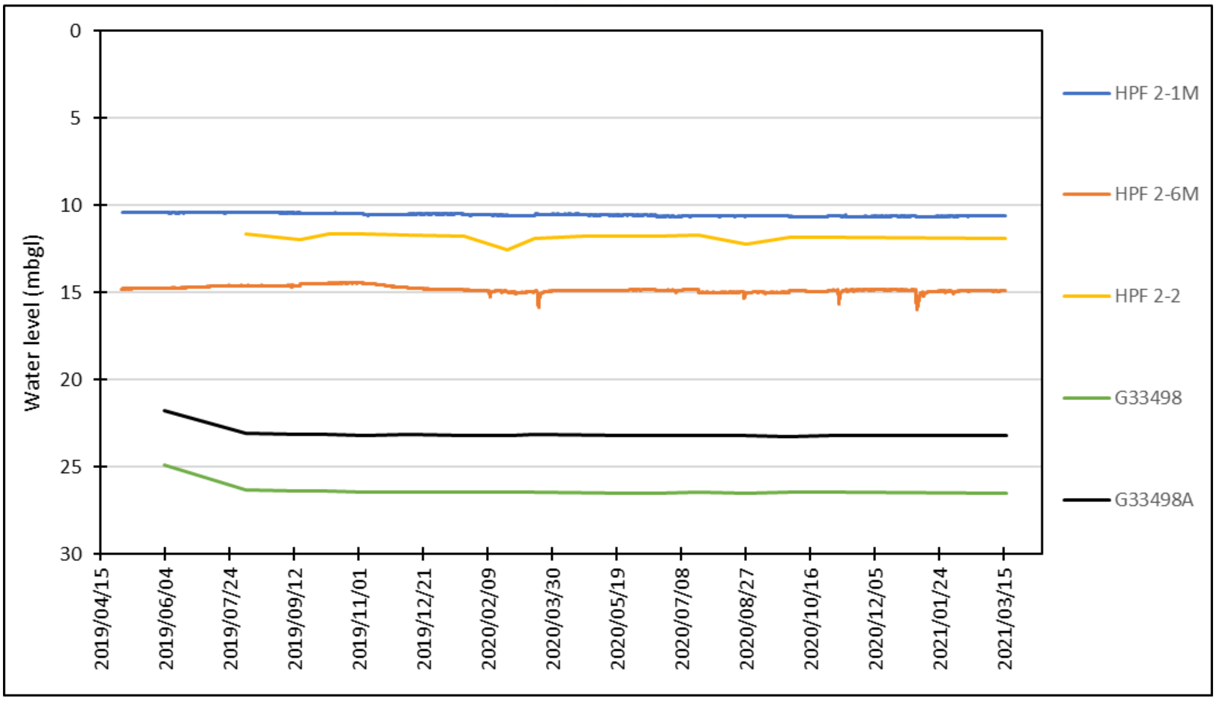


Figure 5-11: Water levels at Hopefield indicate the majority of water levels ranging from 10- 15 m.

Spatial distribution of depth to water levels was generated (**Figure 5-12**) using water level (mbgl) data collected between 2019 - 2021. From this, it was observed that overall water levels around Langebaan Road are shallower (2 -10 mbgl) than Hopefield (10-15 mbgl). This was seen with the TDEM geophysics as Hopfield had thicker layers of unsaturated sands when compared with Langebaan Road. At G46064, G46065 and G46097 the water levels at Hopefield are deepest at around 15 – 20 mbgl. In addition, these boreholes fall within the local groundwater flow path from Hopefield to Langebaan Road suggesting that recharging the aquifer at Hopefield could result in the movement and storage of water at these regions of lower water levels.

The water levels around the Elandsfontein Mine are around 60 mbgl. These water levels are deep due to the dewatering of the aquifer for mining purposes and are not an accurate representation of the natural water levels in this region.

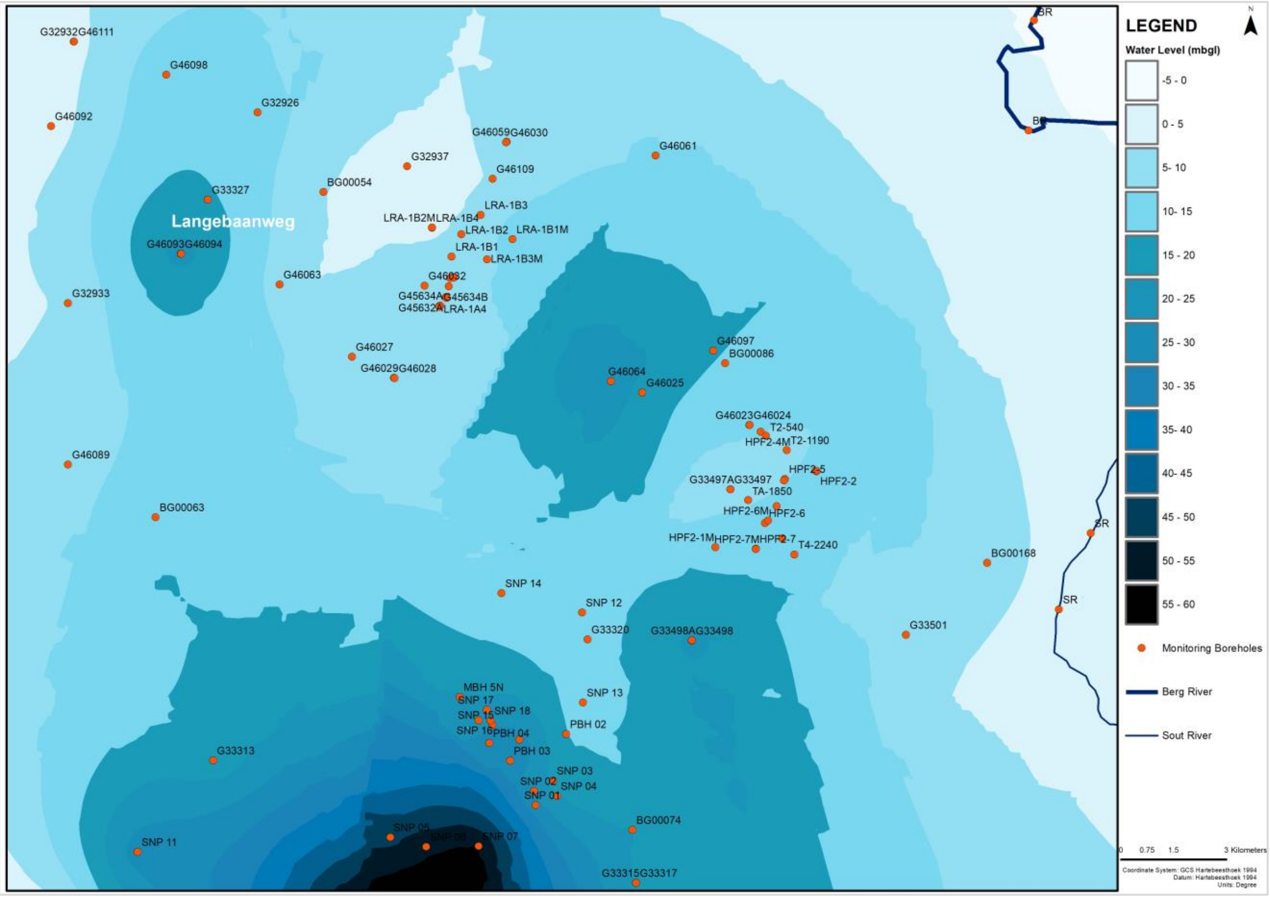


Figure 5-12: Conceptualized spatial distribution of water levels across the study area identifying Hopefield as having deeper depth to water levels when compared to Langebaan Road.

5.2.2 *Unsaturated and Saturated zone infiltration tests*

Unsaturated and Saturated hydraulic conductivities at Langebaan Road and Hopefield

Infiltration tests done using an infiltrometer at Langebaan Road and Hopefield determined that a specific volume of water infiltrates into top soils faster at Hopefield than it does at Langebaan Road. The average unsaturated hydraulic conductivities (K) for Langebaan Road exhibited values ranging from 0.17 m/day – 4.77 m/day and 1.81 m/day - 33.94 m/day at Hopefield (**Table 5-2**). According to Roberts et al. (2011), top soils at Langebaan Road are dominated by calcrete and/or limestone layers and Hopefield's top soils are dominated by the windblown sands of the Witzand Formation. Large calcrete outcrops were observed at Langebaan Road during field visits (**Figure 5-13**). These calcrete layers did not easily allow the infiltration of water from the surface into the soil, thus the infiltration rates and subsequent hydraulic conductivities at Langebaan Road are lower, which contradicts the previously mentioned assumptions that calcrete layers could benefit infiltration by creating preferential pathways for infiltrated water to flow. Additionally, field observations indicated that when the sands at Langebaan Road came into contact with water, they formed a loamy, almost hydrophobic texture that slowed down the infiltration process. This observation was not noted at Hopefield.

Figure 5-13: Calcrete outcrops observed throughout the Langebaan Road Region

Based on geophysical results (**Figure 5-9**) thicker top layers of unsaturated sands are observed at Hopefield than when compared to Langebaan Road. These dry top soils are more susceptible to infiltration resulting in higher infiltration rates and subsequent hydraulic conductivities. This is attributed to the fact that the drier soils have more pore spaces available to receive water and as water starts to infiltrate, these pore spaces fill up and form pathways allowing water to flow easier through the soil. Once the soil has reached maximum saturation, the ability of the soil to receive and transmit water decreases.

G33498 is a borehole situated just southwest of the Hopefield wellfield and is located on a dune dominated by the dry windblown sands of the Witzand formation. This borehole has an average K value of 33.94 m/day which is uncharacteristically high compared to the rest of the boreholes at Hopefield. This is because the sand composition (Witzand formation) of this higher elevated borehole is slightly different than the rest of Hopefield, with the sand particles being slightly finer and drier (**Figure 5-14**).

Field observations further indicated that sands within the immediate vicinity of the Hopefield wellfield are significantly drier than the rest of the study area, allowing for a much faster rate of infiltration.

Figure 5-14: Very fine wind-blown top soils at G33498, situated on a dune

The average saturated hydraulic conductivities at Langebaan Road range between 0.13 m/day – 3.12 m/day. The average saturated hydraulic conductivities at Hopefield range between 0.27 m/day – 2.70 m/day. Saturated hydraulic conductivities follow the same trend as the unsaturated hydraulic conductivity where Hopefield has higher K values than Langebaan Road. As expected, the saturated hydraulic conductivities are lower than the unsaturated conductivities. This is because the soil has reached maximum saturation and the ability of the soil to receive and transmit water has decreased. The saturated hydraulic conductivities at both Langebaan Road and Hopefield are similar to what Boonstra and Soppe (2017) found for loamy sand – medium sand and fine sand textures, respectively.

The saturated hydraulic conductivities are representative of the shallow aquifer at Langebaan Road and Hopefield. The low hydraulic conductivities at Langebaan Road infer that water will not easily flow within the shallow aquifer and therefore MAR schemes, which rely on the aquifer to be able to transmit and store water, are unfavourable.

The saturated hydraulic conductivities at Hopefield are much lower than the unsaturated hydraulic conductivities which infers that the drier soils at Hopefield have the potential to transmit and store water up until soil saturation, whereby hydraulic conductivities then decrease. As such, the shallow aquifer at Hopefield is favourable for MAR in areas where dry soils allow for the infiltration of water into the saturated zone. **Table 5-2** details the unsaturated and saturated hydraulic conductivities representative of different areas within Langebaan Road and Hopefield.

Table 5-2: Average Saturated and Unsaturated Hydraulic Conductivities at Langebaan Road and Hopefield

	BH ID	Coordinates		Unsaturated hydraulic conductivity (m/day)	Saturated hydraulic conductivity (m/day)
Langebaan Road	G32932	-32.92317	18.09342	4.73	0.87
	G33323	-32.8855	18.24770	7.29	0.47
	G33324	-32.55959	12.111943	0.83	0.30
	G46098	-32.93156	18.117	1.72	0.86
	G32926	-32.9412	18.1403	1.20	0.78
	G46055	-32.94622	18.17727	1.93	0.73
	G46109	-32.95819	18.20031	1.12	0.22
	G46093	-32.97735	18.12070	1.01	0.56
	G32938	-32.99873	18.06793	0.17	0.40
	G32933	-32.9899	18.09195	2.17	0.13
	G46106	-33.012867	18.0568167	6.58	0.99
	G32930	-33.15959	18.50182	3.04	0.12
	BG00063	-33.04454	18.11430	2.04	0.28
	LRA 1B2	-32.972362	18.19235	4.77	3.12
	LRA 1B1M	-32.973593	18.205401	1.63	0.46
Hopefield	G46025	-33.01272	18.23847	2.88	0.76
	HPF 2-3M	-33.03268	18.282708	3.85	0.93
	HPF 2-7M	-33.05268	18.26745	11.38	2.70
	G33498	-33.07607	18.2511	33.94	1.13
	G33501	-33.07463	18.30582	1.81	0.27
	G46097	-33.00208	18.25657	2.86	0.94

5.2.3 Constant Discharge tests

Constant Discharge tests were conducted in the study area, to supplement the previous pumping investigations done by Nel (2018, 2019b), following the same conditions as set out by Kruseman and de Ridder (2000). These were collectively used to determine the hydraulic conductivity of the aquifer at Langebaan Road and Hopefield.

Langebaan Road and Hopefield aquifer testing

Two boreholes near the Langebaan Road wellfield were pumped to assess the aquifer hydraulic characteristics at a distance from the wellfield. G46094 is a borehole drilled into the shallow unconfined aquifer at Langebaan Road. Pumping this borehole at a rate of 0.24 L/s for two hours obtained a total drawdown of 3.52 m before recovering to static water level (**Figure 5-15**). Using Cooper and Jacob's curve fitting methods the hydraulic conductivity value for the shallow unconfined aquifer at G46094 is approximately 0.5 m/day. Due to this borehole being drilled into the unconfined aquifer, a lower hydraulic conductivity was expected and is consistent with Nel's (2018) K values of the unconfined aquifer.

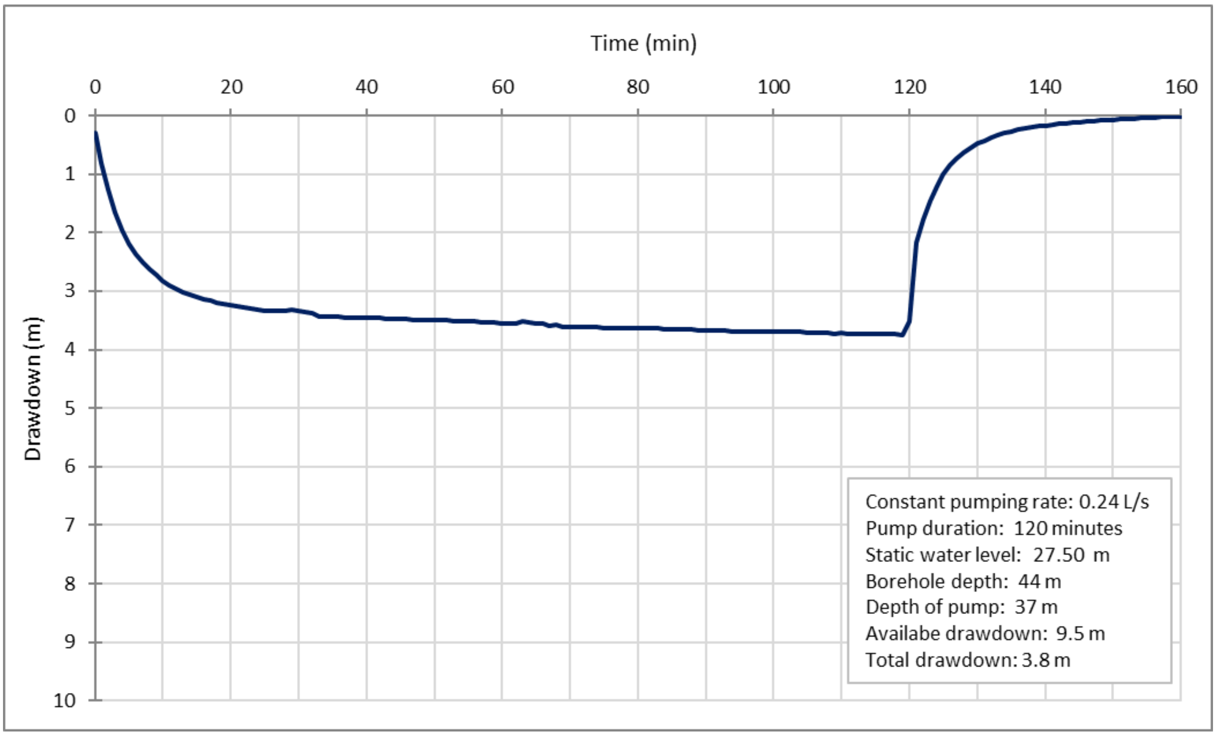


Figure 5-15: G46094 pump test analysis interpreted using Cooper and Jacob's curve fitting method.

G46093 is a borehole drilled into the deeper confined aquifer at Langebaan Road. Pumping this borehole at a rate of 0.6 L/s for 55 min obtained a total drawdown of 0.19 m. The insignificant drawdown at this borehole suggests that G46093 is drilled into a high yielding aquifer zone at screen depth. The hydraulic conductivity estimated using this data would be an overestimation of K as the aquifer was not sufficiently stressed during this pumping event. It is recommended that the deeper aquifer at Langebaan Road be pumped at much higher rates over a longer period to correctly determine K. However since this borehole is drilled into the same geological formation as the Langebaan Road wellfield, it is hypothesized that the hydraulic conductivity values should be similar.

In addition, a borehole to the southwest of the Hopefield wellfield was pumped to assess the aquifer hydraulic characteristics at a distance from the wellfield. G33501 is a borehole drilled into the shallow unconfined aquifer at Hopefield. Pumping this borehole at a rate of 0.5 L/s for two hours obtained a total drawdown of 4.56 m before recovering to static water level (**Figure 5-16**). Using Cooper and Jacob's curve fitting methods the hydraulic conductivity value for the shallow unconfined aquifer at G33501 is 0.08 m/day. Since this borehole is in the unconfined layers of the aquifer, a lower K was expected.

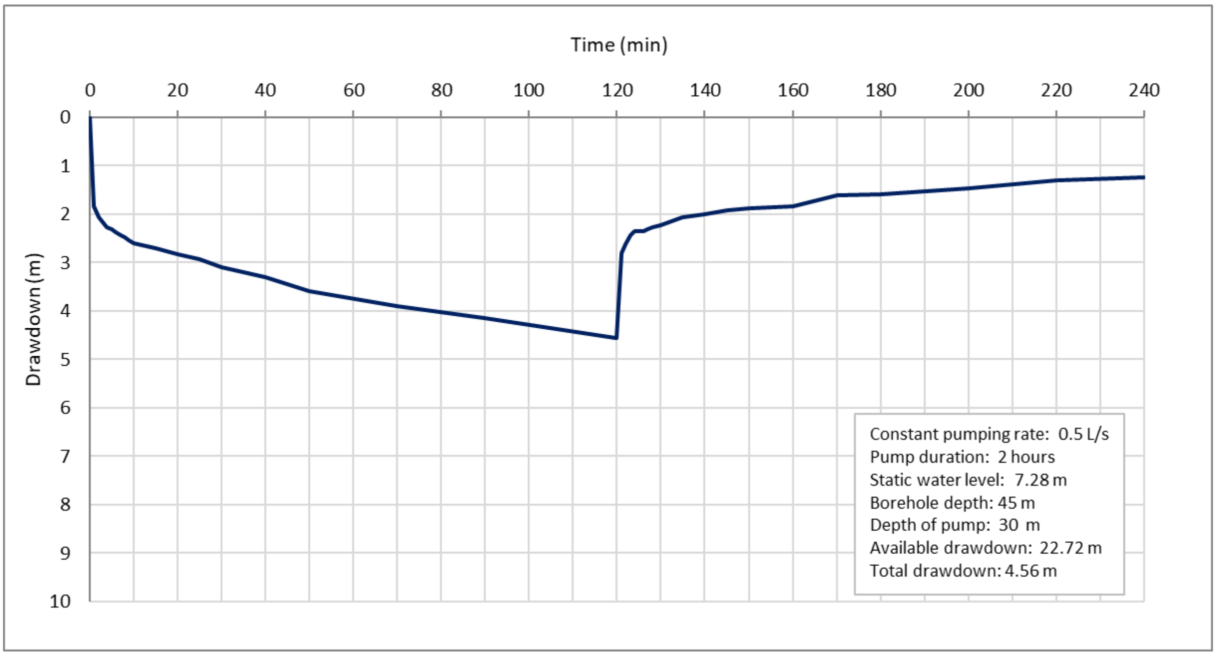


Figure 5-16: G33501 pump test analysis interpreted using Cooper and Jacob's curve fitting method.

According to Nel (2018), the hydraulic conductivity ranged from 0.66 m/day to 39.59 m/day within the Langebaan Road deeper aquifer. This is typical for the medium to coarse sand (Dillon et al. 2009; Murray and Tredoux, 1998) and is considered a high hydraulic conductivity which is the target for Managed Aquifer Recharge. The highest value of hydraulic conductivity was seen at LRA 1B1 as 39.59 m/day and the lowest value was 0.66 m/day at LRA 1B3. LRA 1B3 has a K value similar to G46094 despite it being drilled into the deeper confined Langebaan Road aquifer. This uncharacteristic K value could potentially be the result of finer sands observed at/ around screen depth at LRA 1B3.

The hydraulic conductivities for Hopefield were much lower than Langebaan Road, which was expected of the unconfined system. The highest hydraulic conductivity value at Hopefield was 3.24 m/day at T4 2240 and the lowest was 0.08 m/day at G33501. This is typical for this type of sedimentology (fine sands), except for G33501, which is uncharacteristically low. This could be related to the thick clay delineated in the area around this borehole (**Figure 5-8**). It could also be possible that this borehole was drilled into clay however not captured in the records.

Spatial distribution of hydraulic conductivity within the Managed Aquifer Recharge study site

Hydraulic conductivities derived from unsaturated and saturated infiltration tests, as well as pumping tests, were combined to display the spatial distribution of hydraulic conductivities across the study area (**Figure 5-17**). The unsaturated hydraulic conductivities are characteristic of the top soils in the study area, the saturated conductivities characterise the upper aquifer at Langebaan Road and the shallow aquifer at Hopefield, and the pump test hydraulic conductivities characterise the deeper aquifer systems.

At the Langebaan Road aquifer, low saturated hydraulic conductivities suggest that the shallow aquifer is a low yielding zone and therefore not suitable for Managed Aquifer Recharge. Deeper into the lower Langebaan Road aquifer, evidence of higher yielding zones is characterised by higher hydraulic conductivities. This infers that Managed Aquifer Recharge can be supported in the deeper Langebaan Road aquifer. In comparison, at Hopefield, top soils have high hydraulic conductivities which supports Managed Aquifer Recharge using infiltration techniques. Deeper within the Hopefield aquifer, the hydraulic conductivities decrease suggesting that the deeper Hopefield aquifer is lower yielding than Langebaan Road.

Further investigations by Nel (2019b) show that the recommended sustainable yield over 24 hours at Langebaan Road was 198 l/s and 50 l/s at Hopefield. The overall yields at the Hopefield wellfield were lower than at the Langebaan Road wellfield, yet still yielded a sufficient amount of water for municipal supply. Interestingly, Timmerman (1985) found that even though an aquifer can have a relatively low hydraulic conductivity, it can still have a high yield due to the saturated thickness of the aquifer, which is most likely the case for Hopefield.

Even though the yields at Hopefield were not as high as Langebaan Road, according to communications from Nel, after pumping the Hopefield boreholes for 24 hours the water levels started to stabilize in some instances. This was because the water pumped out of the borehole was discharged too close to the area of pumping thus resulting in a return flow from about 100 m back to the borehole within 24 hours. The pumping test had to be redone with the discharge pipe situated at a further distance from the pumping well. This, however, suggested that there was a good rate of recharge at Hopefield utilizing surface infiltration. This confirms the findings of the infiltration tests at Hopefield and as such, Managed Aquifer Recharge through infiltration should be the target at Hopefield.

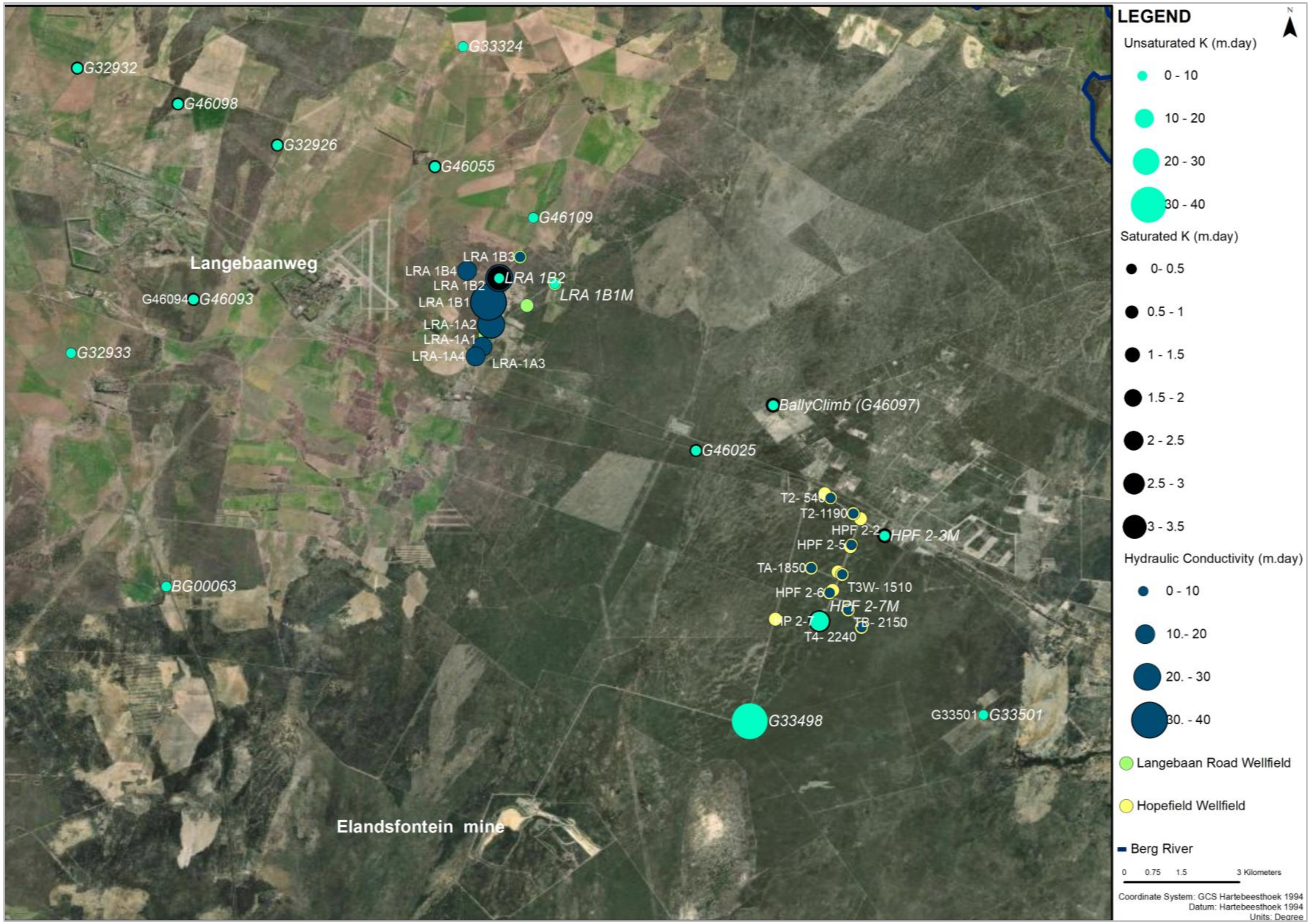


Figure 5-17: Spatial distribution of hydraulic conductivity within the Langebaan Road and Hopefield region identifying aquifer zones best suited for MAR.

5.3 Managed Aquifer Recharge sites based on TDEM geophysics results and hydraulic conductivities in the study area.

In terms of hydraulic conductivity, both the deep aquifer at Langebaan Road and the shallow aquifer at Hopfield are suitable for Managed Aquifer Recharge (MAR) schemes within Saldanha Bay. In the Langebaan Road region, two (2) sites are identified for Managed Aquifer Recharge: The Langebaan Road wellfield and Region A. The Langebaan Road deeper aquifer has high yielding confined zones within the coarse sands and gravels of the Elandsfontyn Formation. It is also already equipped with MAR reversible valves and pumps that can be used to recharge the aquifer, on the condition that the aquifer is capable to store that aditional water. Therefore, the MAR applications that are most suitable for the aquifer at Langebaan Road are Aquifer Storage and Recovery (ASR) or Aquifer Storage, Transport and Recover (ASTR) in high hydraulically conductive (K) sand layers, when the aquifer has fewer pressures acting on it (i.e., the piezometric levels have dropped). As the recommended MAR technique is borehole injection, the quality of the source water being used for MAR should be evaluated.

In the Hopefield region, three (3) sites are identified for Managed Aquifer Recharge: The Hopefield Wellfield, Region B and Region C. The Hopefield aquifer is mostly unconfined within the sands of the Varswater Formation. Hopefield shows evidence of high infiltration rates in addition to high pump yields, despite its lower hydraulic conductivities. This suggests that the MAR applications most suitable for Hopefield would be infiltration-based systems such as infiltration basins and/or galleries. The type of MAR infiltration system proposed in the Hopefield region would depend on the among of land space available for MAR. Infiltration techniques are in most cases known to improve the quality of the source water as it filters through the aquifer however, the effect of the reaction between the source water, groundwater and the aquifer geology should be investigated.

Figure 5-18 summarizes five (5) sites identified for Managed Aquifer Recharge within the Saldanha Bay Local Municipality based on the results from the TDEM geophysical surveys as well the aquifer hydraulic tests. The proposed Managed Aquifer Recharge technique best suited to each site is detailed in **Table 5-3**.

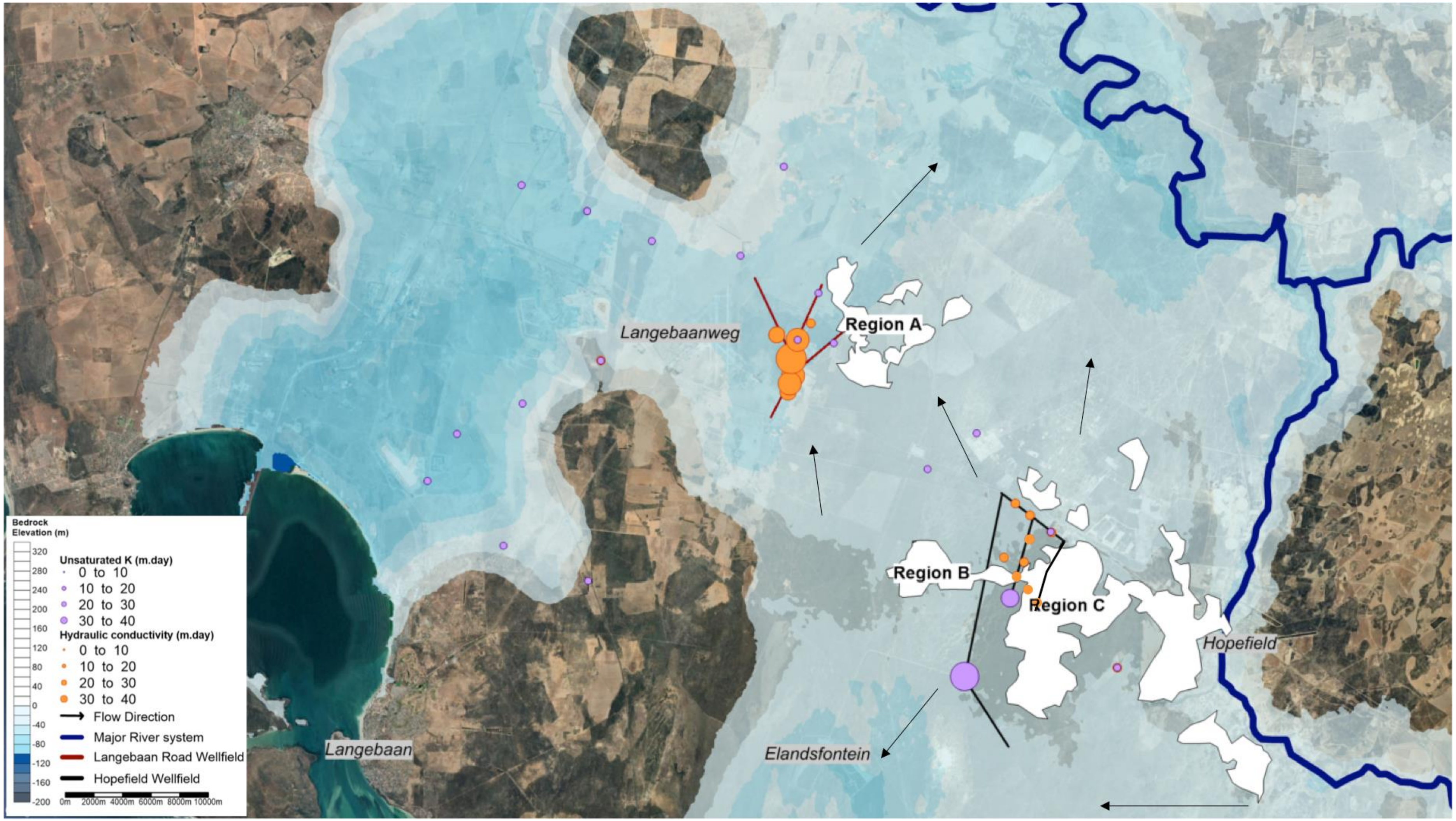
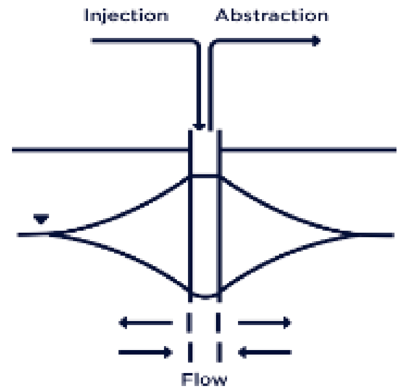
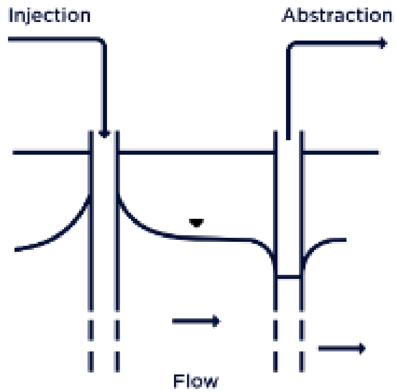


Figure 5-18: Sites identified for Managed Aquifer Recharge within the Saldanha Bay Local Municipality

Table 5-3: Suitable MAR techniques within the Langebaan Road and Hopefield Region based on TDEM geophysics and hydraulic conductivities in the Managed Aquifer Recharge study area.

<table>
<tr><th>Considerations / Evaluations</th><th>Proposed MAR technique/s</th></tr>
<tr><td>LANGEBAAN ROAD WELLFIELD

Situated within the deeper parts of the aquifer that make up the Lower Berg aquifer system
Calcrete topsoil layers do not easily allow the infiltration of water from the surface into the soil, thus Managed Aquifer Recharge via infiltration techniques is not viable
Higher yielding zones within the deeper aquifer are characterised by higher hydraulic conductivities
The presence of clay suggests recharge to the higher yielding deeper aquifer can only take place via borehole injections
Wellfield boreholes are equipped for Managed Aquifer Recharge via Aquifer Storage and Recovery techniques
Wellfield is within the natural local groundwater flow path from Hopefield to Langebaan
Piezometric levels are at 0 - 5 mbgl which suggests that there is currently no space to recharge the aquifer
The deeper aquifer is a pressurised system due to the presence of a clay layer therefore Managed Aquifer Recharge can only occur when there has been a drop in piezometric level by the lowering of the pressure of the system
</td><td>
</td></tr>
<tr><td>REGION A

The absence of the clay layer infers recharge to the main deeper aquifer via the unsaturated zone
Falls directly within the natural groundwater flow path of the local area, so recharge to this area means that water can be stored and later abstracted from the Langebaan Road wellfield
Calcrete topsoil layers do not easily allow the infiltration of water from the surface into the soil, thus Managed Aquifer Recharge via infiltration techniques is not viable.
Higher yielding zones within the deeper aquifer characterised by higher hydraulic conductivities suggest MAR via borehole injections is viable
Water levels are at 0 - 5 mbgl. This suggests that there is currently no space to recharge the aquifer and Managed Aquifer Recharge can only occur when there has been a drop in water level
</td><td>
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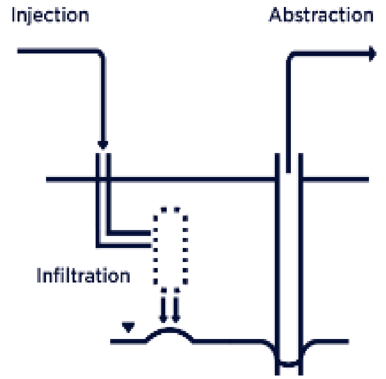
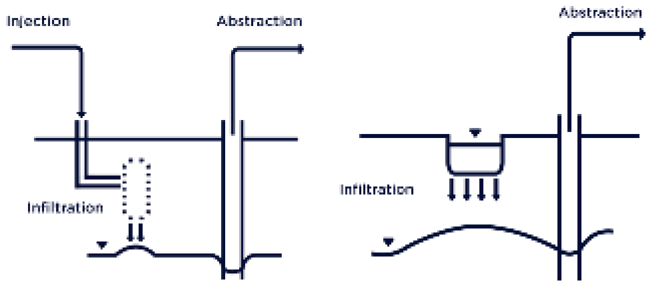
HOPEFIELD WELLFIELD

- The absence of the clay layer infers recharge to the deeper aquifer via the unsaturated zone using MAR infiltration type techniques.
- Evidence of thicker unsaturated sands suggests that **space is available to recharge the aquifer**
- The Hopefield unconfined aquifer has an average water level of about 10 – 15 metres below ground level (mbgl). At G46064, G46065 and G46097 the water levels at Hopefield are deepest at around 15 – 20 mbgl. This suggests that there is currently space to recharge the aquifer
- Local movement of groundwater within the Hopefield wellfield region suggests that the aquifer can be recharged at the Hopefield wellfield, stored, and abstracted from either Region B or the Langebaan Road wellfield
- The top dry soils have high hydraulic conductivities which supports **MAR via infiltration techniques**.
- Lower hydraulic conductivities are observed deeper within the Hopefield aquifer suggesting MAR via deep borehole injection is not viable



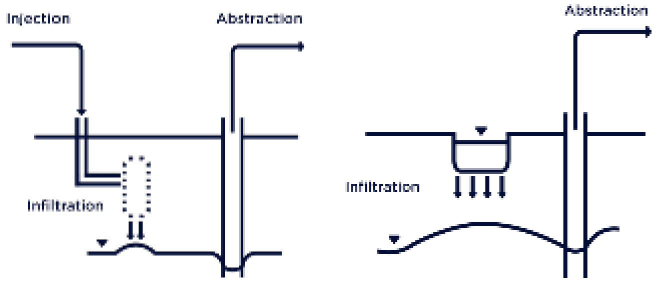
REGION B

- The absence of clay infers that Managed Aquifer Recharge is possible to the deeper main aquifer through infiltration-type techniques
- Local groundwater flow suggests MAR at Region B has the potential to flow towards Langebaan Road (area of lower elevation) or towards the Elandsfontein aquifer unit where it can be abstracted.
- The deepest water level (15 - 20 mbgl) observed in this region coupled with thick unsaturated sands suggests that there is **space to recharge the aquifer**
- The top dry soils have high hydraulic conductivities which supports **MAR using infiltration techniques**
- Lower hydraulic conductivities are observed deeper within the Hopefield aquifer suggesting MAR via deep borehole injection is not viable



REGION C

- The largest area in which clay layers are absent
- The absence of clay infers that Managed Aquifer Recharge is possible to the deeper main aquifer through infiltration-type techniques
- Local movement of groundwater flow suggests groundwater has the potential to flow towards Hopefield wellfield where it can be abstracted. Water also has the potential to flow to the Sout river due to high hydraulic conductivities.
- Water levels at 10 - 15 mbgl coupled with thick unsaturated sands infer **space is available to recharge the aquifer**
- The top dry soils have high hydraulic conductivities which supports **MAR using infiltration techniques**
- Lower hydraulic conductivities are observed deeper within the Hopefield aquifer suggesting MAR via deep borehole injection is not viable.



5.4 Water Quality Investigations

The influence of the different MAR source waters on the native groundwater in Langebaan Road and the Hopefield region were evaluated to determine which source water was best suited for Managed Aquifer Recharge. As previously mentioned, the criteria used to determine whether the groundwater in a zone is suitable for MAR include:

- native groundwater meets drinking water standards;
- groundwater meets drinking water standards after mixing with source water has taken place;
- groundwater quality does not deteriorate after interacting with aquifer material.

5.4.1 Langebaan Road

The groundwater within the MAR targeted deeper Langebaan Road aquifer was analysed for the concentrations of the different chemical elements found within the water (**Figure 5-19**). The results show that majority of the concentrations of dissolved major cations and anions at the Langebaan Road deeper aquifer do not greatly vary spatially and have remained relatively constant when compared with long term water quality results (Tredoux and Engelbrecht, 2009; Nel, 2019b; Zhang, 2019). The analysis indicated that all of the groundwater samples are dominated by Sodium (Na^+) cations and Chloride (Cl^-) anions.

Out of the 18 boreholes sampled, 4 boreholes (G46098, G46092, G32938 and G32933) had Na^+ and Cl^- concentrations that exceeded the SANS 241: 2015 drinking water standard (Na <= 200 and Cl <=300). These boreholes are situated northwest of the Langebaan Road wellfield. These boreholes are at the lower end of the aquifer, where the clay layer is absent or very thin, and thus more exposed to salt spray from the ocean. These boreholes, and subsequent surrounding areas, would therefore be considered unsuitable for Managed Aquifer Recharge. A future recommendation could be to see whether the aquifer water quality in the region of high Na^+ and Cl^- could be improved by the flushing and reinjecting of Managed Aquifer Recharge source water.

The majority of the deeper groundwater at Langebaan Road had similar water compositions, indicated with the red oval, (**Figure 5-19**), so mixing was done using groundwater at LRA 1B4 as a representative for the fresh groundwater in the Langebaan Road area. All raw data on the water quality investigations is available in Appendix B. According to SANS 241-1:2015, the elevated Na^+ and Cl^- will provide a distinctly salty taste to the water and do not quench thirst, but no human health effects are expected at the concentration shown in **Figure 5-19**.

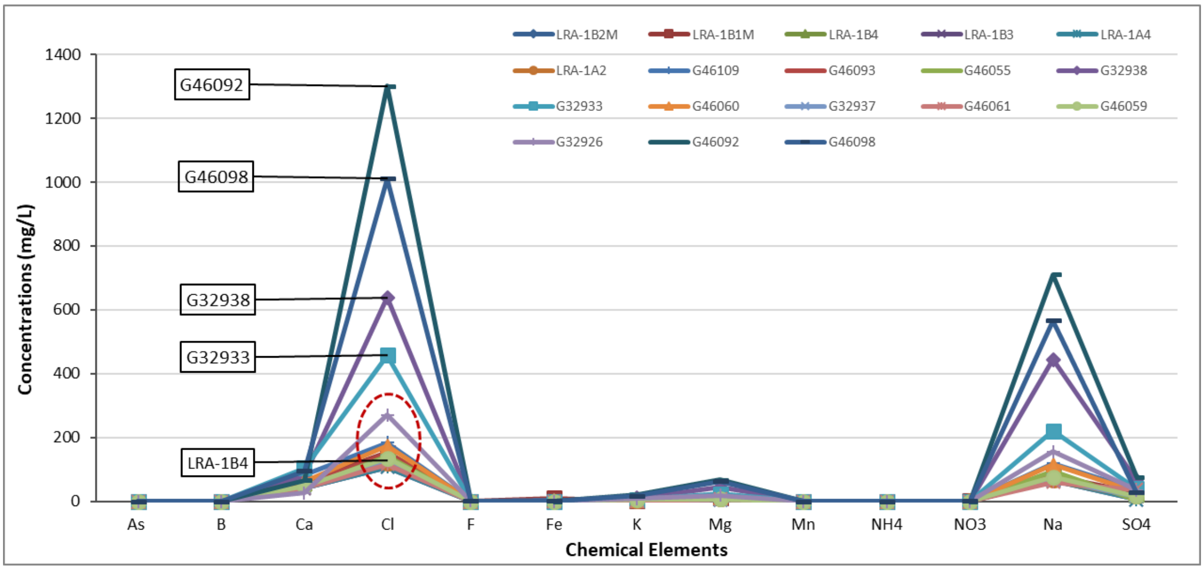


Figure 5-19: Chemical compositions of the boreholes situated within the deeper Langebaan Road Aquifer system

Mixing between the Misverstrand Dam water and Langebaan Road

Forward modelling between the excess Berg River water collected at Misverstrand Dam and LRA 1B4 was undertaken with a 2%, 10%, 30%, 50%, 70% and 90% Managed Aquifer Recharge source water to groundwater recharge ratio. This was done to simulate the MAR process of different volumes of the excess Berg River water recharging the Langebaan Road aquifer. The water sampled from the Misverstrand Dam in both seasons meets the SANS 241-2015 drinking water standards and would require little to no treatment of the chemical composition of the water before recharging the aquifer.

When mixed with groundwater at LRA 1B4, the model predicted no negative influence on the groundwater in terms of the drinking water standards. The electrical conductivity (mS/m) of the groundwater at LRA 1B4 gradually decreased when mixed with the river water (**Figure 5-20**). This was also noted by Tredoux and Engelbrecht (2009) injection tests at Langebaan Road resulted in initially high EC values (150 mS)/m which gradually decreased and stabilised at 50 mS/m as injection took place. Similar results were observed by García-Menéndez et al. (2021) whereby mixing native groundwater with recharge water of fewer salts resulted in a significant decrease in electrical conductivity values over a 40 day period. García-Menéndez et al. (2021) also found that saline groundwater turned into freshwater after 6 months of injection. This means that in terms of salts, MAR using the excess Berg River water has the potential to improve the quality of the groundwater. This suggests that the excess water captured by the Misverstrand Dam is a suitable water resource for MAR at Langebaan Road.

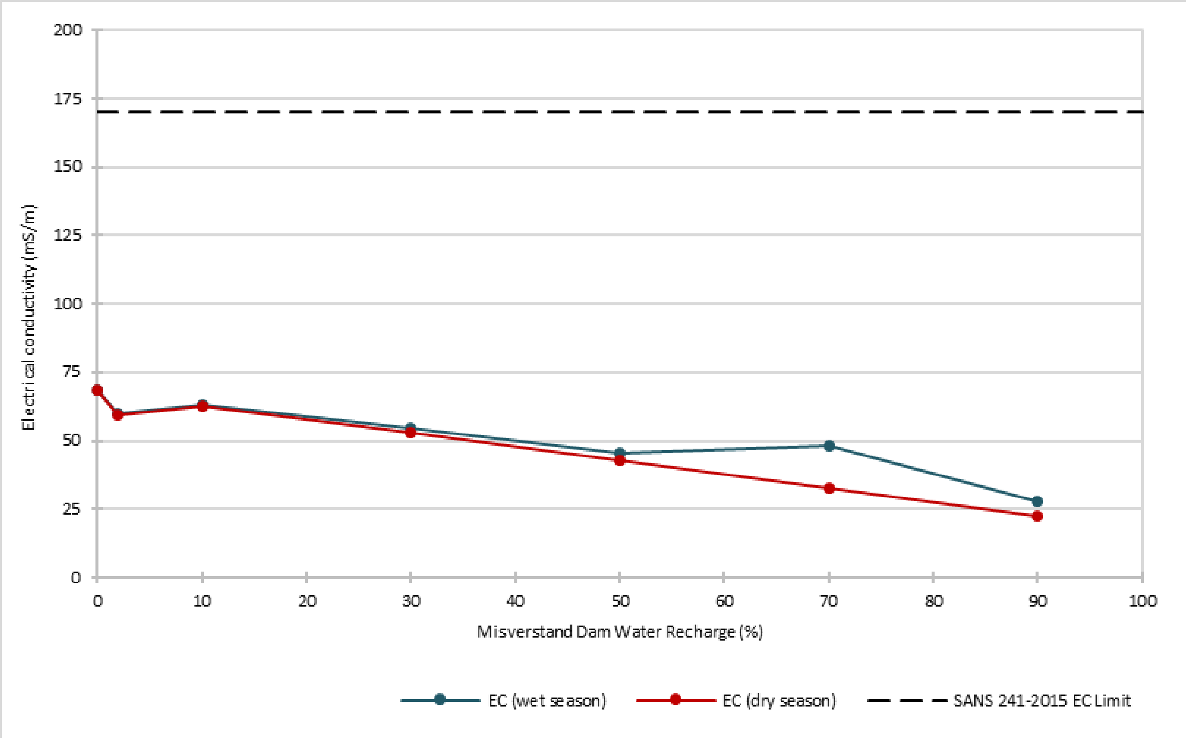


Figure 5-20: Electrical conductivity concentration of groundwater at LRA 1B4 with an increase in Misverstrand Dam source water

The quality of the groundwater-Dam mix (**Figure 5-21**) reveals that the quality of the groundwater gradually moves closer to that of the river water. As the Dam water has fewer concentrations of cations and anions, the groundwater will eventually have fewer dissolved minerals as MAR takes place.

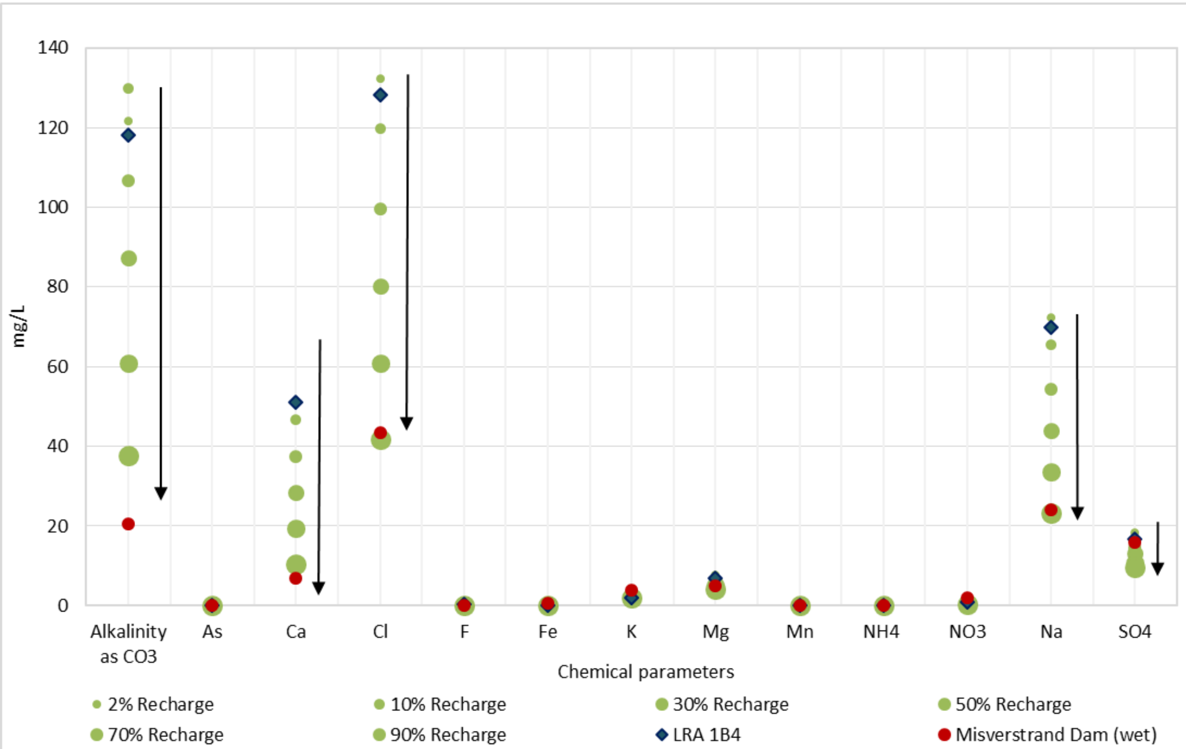


Figure 5-21: Final water quality of the mix between the Misverstrand Dam and LRA 1B4

The outputs of the 2% -90% mix all fall within the SANS 241-2015 drinking water standard, with no concerning outliers. This suggests that the groundwater would be safe for human consumption after abstraction and infers that little to no post-treatment of the water is required. This could change as the quality of the Dam water has the potential to change over the years so it is recommended that this source water always be tested before injection into the aquifer. Also, as the purpose of MAR is to replenish the aquifer once it has been depleted, it is most likely that the excess Dam water in the wet season would be used to recharge the aquifer.

Mixing between the West Coast District Municipal Pipeline water and Langebaan Road

Forward modelling between the West Coast Municipal (WCDM) pipeline water and LRA 1B4 was undertaken with a 2%, 10%, 30%, 50%, 70% and 90% source water to groundwater recharge ratio. This was done to simulate the Managed Aquifer Recharge process of different volumes of the pipeline water recharging the Langebaan Road aquifer. The water in the pipeline is treated Berg River water from the Withoogte water treatment works. As seen in **Figure 5-22**, when mixed with groundwater at LRA 1B4, the model predicted no negative influence of the pipeline water on the groundwater. As the pipeline water has fewer concentrations of cations and anions, the groundwater will eventually have fewer dissolved minerals as MAR takes place.

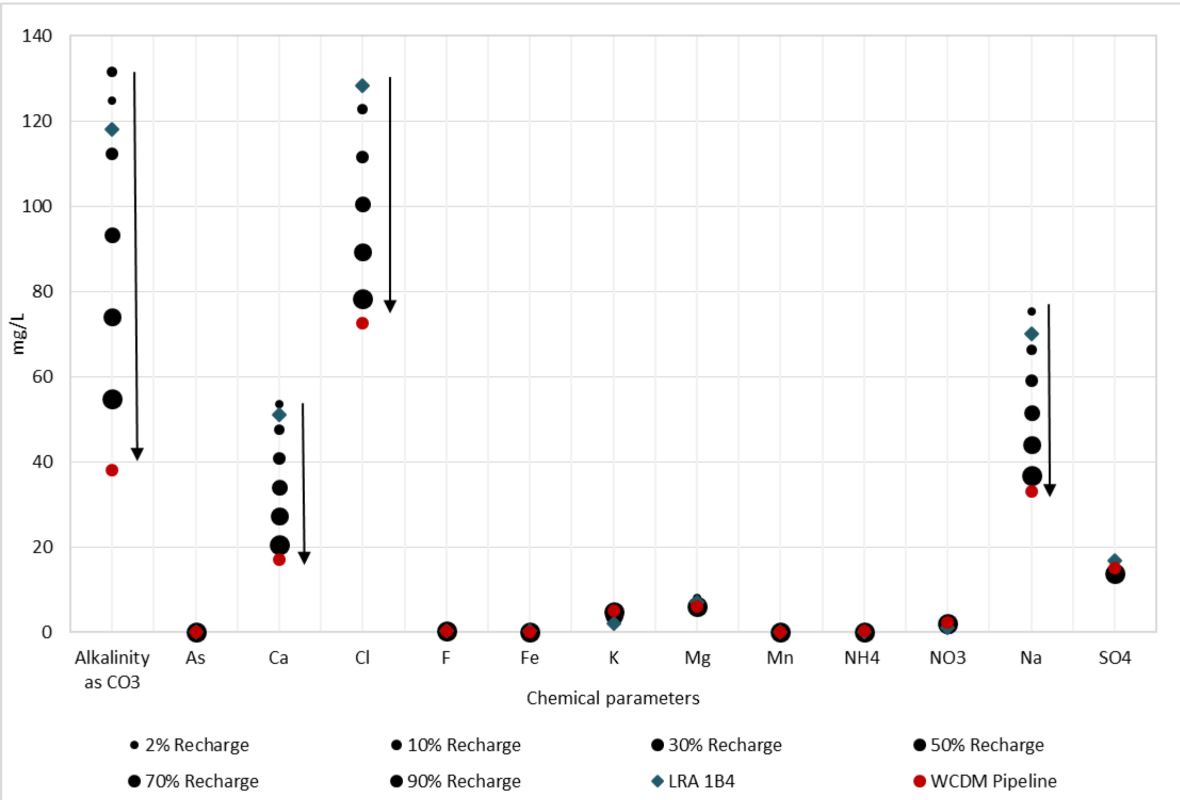


Figure 5-22: Final water quality of the mix between the WCDM Pipeline and LRA 1B4

As expected, the water sampled from the pipeline meets the SANS 241-2015 drinking water standards and would require little to no treatment before recharging the aquifer, as this is the potable water piped from the WCDM pipeline directly to the consumer. Similar to Murray and Tredoux's (2002) findings, the municipal source water is highly compatible with the groundwater as the injected water is lower in total dissolved solids (TDS) than the groundwater, particularly in the case of calcium as this water resource is of consistent and reliable quality, the WDCM pipeline has the potential to become the most suitable Managed Aquifer Recharge water resource within the Saldanha Bay Local Municipality.

Mixing between the Vredenburg wastewater treatment plant and Langebaan Road

Forward modelling between the Vredenburg wastewater treatment plant (WWTP) in February and July 2020 and LRA 1B4 was undertaken with a 2%, 10%, 30%, 50%, 70% and 90% source water to groundwater recharge ratio. This was done to simulate the Managed Aquifer Recharge process of different volumes of the treated WWTP water recharging the Langebaan Road aquifer.

When the WWTP was mixed with groundwater at LRA 1B4, the model predicted some negative influences on the groundwater at LRA 1B4 in terms of the drinking water standards. The electrical conductivity (mS/m) of the groundwater at LRA 1B4 increased when mixed with the WWTP, more so in July than February 2020 (**Figure 5-23**). This means that in terms of salts, MAR using the WWTP has the potential to degrade the quality of the groundwater.

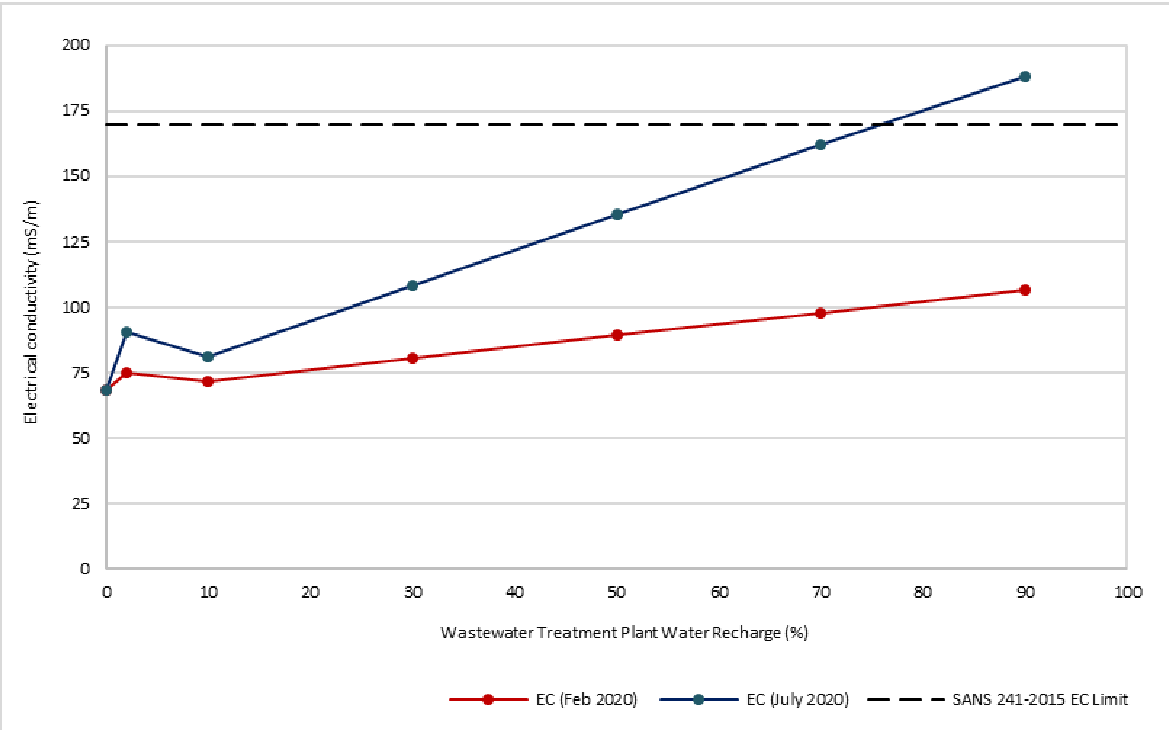


Figure 5-23: Electrical conductivity concentration of groundwater at LRA 1B4 with an increase in WWTP source water

The February 2020 sample of the WWTP had an initial nitrate (NO_3) concentration (34.75 mg/L) that exceeded the SANS 241: 2015 drinking water standard. When mixed with the LRA 1B4 groundwater at 2%, 10% and 30%, the resulting groundwater was not negatively impacted in terms of the drinking water standard. At a 35% and higher mix, the NO_3 concentrations in the groundwater start to exceed what is recommended for drinking water. This is not a cause for too much concern as nitrate concentrations reduce over time in a sand aquifer.

The water quality of the February 2020 mix (**Figure 5-24**) reveals that all the chemical compositions (except for nitrate) fall within the SANS 241-2015 drinking water standard. In most cases, the addition of the treated wastewater to the groundwater increased the dissolved minerals in the groundwater. That is, the groundwater is assimilating the wastewater quality. An exception to this is Alkalinity (as CO_3) and Calcium, where the addition of the treated wastewater results in a decrease in the chemical composition of these salts. This infers that there is a potential to use the WWTP (Feb 2020) as a water resource for MAR, on the condition that the nitrate is oxidised out of the water first.

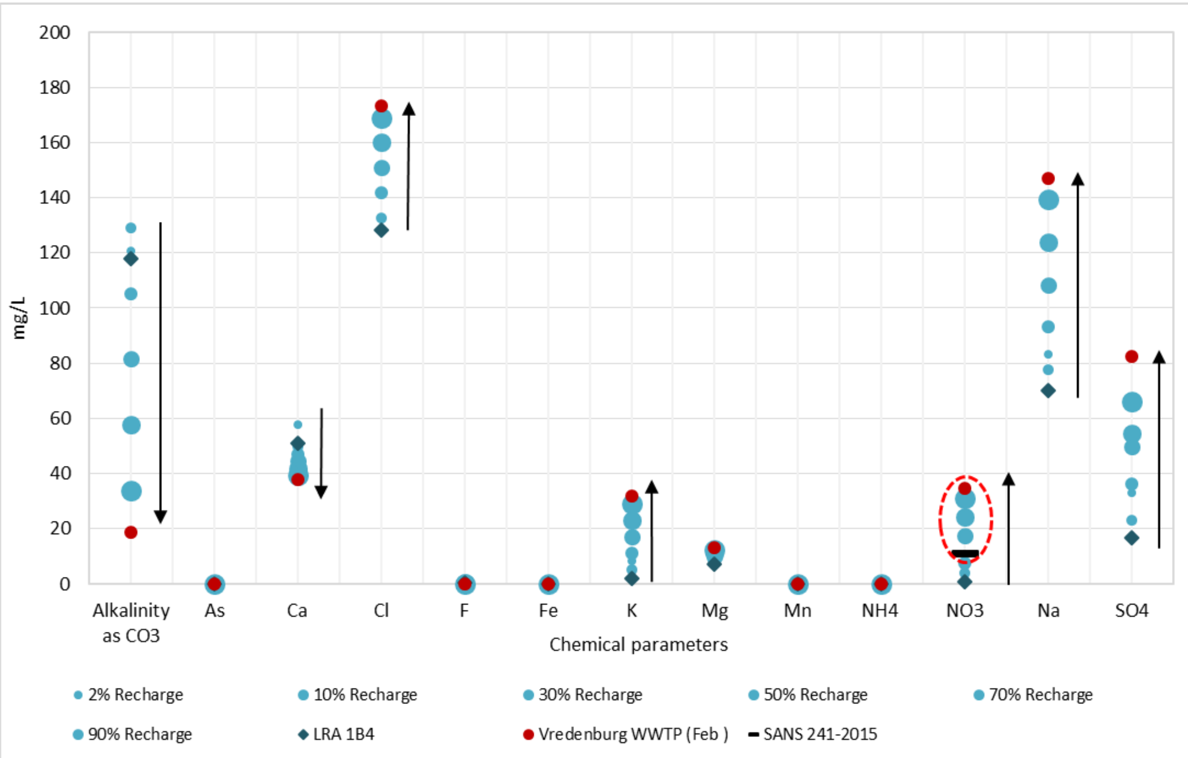


Figure 5-24: Final water quality of the mix between the February 2020 WWTP and LRA 1B4

Similarly, In July 2020 the WWTP water had an electrical conductivity (223 mS/m), chloride (441.56 mg/L), ammonium (59.45 mg/L) and sodium (253 mg/L) concentrations that exceeded the SANS 242-2015 drinking water standard. When mixed with the groundwater it almost instantly degrades the water quality at LRA 1B4 (**Figure 5-25**) as it salinizes the aquifer system.

As nitrate can be oxidised out of the water before injection, it should not carry a huge concern when deciding on whether to use the WWTP as a source of recharge water within freshwater zones at Langebaan Road. Similar to nitrates, ammonium will decrease with an extended residence time in the aquifer. The concern should be the reliability of the quality of the water as that can change if treatment methods change.

The huge difference in the WWTP water quality between the February and July 2020 samples suggests that the quality of this water is unreliable and that thought needs to go into the pre-treatment of this water before it enters the aquifer. As such, the wastewater treatment plant is the least suitable water resource for Managed Aquifer Recharge at Langebaan Road.

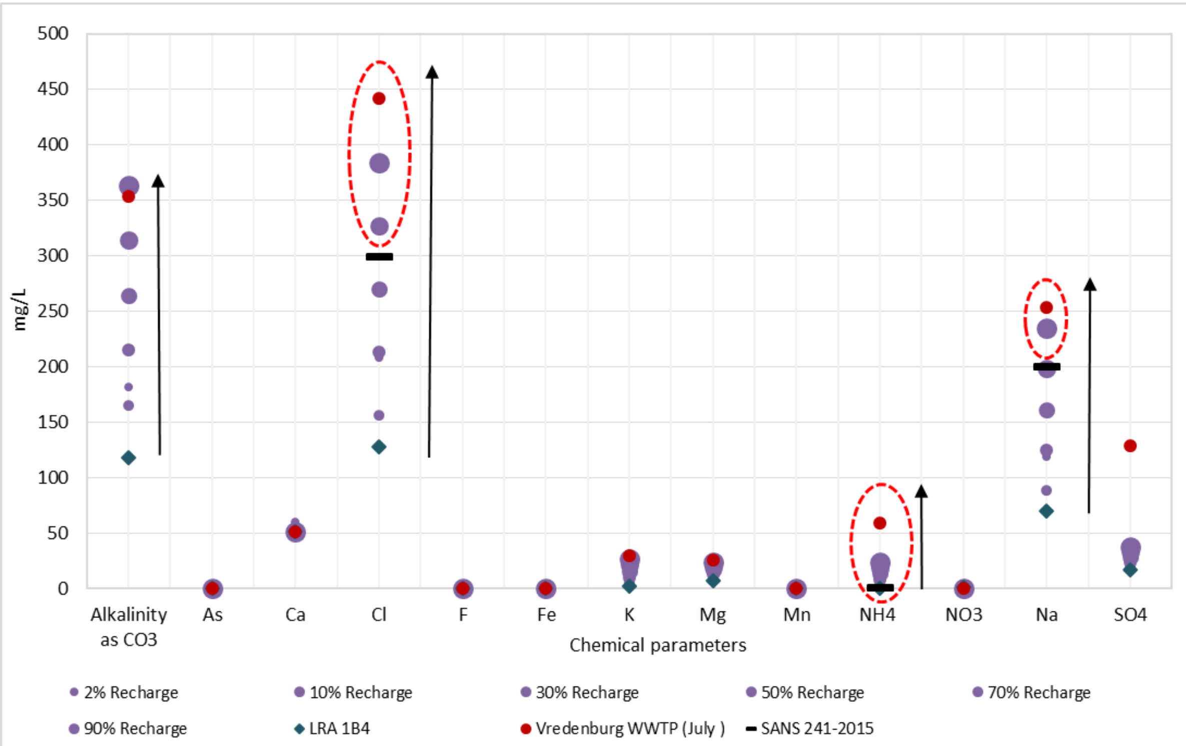


Figure 5-25: Final water quality of the mix between the July 2020 WWTP and LRA 1B4

5.4.2 Hopefield

The results of the analysis of the different chemical elements found within the groundwater at Hopefield show that the concentration of dissolved major cations and anions at the Hopefield aquifer does not greatly vary spatially (**Figure 5-26**). Similar to Langebaan Road, the analysis indicated that all of the groundwater samples are dominated by Na^+ cations and Cl^- anions. The elevated Na^+ and Cl^- will provide a distinctly salty taste to the water and do not quench thirst, but no human health effects are expected at the concentration shown in the Figure below (SANS 241-1:2015).

The majority of the groundwater at Hopefield had similar water compositions (indicated in the red oval) so mixing was done using groundwater at HPF 2-7M as a representative for the fresh groundwater in the Hopefield area. Out of the 9 boreholes sampled, only HPF 2-4M had Na^+ and Cl^- concentrations that slightly exceed the SANS 241: 2015 drinking water standard (Na <= 200 and Cl <=300). This borehole would therefore be considered unsuitable for MAR at this point.

A future recommendation for this region would be to see whether this borehole could be flushed out and reinjected with source water to observe whether the mixing improves the overall quality of the water at this borehole.

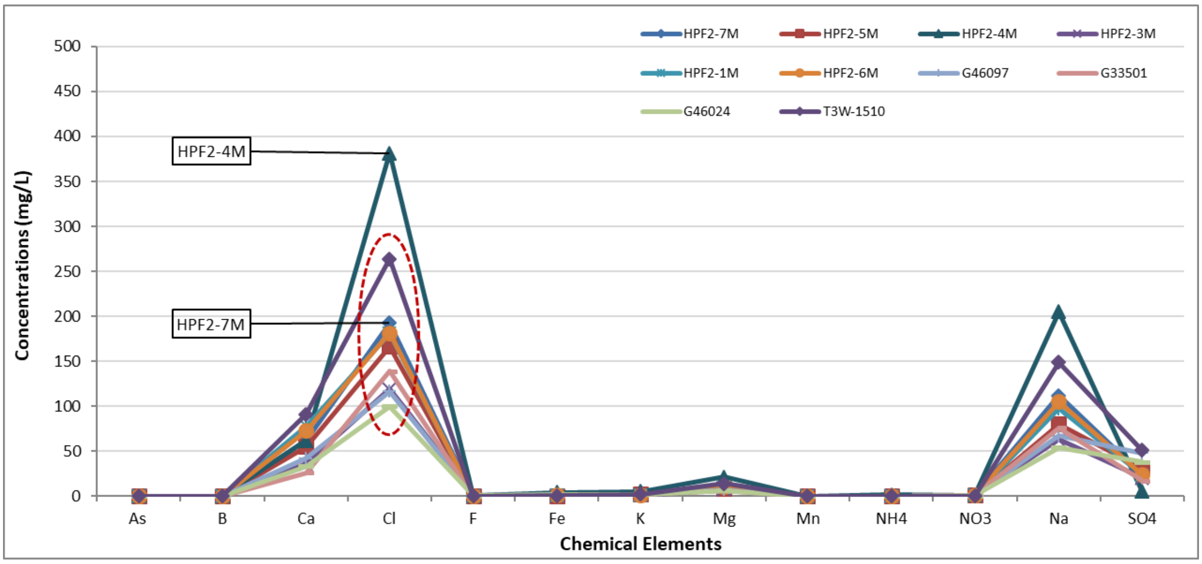


Figure 5-26: Chemical compositions of the boreholes situated within the Hopefield Aquifer system

The geochemical model at Hopefield requires a two-step model as the recommended Managed Aquifer Recharge application in the Hopefield region is infiltration galleries/ basins. Due to this, water will react first with the geology in the unsaturated zone before mixing with the native groundwater in the system. The aquifer material data used to represent the Hopefield aquifer material was obtained just south of Hopefield wellfield, close to the Elandsfontein Phosphate Mine.

Mixing between the Misverstrand Dam water and Hopefield

The first step in this two-step geochemical model was the reaction between the excess Berg River water collected at the Misverstrand Dam water and the aquifer material at Hopefield. The reaction between the aquifer material and the river water resulted in mainly the increase in the concentration of salts in the river water as it infiltrated into the groundwater (**Table 5-4**). Overall, the addition of the river water has no negative impact on the aquifer, as well as the increase in the dissolved minerals in the Dam water does not exceed what is permissible in terms of the SANS 241:2015 drinking water standard.

Table 5-4: Reaction between the excess Berg River water and the aquifer material at Hopefield

			Input 1		Output 1
Parameter	Units	SANS 241-2015	Misverstrand Dam (wet)	Elandsfontein Soil -Unit E	Reaction
pH		>=5 to <=9.7	6.82	5.31	6.72
EC	(mS/cm)	<=170	24.20	2.70	26.00
Alkalinity as CO3	mg/L		20.50	0.31	28.28
As	mg/L	<= 0.01	0.00	0.00	0.00
Ca	mg/L		7.00	1.20	8.20
Cl	mg/L	<= 300	43.37	3.19	46.55
F	mg/L	<= 1.5	0.15	0.19	0.34
Fe	mg/L	<= 2	0.56	0.50	1.07
K	mg/L		4.00	0.41	4.41
Mg	mg/L		5.00	0.51	5.51
Mn	mg/L	<= 0.4	0.04	0.01	0.05
NH4	mg/L	<= 1.5	0.15	0.01	0.00
NO3	mg/L	<= 11	2.04	0.00	2.01
Na	mg/L	<= 200	24.00	1.91	25.91
SO4	mg/L	<= 500	15.94	3.68	19.75

The output of the reaction between the river water and the aquifer material was then used as the input into the second mixing model. This new source water (Output 1- wet) was mixed with HPF 2-7M at a ratio of 2%, 10%, 30%, 50%, 70% and 90% of source water to groundwater. This was done to simulate the Managed Aquifer Recharge process of different volumes of the Misverstrand Dam water recharging the Hopefield aquifer through infiltration.

The results of this mix indicate that there is no negative influence on the groundwater at HPF 2-7M in terms of the drinking water standard (**Figure 5-27**). The water quality at HPF 2-7M seems to improve as shown by a decrease in the majority of the given parameters. This suggests that the excess water from the Misverstrand Dam Weir when it is in flood can be used as a suitable water resource for MAR to the Hopefield aquifer.

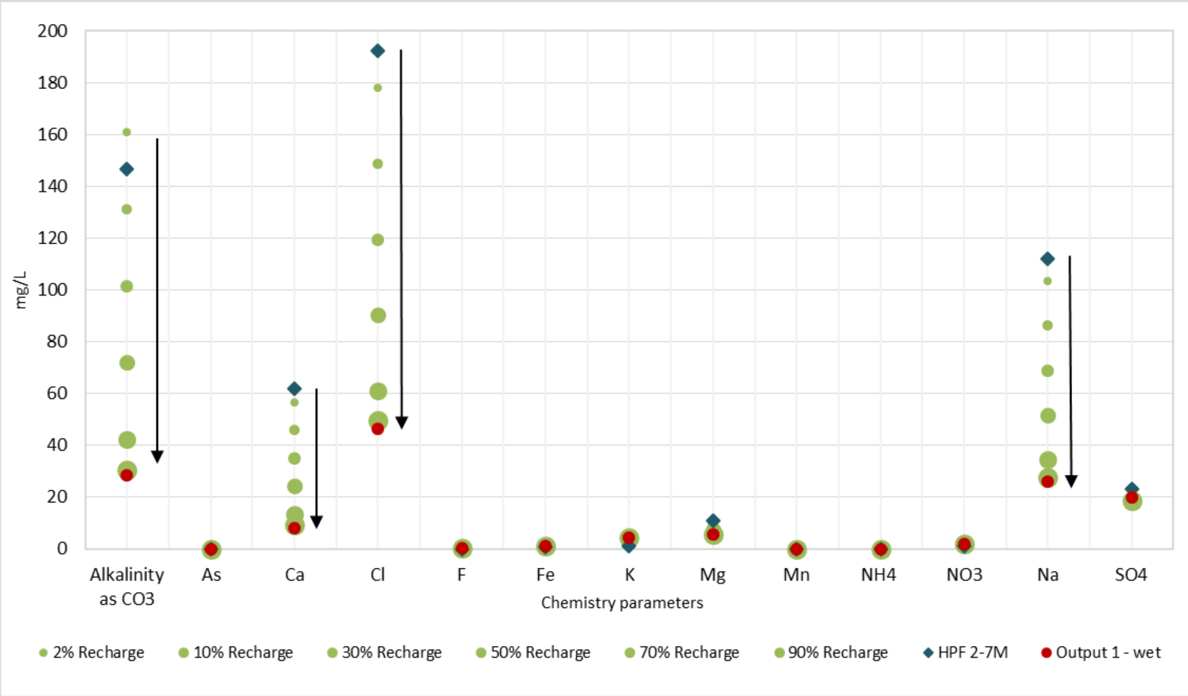


Figure 5-27: Final water quality of the mix between excess Berg River wet season Output 1 and HPF 2-7M

Mixing between the West Coast District Municipal Pipeline water and Hopefield

The first step in this two-step geochemical model was the reaction between the West Coast Municipal pipeline water and the aquifer material at Hopefield. The reaction between the WCDM pipeline water and HPF 2-7M soils shows that there is barely an effect on the source water when it passes through the Hopefield aquifer material. There is a slight increase and/or decrease in the concentrations of the source water observed (**Table 5-5**). But in general, the infiltration of the West Coast Municipal pipeline water through the Hopefield aquifer will result in no negative influence on the groundwater and the aquifer in terms of it meeting the SANS 241:2015 drinking water standard.

Forward modelling between the West Coast Municipal pipeline water (Output 1) and HPF 2-7M was undertaken with a 2%, 10%, 30%, 50%, 70% and 90% source water to groundwater recharge ratio. As expected, the model predicted no negative influence on the groundwater (**Figure 5-28**) and identifies the WCDM pipeline as a suitable water resource for MAR.

Table 5-5: Reaction between the West Coast Municipal pipeline water and the aquifer material at Hopefield

			Input 1		Output 1
Parameter	Units	SANS 241-2015	WCDM Pipeline	Elandsfontein Soil -Unit E	Reaction
pH		>=5 to <=9.7	7.23	5.31	7.15
EC	(mS/cm)	<=170	35.50	2.70	37.80
Alkalinity as CO3	mg/L		38.00	0.31	45.00
As	mg/L	<= 0.01	0.00	0.00	0.00
Ca	mg/L		17.00	1.20	18.20
Cl	mg/L	<= 300	72.59	3.19	75.80
F	mg/L	<= 1.5	0.15	0.19	0.34
Fe	mg/L	<= 2	0.01	0.50	0.51
K	mg/L		5.00	0.41	5.42
Mg	mg/L		6.00	0.51	6.51
Mn	mg/L	<= 0.4	0.00	0.01	0.01
NH4	mg/L	<= 1.5	0.15	0.01	0.00
NO3	mg/L	<= 11	2.32	0.00	2.32
Na	mg/L	<= 200	33.00	1.91	34.92
SO4	mg/L	<= 500	14.97	3.68	18.37

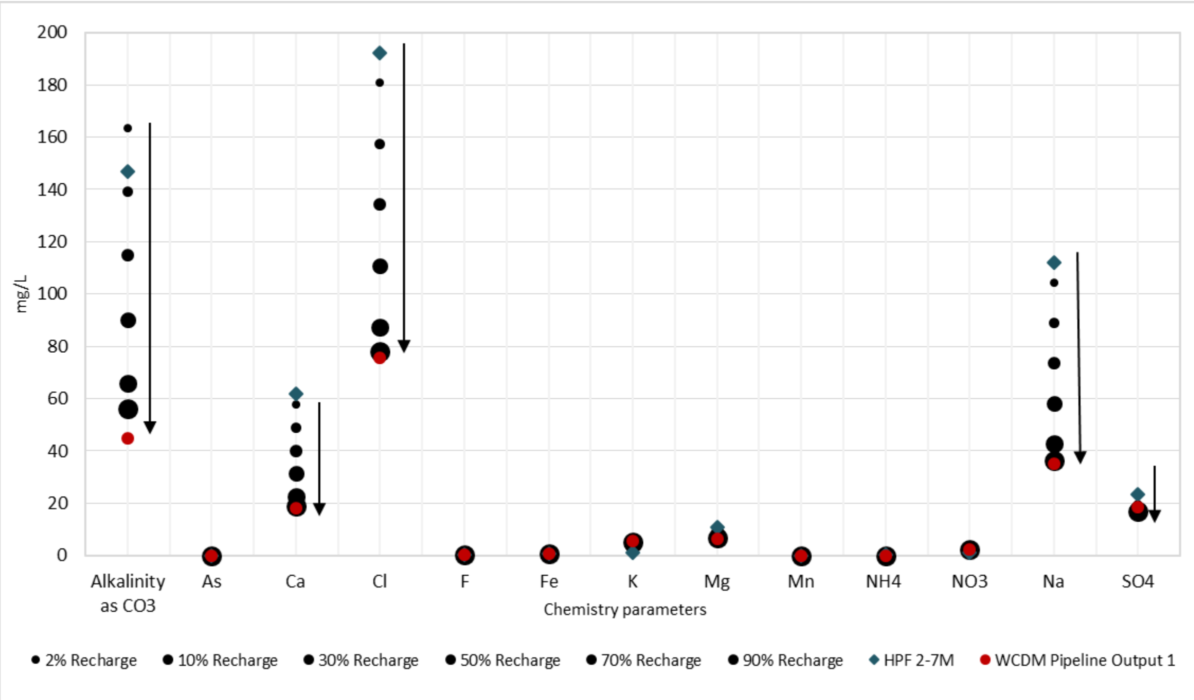


Figure 5-28:Final water quality of the mix between WCDM Pipeline Output 1 and HPF 2-7M

Mixing between the Vredenburg wastewater treatment plant and Hopefield

The reaction between the Wastewater Treatment Plant (WWTP) water in February 2020 and HPF 2-7M soils, (**Table 5-6**) shows a decrease in the electrical conductivity of the source water as it infiltrates through the ground. This indicates that the movement of the water through the soils is improving the quality of the water. The majority of the other parameters in the water increase, with NO_3 exceeding the SANS 241-2015 drinking water limit. This is because the nitrate concentration in the source water was initially so high. The concentration of NO_3 in the WWTP water is the same after infiltration through the aquifer material which suggests that infiltration alone will not be enough to treat the WWTP water and pre-treatment is still required.

Table 5-6: Reaction between the February 2020 WWTP water and the aquifer material at Hopefield

			Input 1		Output 1
Parameter	Units	SANS 241-2015	WWTP (Feb 2020)	Elandsfontein Soil -Unit E	Reaction
pH		>=5 to <=9.7	6.61	5.31	6.56
EC	(mS/cm)	<=170	116.70	2.70	113.10
Alkalinity as CO3	mg/L		18.60	0.31	21.61
As	mg/L	<= 0.01	0.01	0.00	0.00
Ca	mg/L		38.00	1.20	39.22
Cl	mg/L	<= 300	173.44	3.19	176.73
F	mg/L	<= 1.5	0.19	0.19	0.38
Fe	mg/L	<= 2	0.17	0.50	0.67
K	mg/L		32.00	0.41	32.43
Mg	mg/L		13.00	0.51	13.52
Mn	mg/L	<= 0.4	0.06	0.01	0.07
NH4	mg/L	<= 1.5	0.15	0.01	0.00
NO3	mg/L	<= 11	34.75	0.00	34.75
Na	mg/L	<= 200	147.00	1.91	149.00
SO4	mg/L	<= 500	82.53	3.68	76.56

The February 2020 Output 1 was mixed with HPF 2-7M at a ratio of 2%, 10%, 30%, 50%, 70% and 90% of source water to groundwater (**Figure 5-29**). The results of this mix show elevated nitrate concentrations. This suggests that the pre-treatment of this water is required and the nitrate can be oxidised out of the water before infiltration takes place. Without the elevated nitrate concentrations, the WWTP February 2020 water would be suitable for MAR to the Hopefield aquifer.

There are slight water quality benefits to infiltrating treated wastewater through the unsaturated zone using infiltration galleries, as seen by the decrease in the pH, EC, As, NH_4 and SO_4 of the infiltrated water. This is similar to what Bekele et al. (2013) found. Infiltration, however, did not seem beneficial in decreasing nitrate concentrations of the infiltrated water, which could be attributed to the aerobic conditions of the unsaturated zone. This means that if the removal of nitrate concentrations in the water is essential, recharged via infiltration cannot rely entirely upon processes in the vadose zone for nitrate removal.

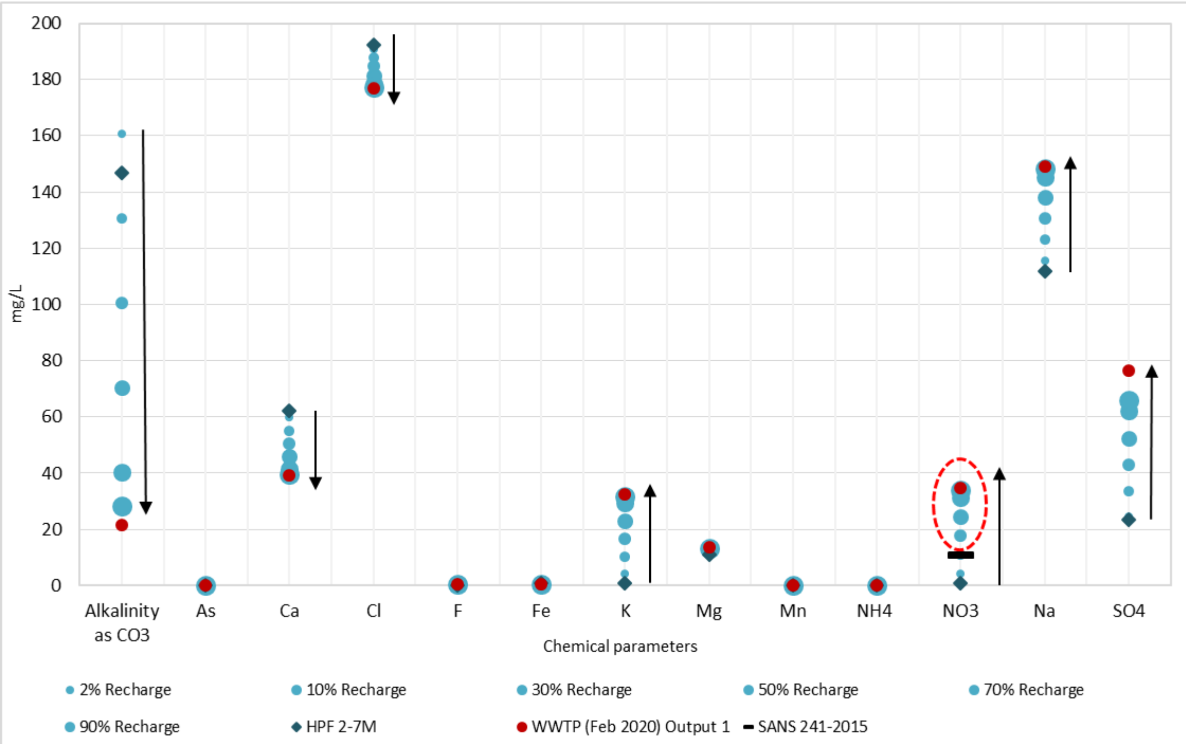


Figure 5-29:Final water quality of the mix between the February 2020 WWTP Output 1 and HPF 2-7M

In July 2020, a similar trend is seen in the February 2020 model where the electrical conductivity of the source water decreases after it moves through the Hopefield aquifer (**Table 5-7**). Although this is evidence of the water being treated as it infiltrated through the aquifer, it still exceeds the drinking water standards along with chloride, ammonium and sodium. Additionally, the output of this reaction has negative impacts on the aquifer as it introduces these high salt concentrations into the system.

The result of the mixing between the Wastewater treatment plant water in July 2020 and the source water shows that the WWPT is the least unsuitable for MAR at Hopefield as it not only does not meet the SANS 241-2015 drinking water standard but also leads to the degradation of the native water within the aquifer (**Figure 5-30**). It is recommended that WWTP undergo extensive treatment before and/or after it is used to recharge the aquifer.

Table 5-7: Reaction between the July 2020 WWTP water and the aquifer material at Hopefield

			Input 1		Output 1
Parameter	Units	SANS 241-2015	WWTP (July 2020)	Elandsfontein Soil -Unit E	Reaction
pH		>=5 to <=9.7	7.25	5.31	6.83
EC	(mS/cm)	<=170	223.00	2.70	211.80
Alkalinity as CO3	mg/L		353.30	0.31	465.96
As	mg/L	<= 0.01	0.00	0.00	0.00
Ca	mg/L		51.00	1.20	52.26
Cl	mg/L	<= 300	441.65	3.19	445.29
F	mg/L	<= 1.5	0.24	0.19	0.43
Fe	mg/L	<= 2	0.22	0.50	0.72
K	mg/L		30.00	0.41	30.45
Mg	mg/L		26.00	0.51	26.54
Mn	mg/L	<= 0.4	0.09	0.01	0.09
NH4	mg/L	<= 1.5	59.45	0.01	27.07
NO3	mg/L	<= 11	0.50	0.00	0.00
Na	mg/L	<= 200	253.00	1.91	255.19
SO4	mg/L	<= 500	128.38	3.68	45.00

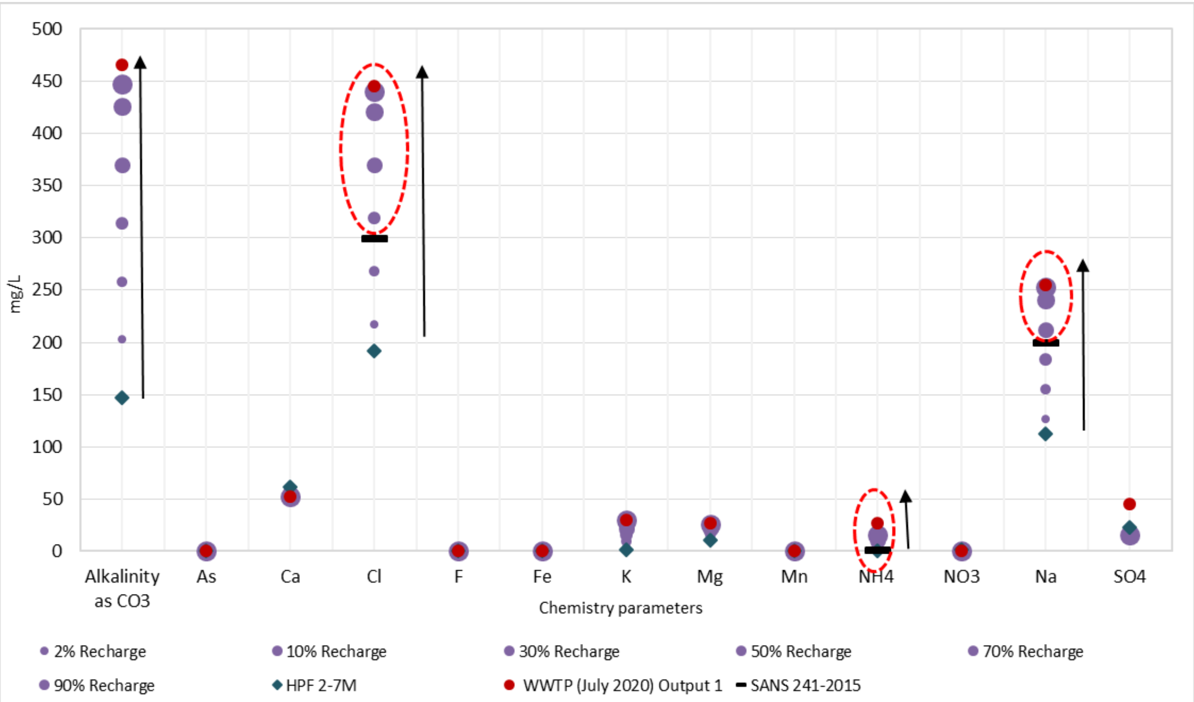


Figure 5-30: Final water quality of the mix between the July 2020 WWTP Output 1 and HPF 2-7M

5.4.3 Suitability of the different water resources for MAR

The majority of groundwater at Langebaan Road and Hopefield is of good enough quality in terms of the SANS 241-2015 drinking water standards to be recharged with the WCDM pipeline, WWTP and excess Berg River water. The groundwater does not significantly change throughout the year and the pipeline water is consistent throughout the year therefore the pipeline water is the most suitable water resource used for MAR in the region. The pipeline runs through both the Langebaan road and Hopefield region so the transport of water to these areas should not be cause for concern.

The water from the Berg River changes seasonally. The changes may not be drastic however modelling both seasons was needed to ensure the best river water quality is used for MAR. The Berg River would be suitable for MAR at Langebaan Road and Hopefield as it does not negatively impact the aquifer. It is, however, situated at a distance and a lower elevation from both Langebaan Road and Hopefield and therefore some thought is needed as to how the excess water would move into/be transported to the Langebaan Road and Hopefield regions. Also, it is unlikely that MAR would take place in the dry season, rather than in the wet season where there is excess water from the Berg River available for recharge. The quality of the river water in the wet season has higher EC, Cl, Fe and Na concentrations than compared to the pipeline water. These concentrations are not significant enough that the water is unsuitable for drinking and should be considered a second option as the source water for MAR at both Langebaan Road and Hopefield.

The February 2020 WWTP water has high nitrate concentrations (34.75 mg/L) so when mixed with the groundwater, it increases the overall NO_3 concentrations of the groundwater. The nitrate concentrations have the potential to decrease over time in the aquifer but the pre-treatment of the water may still be required. Similarly, the July WWTP water has overall increased chemical ion concentrations that make it unsuitable for recharge as is. The WWTP is also situated in Vredenburg so some thought would have to go into how the water will be transported to the Langebaan road and Hopefield aquifer region.

The purpose of MAR is for water supply so the water needs to meet the SANS 241:2015 drinking water standards. MAR is also an application that should improve the state of the groundwater and the WWTP as a water resource has shown very little evidence of improving the groundwater in these areas. As such, it is not recommended to use the treated wastewater as the source water for MAR unless the WWTP water undergoes pre and/or post-treatments.

6 CONCLUSION

From the investigations conducted in the Saldanha Bay Local Municipal region, sites suitable for Managed Aquifer Recharge (MAR) were identified, and recommendations are made regarding the most suitable Managed Aquifer Recharge methods at each site, as well considerations for the different water resources to be used for the Managed Aquifer Recharge process.

Using airborne Time Domain Electromagnetic (TDEM) geophysics, the different geological zones that make up the Lower Berg aquifer systems were delineated. As such, it was possible to identify five suitable sites for Managed Aquifer Recharge based on their locations relative to the deepest parts of the aquifer, the absence/ presence of confining clay layers as well as the potential local groundwater flow paths for the study area. These sites included the Langebaan Road wellfield, Region A (situated to the north-east of the Langebaan Road Wellfield), the Hopefield wellfield, Region B (situated to the west of the Hopefield wellfield) and Region C (situated to the east of the Hopefield wellfield). The Langebaan Road wellfield main aquifer was situated under a confining clay layer with water levels ~ 5 metres below ground level suggesting Managed Aquifer Recharge to this area would only be possible once the pressure in the aquifer system is low enough to accept recharged water. The main aquifer at the Hopefield wellfield and Regions A, B and C have evidence of missing clay layers and therefore Managed Aquifer Recharge to the deeper parts of the aquifer is possible through infiltration techniques. These sites were then further evaluated in terms of their hydraulic properties.

Aquifer testing in the form of infiltration tests and pumping tests (previous and in situ pumping tests) were used to evaluate the vertical and horizontal properties seen within the Langebaan Road and Hopefield aquifer system. At Langebaan Road, aquifer hydraulic testing showed that the deeper aquifer had the highest hydraulic conductivities (0.66 – 39.59 m/day) and therefore is most suitable for Managed Aquifer Recharge when compared to the shallower aquifer. The confining clay layers over large parts of the Langebaan Road area suggest that the most suitable Managed Aquifer Recharge application should be through borehole injections (Aquifer Storage and Recovery at the Langebaan Road wellfield, and Aquifer Storage, Transport and Recovery at Region A) when water levels have dropped and recharged is required.

At Hopefield, hydraulic testing showed that the shallower aquifer had sufficiently high infiltration rates (1.63 – 33.94 m/day) and vertical hydraulic conductivities, making it the most suitable for Managed Aquifer Recharge compared to the deeper aquifer. This coupled with the absence of clay layers up until ~50 mbgl identifies surface/subsurface infiltration type applications as the most suitable Managed Aquifer Recharge application at the Hopefield wellfield, Region B and Region C. Infiltration galleries are recommended at the Hopefield wellfield and infiltration galleries and/or infiltration basins are recommended at Region B and Region C, where there is sufficient land space.

Water quality investigations including the sampling and analysis of the deeper Langebaan Road aquifer and the Hopefield aquifer were conducted to determine the hydrochemical properties of the groundwater suitable for the Managed Aquifer Recharge process. These investigations concluded that both the aquifer at Langebaan Road and Hopefield has water qualities that meet the recommended SANS 241: 2015 drinking water standard, except for three boreholes northwest of the Langebaan Road wellfield. These boreholes are at the lower end of the aquifer, where the clay layer is absent or very thin, and thus more exposed to salt spray from the ocean. Managed Aquifer Recharge was deemed unsuitable in these three borehole regions.

Geochemical investigations using the PHREEQC software identified which water resource options are best suited to the Managed Aquifer Recharge scheme with the Langebaan Road and Hopefield regions. Various mixing and reaction models showed that the most suitable water resource for Managed Aquifer Recharge is the West Coast District Pipeline water. The water in the pipeline is treated Berg River water from the Withoogte water treatment works. Overall, this water has a better quality in terms of the SANS 241-2015 drinking water standard and additionally, the pipeline already runs through both the Langebaan Road and Hopefield wellfields. A close second Managed Aquifer Recharge water source option is the raw Berg River water, particularly in the wet season when the Misverstrand Dam usually floods. The water quality is suitable to recharge the aquifer without degrading the natural aquifer system. Some thought would need to be put into how the excess water from the Dam which is at a lower elevation to both the wellfields, would be transported to the aquifer.

The wastewater treatment plant should be the last water source option for Managed Aquifer Recharge in the Langebaan and Hopefield region. The quality of the water varies greatly from month to month, with high amounts of nitrates, sodium and other salts that need to be removed from the water before it is used to recharge the aquifer. It is recommended that this water be treated to a significantly better water quality before it can be considered for Managed Aquifer Recharge. Also, the treatment plants are situated in Vredenburg so some thought would need to be put into the transport of this water to the Langebaan Road Hopefield region.

7 RECOMMENDATIONS

Additional Managed Aquifer Recharge studies within the Saldanha Bay Local Municipality should be carried out taking into consideration the following recommendations:

- Drilling in the regions identified as having missing clay layers. The airborne TDEM geophysical survey provided a significant understanding of the aquifer structure in terms of its geological material, including where the confining clay layers were missing, however, drilling in these areas is recommended to confirm the absence of the clay layers before Managed Aquifer Recharge in these areas commence.

- To investigate the potential pressure difference caused by clay lenses throughout the aquifer. These pressure differences could result in a more complex local groundwater flow path in the Langebaan Road aquifer unit and as such, understanding the detailed way in which the recharged water will flow should allow for the matter management and optimisation of the Managed Aquifer Recharge scheme.

- Increase the spatial distribution of the pumping tests and infiltration tests in the area. Additional pumping tests done at a distance from the Langebaan Road and Hopefield wellfield are recommended along with additional infiltration tests in the Hopefield region to better understand the widespread hydraulic properties of the entire aquifer system as well as to observe how the aquifer will react to Managed Aquifer Recharge process on a larger spatial scale.

- An in-depth study of the various groundwater risk associated with Managed Aquifer Recharge is required, largely focusing on clogging risks. The mixing of the different sources and groundwater has the potential to cause the precipitation of solids in the groundwater, leading to clogging effects. The precipitation of iron oxides, calcium carbonates and manganese oxides are largely responsible for geochemical clogging in systems and are of concern in the areas because all three are present in the groundwater as the geology of the area is calcium-rich. As such, minerals predicted to precipitate during the source water groundwater process should be investigated.

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9 APPENDICES

9.1 Appendix A

9.1.1 Infiltration Tests

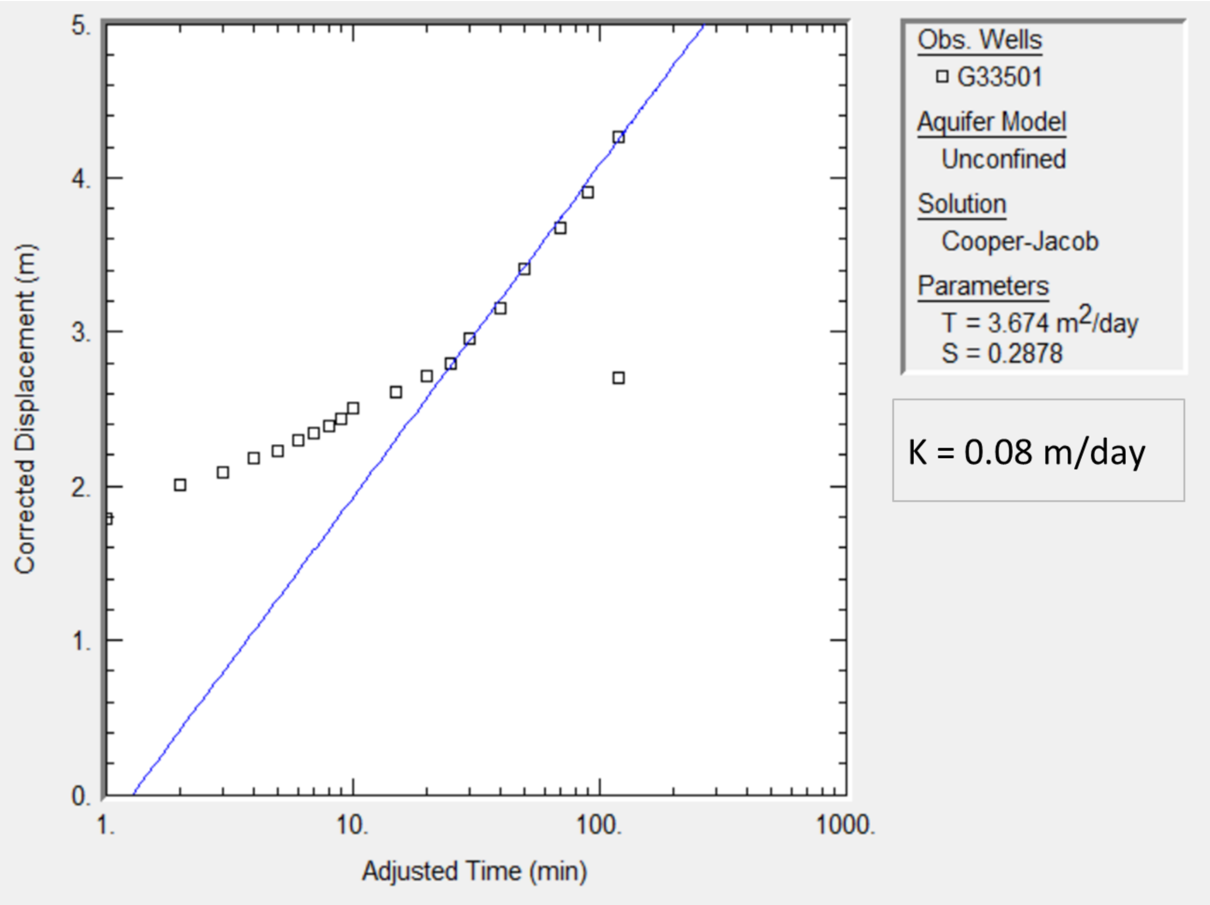
Unsaturated Infiltration tests

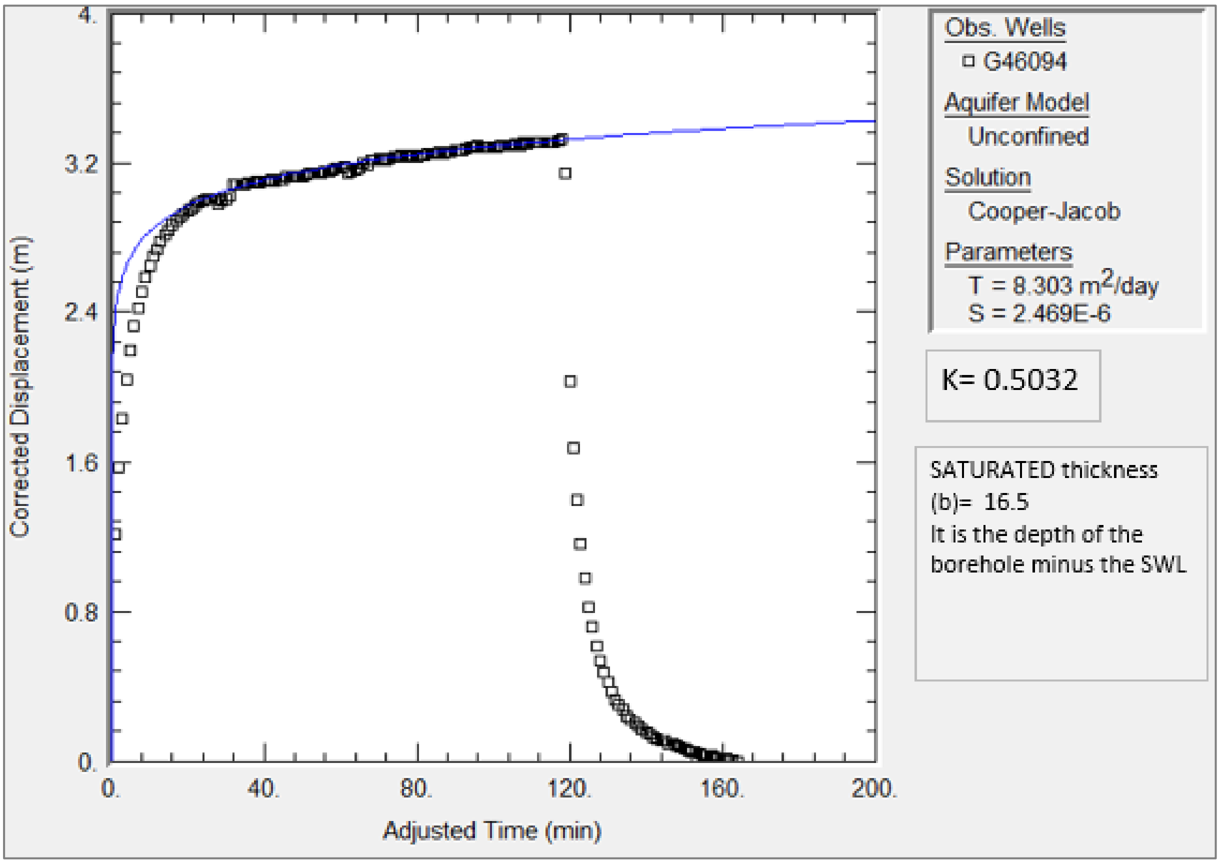
BH ID	K (infiltrometer) (m/day)				Av K (m/day)
G32932	1.81	4.4	13.31		4.733
G33323	6.98	7.04	7.87		7.286
G33324	0.53	1.01	1.07		0.830
G46098	1.69	3.34	0.9		1.719
G32926	2.04	1.19	0.71		1.199
G46055	2.26	1.65			1.931
G46109	0.58	1.1	2.2		1.120
G46093	2.73	0.37			1.005
G32938	0.95	0.03			0.169
G32933	2.63	1.79			2.170
G46106	3	6.46	14.72		6.583
G32930	6.17	1.5			3.042
BG00063	1.6	2.6			2.040
LRA 1B2	1.17	4.5	20.65		4.773
LRA 1B1M	1.65	1.62			1.635
G46025	1.21	8.21	2.41		2.882
HPF 2-3M	3.54	2.88	5.59		3.848
HPF 2-7M	5.99	13.22	23.59	8.97	11.377
G33498	40.63	28.35			33.939
G33501	0.94	3.17	1.99		1.810
HPF 1	1.15	1.16	2.55		1.504
G46097	4	1.51	3.88		2.862

Saturated Infiltration Tests

BH ID	K (augured) (m/day)					Av K (m/day)
G32932	0.85	1.03	0.75			0.869
G33323	0.51	0.44				0.474
G33324	0.42	0.51	0.46	0.11	0.24	0.304
G46098	1.21	0.61				0.859
G32926	0.7	0.86				0.776
G46055	0.19	1.73	1.16			0.725
G46109	0.24	0.31	0.2	0.16		0.221
G46093	0.66	0.51	0.53			0.563
G32938	0.34	0.38	0.48			0.396
G32933	0.08	0.22	0.13	0.13		0.131
G46106	2.34	0.57	0.72			0.987
G32930	0.2	0.13	0.06			0.116
BG00063	0.59	0.51	0.07			0.276
LRA 1B2	3.2	4.37	2.18			3.124
LRA 1B1M	0.44	0.49				0.464
G46025	0.76					0.760
HPF 2-3M	0.99	0.88				0.933
HPF 2-7M	1.87	3.9				2.701
G33498	1.13	3.09				1.869
G33501	0.33	0.36				0.345
HPF 1	1.05					1.050
G46097	0.83	1.06				0.938

9.1.2 Pumping Tests





9.2 Appendix B

9.2.1 Groundwater quality over the study area

Langebaan Road

Paramaters	Units	SANS 241-1: 2015	LRA-1B2M	LRA-1B1M	LRA-1B4	LRA-1B3	LRA-1A4	LRA-1A2	G46109	G46093	G46055
As	mg/L	<= 0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	mg/L	<= 2.4	0.078	0.09	0.07	0.07	0.06	0.06	0.18	0.20	0.10
Ca	mg/L		51	59	51	41	43	49	84	51	41
Cl	mg/L	<= 300	129.1	152.9	128.28	107.21	107.63	121.04	183.25	151.65	142.39
F	mg/L	<= 1.5	0.26	0.17	0.25	0.2	0.32	0.22	0.6	0.34	0.28
Fe	mg/L	<= 2	0.406	9.69	0.17	0.74	0.04	0.27	3.87	0.99	1.43
K	mg/L		2	1	2	2	2	1	5	2	3
Mg	mg/L		7	10	7	6	6	7	22	7	8
Mn	mg/L	<= 0.4	0.009	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.13
NH4	mg/L	<= 1.5	0.2	0.15	0.36	0.16	0.15	0.16	0.17	0.15	0.15
NO3	mg/L	<= 11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Na	mg/L	<= 200	73	81	70	64	66	66	119	88	94
SO4	mg/L	<= 500	16.39	26.84	16.69	5.44	5.18	15.78	34.75	7.54	4.11
Paramaters	**Units**	**SANS 241-1: 2015**	**G32938**	**G32933**	**G46060**	**G32937**	**G46061**	**G46059**	**G32926**	**G46092**	**G46098**
As	mg/L	<= 0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	mg/L	<= 2.4	0.35	0.13	0.12	0.08	0.06	0.08	0.24	0.50	0.50
Ca	mg/L		79	105	62	46	42	48	27	66	95
Cl	mg/L	<= 300	638.13	458	173.07	124.95	116.83	135.52	270.69	1300.4	1011.17
F	mg/L	<= 1.5	1.31	0.42	0.26	0.15	0.22	0.25	0.6	0.94	1.04
Fe	mg/L	<= 2	0.11	0.17	0.62	0.01	0.01	0.01	0.10	0.02	1.99
K	mg/L		10	5	2	1	1	5	8	20	17
Mg	mg/L		44	24	10	6	7	7	19	68	63
Mn	mg/L	<= 0.4	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02
NH4	mg/L	<= 1.5	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
NO3	mg/L	<= 11	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.36
Na	mg/L	<= 200	444	220	114	68	60	76	156	711	567
SO4	mg/L	<= 500	66.3	39.09	28.76	15.78	36.3	15.37	34.89	76.34	27.32

Hopefield

Paramaters	Units	SANS 241-1: 2015	HPF2-7M	HPF2-5M	HPF2-4M	HPF2-3M	HPF2-1M	HPF2-6M	G46097	G33501	G46024	T3W-1510
As	mg/L	<= 0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	mg/L	<= 2.4	0.101	0.049	0.1	0.049	0.076	0.093	0.07	0.076	0.06	0.1
Ca	mg/L		62	55	62	36	78	73	42	26	33	91
Cl	mg/L	<= 300	192.37	166.26	381.52	119.12	181.07	181.56	116.37	139.1	99.73	263.74
F	mg/L	<= 1.5	0.15	0.15	0.27	0.24	0.15	0.15	0.28	0.15	0.22	0.15
Fe	mg/L	<= 2	0.801	0.107	3.94	0.551	1.626	0.996	1.64	0.213	2.10	0.438
K	mg/L		1	2	5	1	1	1	2	2	2	2
Mg	mg/L		11	9	21	7	10	11	7	6	6	14
Mn	mg/L	<= 0.4	0.008	0.008	0.075	0.014	0.011	0.009	0.01	0.01	0.01	0.011
NH4	mg/L	<= 1.5	0.15	0.15	1.33	0.15	0.15	0.16	0.15	0.15	0.15	0.15
NO3	mg/L	<= 11	1	1	1	1	1	1	0.50	1	0.50	0.05
Na	mg/L	<= 200	112	80	205	63	97	105	67	76	54	149
SO4	mg/L	<= 500	23.35	31.06	5.06	20.44	23.48	23.99	47.97	17.23	37.89	50.76

9.2.2 *PhreeqC mixing model outputs*

Langebaan Road

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Vredenburg WWTP (Feb)	LRA 1B4	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	6.61	7.8	7.62	7.68	7.51	7.32	7.10	6.80
EC	(mS/m)	<=170	116.7	68.5	74.90	71.80	80.60	89.30	98.00	106.70
Alkalinity as CO3	mg/L		18.6	118.1	120.84	129.12	105.30	81.48	57.64	33.82
As	mg/L	<= 0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ca	mg/L		38	51	57.59	49.74	47.13	44.53	41.92	39.32
Cl	mg/L	<= 300	173.44	128.28	160.46	132.84	141.88	150.92	159.96	169.00
F	mg/L	<= 1.5	0.19	0.25	0.28	0.24	0.23	0.22	0.21	0.20
Fe	mg/L	<= 2	0.172	0.169	0.20	0.17	0.17	0.17	0.17	0.17
K	mg/L		32	2	8.36	5.00	11.01	17.01	23.01	29.01
Mg	mg/L		13	7	9.46	7.60	8.80	10.00	11.20	12.40
Mn	mg/L	<= 0.4	0.061	0.008	0.02	0.01	0.02	0.03	0.05	0.06
NH4	mg/L	<= 1.5	0.15	0.036	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	34.75	1	6.53	4.17	7.56	17.73	24.50	31.28
Na	mg/L	<= 200	147	70	83.09	77.73	93.15	108.56	123.96	139.36
SO4	mg/L	<= 500	82.53	16.69	32.88	23.28	36.45	49.63	54.54	66.10

> SANS 241 - 2015

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Vredenburg WWTP (July)	LRA 1B4	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	7.25	7.80	7.21	7.34	7.07	6.96	6.89	6.85
EC	(mS/m)	<=170	223.00	68.50	90.60	81.00	108.40	135.40	162.00	188.20
Alkalinity as CO3	mg/L		353.30	118.10	182.28	164.94	214.80	264.48	314.04	363.42
As	mg/L	<= 0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Ca	mg/L		51.00	51.00	60.20	51.02	51.02	51.06	51.06	51.06
Cl	mg/L	<= 300	441.65	128.28	208.22	156.70	213.50	270.26	327.02	383.96
F	mg/L	<= 1.5	0.24	0.25	0.29	0.25	0.25	0.25	0.24	0.24
Fe	mg/L	<= 2	0.22	0.17	0.21	0.17	0.18	0.19	0.20	0.21
K	mg/L		30.00	2.00	7.97	4.81	10.41	16.02	21.63	27.23
Mg	mg/L		26.00	7.00	12.07	8.90	12.71	16.51	20.32	24.13
Mn	mg/L	<= 0.4	0.09	0.01	0.03	0.02	0.03	0.05	0.06	0.08
NH4	mg/L	<= 1.5	59.45	0.04	4.45	2.48	8.13	13.66	19.04	24.29
NO3	mg/L	<= 11	0.50	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	mg/L	<= 200	253.00	70.00	119.29	88.35	125.02	161.69	198.33	234.96
SO4	mg/L	<= 500	128.38	16.69	20.98	19.16	24.32	29.12	33.53	37.65

> SANS 241 - 2015

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Misverstrand Dam (wet)	LRA 1B4	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	6.82	7.80	7.64	7.69	7.54	7.37	7.18	6.94
EC	(mS/m)	<=170	24.20	68.50	60.10	63.10	54.50	45.70	48.40	27.90
Alkalinity as CO3	mg/L		20.50	118.10	121.92	129.72	107.22	84.66	62.16	39.59
As	mg/L	<= 0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Ca	mg/L		7.00	51.00	51.38	46.61	37.81	29.01	20.21	11.40
Cl	mg/L	<= 300	43.37	128.28	134.44	119.83	102.85	85.87	68.85	51.87
F	mg/L	<= 1.5	0.15	0.25	0.28	0.24	0.22	0.20	0.18	0.16
Fe	mg/L	<= 2	0.56	0.17	0.28	0.21	0.29	0.37	0.45	0.52
K	mg/L		4.00	2.00	2.76	2.20	2.60	3.00	3.40	3.80
Mg	mg/L		5.00	7.00	7.66	6.70	6.10	5.50	4.90	4.30
Mn	mg/L	<= 0.4	0.04	0.01	0.02	0.01	0.02	0.03	0.03	0.04
NH4	mg/L	<= 1.5	0.15	0.04	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	2.04	1.00	0.98	0.90	1.13	1.35	1.58	1.81
Na	mg/L	<= 200	24.00	70.00	73.43	65.43	56.21	47.01	37.82	28.60
SO4	mg/L	<= 500	15.94	16.69	14.47	14.43	14.53	14.67	14.83	15.03

> SANS 241 - 2015

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Misverstrand Dam (dry)	LRA 1B4	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	7.23	7.80	7.73	7.74	7.69	7.62	7.52	7.34
EC	(mS/m)	<=170	18.1	68.5	59.2	62.6	52.8	42.9	32.8	22.6
Alkalinity as CO3	mg/L		22.20	118.10	121.56	129.54	106.62	87.30	60.78	37.82
As	mg/L	<= 0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ca	mg/L		6.00	51.00	51.18	46.53	37.51	28.51	19.51	10.50
Cl	mg/L	<= 300	32.07	128.28	132.17	118.70	99.45	80.19	60.94	41.69
F	mg/L	<= 1.5	0.15	0.25	0.28	0.24	0.22	0.20	0.18	0.16
Fe	mg/L	<= 2	0.02	0.17	0.17	0.15	0.12	0.10	0.07	0.04
K	mg/L		2.00	2.00	2.36	2.00	2.00	2.00	2.00	2.00
Mg	mg/L		4.00	7.00	7.66	6.70	6.10	5.50	4.90	4.30
Mn	mg/L	<= 0.4	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00
NH4	mg/L	<= 1.5	0.15	0.04	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	0.50	1.00	0.00	0.00	0.00	0.00	0.52	0.45
Na	mg/L	<= 200	18.00	70.00	72.23	64.83	54.42	44.03	33.61	23.20
SO4	mg/L	<= 500	9.69	16.69	18.30	15.99	14.59	13.19	10.83	9.77
									> SANS 241 - 2015	

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	WCDM Pipeline	LRA 1B4	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	7.23	7.80	7.02	7.73	7.65	7.56	7.45	7.30
EC	(mS/m)	<=170	36.50	68.50	62.10	64.30	58.00	51.70	43.50	38.80
Alkalinity as CO3	mg/L		38.00	118.10	124.80	131.46	112.32	93.18	74.04	54.88
As	mg/L	<= 0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Ca	mg/L		17.00	51.00	53.38	47.61	40.80	34.01	27.20	20.40
Cl	mg/L	<= 300	72.59	128.28	140.29	122.77	111.61	100.47	89.31	78.17
F	mg/L	<= 1.5	0.15	0.25	0.28	0.24	0.22	0.20	0.18	0.16
Fe	mg/L	<= 2	0.01	0.17	0.17	0.15	0.12	0.09	0.06	0.03
K	mg/L		5.00	2.00	2.96	2.30	2.90	3.50	4.10	4.70
Mg	mg/L		6.00	7.00	8.06	6.90	6.70	6.50	6.30	6.10
Mn	mg/L	<= 0.4	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00
NH4	mg/L	<= 1.5	0.15	0.04	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	2.32	1.00	1.03	0.93	1.22	1.51	1.80	2.09
Na	mg/L	<= 200	33.00	70.00	75.22	66.33	58.92	51.52	44.12	36.71
SO4	mg/L	<= 500	14.97	16.69	14.26	14.31	14.18	14.04	13.92	13.81
									> SANS 241 - 2015	

Hopefield

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	WWTP (Feb 2020) Output 1	HPF 2-7M	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	6.56	7.58	7.50	7.37	7.22	7.02	6.74	6.57
EC	(mS/cm)	<=170	113.10	97.7	96.50	100.00	103.50	106.90	110.40	111.80
Alkalinity as CO3	mg/L		21.61	146.8	160.74	130.62	100.56	70.50	40.40	28.37
As	mg/L	<= 0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ca	mg/L		39.22	62.00	59.76	55.19	50.62	46.09	41.52	39.70
Cl	mg/L	<= 300	176.73	192.37	190.91	187.79	184.64	181.52	178.40	177.12
F	mg/L	<= 1.5	0.38	0.15	0.17	0.22	0.27	0.31	0.36	0.38
Fe	mg/L	<= 2	0.67	0.80	0.79	0.76	0.74	0.71	0.68	0.67
K	mg/L		32.43	1.00	4.14	10.44	16.72	23.01	29.30	31.81
Mg	mg/L		13.52	11.00	11.26	11.76	12.26	12.77	13.27	13.47
Mn	mg/L	<= 0.4	0.07	0.01	0.02	0.03	0.04	0.05	0.06	0.07
NH4	mg/L	<= 1.5	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	34.75	1.00	4.29	11.06	17.82	24.58	31.35	34.06
Na	mg/L	<= 200	149.00	112.00	115.75	123.16	130.58	137.98	145.39	148.33
SO4	mg/L	<= 500	76.56	23.35	24.49	33.75	43.09	52.54	62.07	65.92
									> SANS 241 - 2015	

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	WWTP (July 2020) Output 1	HPF 2-7M	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	6.83	7.58	7.24	6.89	6.87	6.81	6.77	6.76
EC	(mS/cm)	<=170	211.80	97.7	105.50	127.40	149.20	170.90	192.60	201.20
Alkalinity as CO3	mg/L		465.96	146.8	202.68	258.42	314.10	369.84	425.58	447.90
As	mg/L	<= 0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ca	mg/L		52.26	62.00	61.08	59.12	57.19	55.23	53.30	52.50
Cl	mg/L	<= 300	445.29	192.37	217.82	268.49	319.18	369.77	420.47	440.68
F	mg/L	<= 1.5	0.43	0.15	0.18	0.23	0.29	0.35	0.40	0.43
Fe	mg/L	<= 2	0.72	0.80	0.79	0.78	0.76	0.74	0.73	0.72
K	mg/L		30.45	1.00	3.95	9.84	15.74	21.64	27.54	29.89
Mg	mg/L		26.54	11.00	12.56	15.67	18.79	21.90	25.01	26.25
Mn	mg/L	<= 0.4	0.09	0.01	0.02	0.03	0.05	0.07	0.08	0.09
NH4	mg/L	<= 1.5	27.07	0.15	1.02	4.30	7.61	11.03	14.52	15.94
NO3	mg/L	<= 11	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	mg/L	<= 200	255.19	112.00	126.40	155.09	183.78	212.47	241.16	252.66
SO4	mg/L	<= 500	45.00	23.35	21.13	19.50	17.98	16.73	15.70	15.33
									> SANS 241 - 2015	

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Output 1 - wet	HPF 2-7M	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	6.72	7.58	7.52	7.41	7.27	7.10	6.85	6.70
EC	(mS/cm)	<=170	26.00	97.7	88.10	74.50	60.80	47.00	32.90	27.20
Alkalinity as CO3	mg/L		28.28	146.8	160.92	131.28	101.58	71.94	42.26	30.40
As	mg/L	<= 0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ca	mg/L		8.20	62.00	56.63	45.89	35.12	24.35	13.58	9.28
Cl	mg/L	<= 300	46.55	192.37	177.87	148.69	119.51	90.33	61.16	49.49
F	mg/L	<= 1.5	0.34	0.15	0.17	0.21	0.25	0.28	0.32	0.34
Fe	mg/L	<= 2	1.07	0.80	0.83	0.88	0.94	0.99	1.04	1.06
K	mg/L		4.41	1.00	1.34	2.02	2.71	3.39	4.07	4.34
Mg	mg/L		5.51	11.00	10.45	9.35	8.26	7.16	6.06	5.62
Mn	mg/L	<= 0.4	0.05	0.01	0.01	0.02	0.03	0.04	0.05	0.05
NH4	mg/L	<= 1.5	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	2.01	1.00	1.01	1.22	1.43	1.64	1.85	1.94
Na	mg/L	<= 200	25.91	112.00	103.45	86.21	68.99	51.75	34.53	27.63
SO4	mg/L	<= 500	19.75	23.35	19.73	19.43	19.14	18.90	18.70	18.65
									> SANS 241 - 2015	

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	Output 1 - dry	HPF 2-7M	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	7.11	7.58	7.55	7.51	7.45	7.36	7.20	7.10
EC	(mS/cm)	<=170	20.10	97.7	87.50	72.90	58.10	43.10	27.80	21.60
Alkalinity as CO3	mg/L		31.24	146.8	161.28	132.36	103.38	74.40	45.46	33.87
As	mg/L	<= 0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ca	mg/L		7.20	62.00	56.55	45.57	34.62	23.65	12.68	8.30
Cl	mg/L	<= 300	35.27	192.37	176.77	145.32	113.88	82.43	50.98	38.43
F	mg/L	<= 1.5	0.34	0.15	0.17	0.21	0.25	0.28	0.32	0.34
Fe	mg/L	<= 2	0.52	0.80	0.77	0.72	0.66	0.60	0.55	0.53
K	mg/L		2.41	1.00	1.14	1.42	1.71	1.99	2.27	2.38
Mg	mg/L		4.51	11.00	10.35	9.05	7.76	6.46	5.16	4.64
Mn	mg/L	<= 0.4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NH4	mg/L	<= 1.5	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	0.50	1.00	0.86	0.78	0.70	0.61	0.53	0.49
Na	mg/L	<= 200	19.91	112.00	102.86	84.42	65.98	47.57	29.13	21.76
SO4	mg/L	<= 500	13.96	23.35	19.24	17.93	16.61	15.28	13.94	13.40
									> SANS 241 - 2015	

			Source water	Groundwater						
Parameter	Units	SANS 241-2015	WCDM Pipeline Output 1	HPF 2-7M	2% Recharge	10% Recharge	30% Recharge	50% Recharge	70% Recharge	90% Recharge
pH		>=5 to <=9.7	7.15	7.58	7.54	7.49	7.42	7.33	7.21	7.14
EC	(mS/cm)	<=170	37.80	97.9	89.30	78.10	66.80	55.50	44.00	39.30
Alkalinity as CO3	mg/L		45.00	146.8	163.56	139.14	114.72	90.36	65.94	56.16
As	mg/L	<= 0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ca	mg/L		18.20	62.00	57.63	48.90	40.12	31.35	22.58	19.08
Cl	mg/L	<= 300	75.80	192.37	180.81	157.48	134.15	110.83	87.50	78.14
F	mg/L	<= 1.5	0.34	0.15	0.17	0.21	0.25	0.28	0.32	0.34
Fe	mg/L	<= 2	0.51	0.80	0.77	0.71	0.66	0.60	0.54	0.52
K	mg/L		5.42	1.00	1.44	2.33	3.21	4.09	4.98	5.33
Mg	mg/L		6.51	11.00	10.55	9.65	8.76	7.86	6.96	6.60
Mn	mg/L	<= 0.4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NH4	mg/L	<= 1.5	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
NO3	mg/L	<= 11	2.32	1.00	1.05	1.33	1.61	1.89	2.17	2.28
Na	mg/L	<= 200	34.92	112.00	104.35	88.92	73.50	58.07	42.65	36.46
SO4	mg/L	<= 500	18.37	23.35	19.59	18.98	18.38	17.78	17.19	16.95
									> SANS 241 - 2015	