Investigating the natural groundwater recharge and discharge processes of the Saldanha Bay Aquifer Systems along the West Coast of South Africa

A thesis submitted in fulfilment of the requirement for the degree of Magister Scientiae in Environmental and Water Science, Department of Earth Science, Faculty of Natural Science, University of the Western Cape

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ABSTRACT

Saldanha Bay Local Municipality is partially dependent on groundwater as part of its bulk water supply as surface water resources in the area are extremely limited and fully allocated. Due to this, there is lots of pressure on the groundwater resources by industrial development and residential growth. Despite studies being conducted on these aquifer systems since 1976, they are still poorly understood, especially with regard to their recharge and discharge processes. This study aimed at providing better insight and understanding of the natural groundwater recharge and discharge processes to assist in the better management of groundwater resources in the Saldanha Bay Local Municipality area.

The objectives of the study included: (1) identify the aquifer geological layers and extent, (2) delineate groundwater flow paths of the aquifer systems and (3) determine groundwater recharge mechanisms taking place throughout the area.

To address the first objective, a Time Domain Electromagnetic airborne geophysical survey was carried out with a 1 kilometre spacing across the Saldanha Bay Local Municipality area and with a 10-kilometre spacing (coarser detail) in the surrounding areas. The area covered by the airborne survey included the potential recharge area along the Aurora-Piketberg Mountain Range, the faults from Porterville and Malmesbury, as well as all the potential flow paths from the recharge areas to the Langebaan Lagoon Ramsar discharge area. Hydrochemical, stable isotope (oxygen-18, deuterium) and radioactive isotope (tritium) investigations were carried out to address the second objective and the third objective was addressed through the assessment of long-term groundwater levels, infiltration tests and PhreeqC evaporation modelling. These methods allowed for the determination of different water quality spatially across the aquifer, delineation of flow paths through the saturated and unsaturated zones, identification of inter-aquifer flow, and different recharge processes in the area.

The main finding of the geophysical study was the lithology and extent of the Aquifer systems within the Saldanha Bay Local Municipality area. The data showed that regional groundwater sources, which included the high lying areas that surrounded Saldanha Bay (Moorreesburg and the Aurora-Piketberg Mountain Range) contributed a large amount of groundwater to the aquifer systems. Saturated sands near the granite hills were found to promote the occurrence of local groundwater recharge processes through granite hill recharge at the foot of granitic outcrops close to the coast. The geophysics identified the Langebaan Lagoon at Geelbek to be the main discharge zone, with some groundwater discharge occurring at the Berg River, north of the River where the salt pans occur and the Atlantic Ocean. It was also found that the lower aquifer in the Langebaan Road region was discharging into the upper aquifer. This was later assessed through PhreeqC evaporation modelling.

Hydrochemical results indicated that groundwater in the area, both upper and lower aquifer units, were of Na-Cl type water. The upper aquifer was found to be more saline, with electrical conductivity (EC) ranging from 92 – 800 mS/m, compared to the lower aquifer (9 – 105 mS/m). This suggested that piston flow recharge from rainfall is highly unlikely in the area, as recently recharged water would have a lower EC value due to shorter residence times and less interaction with the subsurface.

Infiltration results showed that K_{unsat} values for Langebaan Road ranged from 0.37 – 1.21 m/day and K_{unsat} values at Hopefield range between 3.46 - 8.64 m/day. The average hydraulic conductivity of the Table Mountain Group (TMG) sands near Aurora were around 2.17 – 3.03 m/day. Thus indicating, very slow infiltration in the Langebaan Road area and rapid infiltration in the Hopefield and Aurora areas. Analyses of groundwater level trend at boreholes on the Aurora-Piketberg Mountain Range showed an almost immediate response to rainfall events occurring on the mountains, suggesting seasonal winter recharge. The rest of the catchment shows no response to local rainfall in the area indicating very little to no recharge from local rains. This, again, indicated that recharge mainly occurs through rainfall taking place a distance away from the study area (Aurora-Piketberg Mountain Range).

Stable isotope ranges for groundwater were similar across all samples (oxygen-18 = -2.8 to -4.56; deuterium = -11.7 to -19), indicating the same recharge source. Isotope signatures started to differ when assessing tritium. Results indicated that granite hill recharge takes place at the foot of granite hills as boreholes in this area contain water that has a signature similar to the present-day tritium input in the area (1.6 TU). Tritium analyses also indicated that the Aurora-Piketberg Mountain Range and the high lying Moorreesburg area was a regional recharge zone to aquifers contained within the study area.

PhreeqC modelling indicated that the saline upper aquifer is mainly due to evaporative processes after the lower aquifer discharges water into the upper aquifer. Modelling showed that the lower aquifer water started to resemble the upper aquifer water at approximately 22 – 30% evaporation, thus proving the postulated discharge of the lower aquifer into the upper aquifer in the Langebaan Road area.

Due to the time constraints, the postulated Moorreesburg recharge area could not be fully assessed. It was found that there are very limited boreholes and borehole information in the area and it is therefore recommended that further studies be conducted to understand the Moorreesburg recharge zone in more detail. It is also recommended that an attempt to quantify recharge should take place in the area to get a more comprehensive picture of the regional groundwater recharge processes and flow to aquifers contained within the Saldanha Bay Local Municipality area to better manage this important resource.

Keywords: groundwater, recharge, discharge, Saldanha Bay, geophysics, isotopes, tritium, aquifer

DECLARATION

I declare that ‘***Investigating the natural groundwater recharge and discharge processes of the Saldanha Bay Aquifer Systems along the West Coast of South Africa’*** is my work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete reference.

Full name: Aqeela Parker Date: June 2022

Signature: ____________________

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1. CHAPTER 1 – GENERAL INTRODUCTION

This chapter outlines the importance of groundwater in the Saldanha Bay Local Municipality area, situated along the West Coast of South Africa, and provides context to the present study as well as stating its significance. Chapter 1 also highlights the aim, objectives, and research questions of the study to be fulfilled and further outlines the descriptive summary of the subsequent chapters.

1.1 BACKGROUND

The Saldanha Bay Local Municipality is partially dependent on groundwater resources as part of its bulk water supply. During periods of drought their dependence on groundwater increases, while any future development in the area will also be dependent on groundwater.

The only surface water resource within the Saldanha Bay Local Municipality area (the Berg River) is fully allocated and thus groundwater will be the next alternative to investigate. The area does not have many surface water resources and receives approximately 300 mm/annum of rainfall on average. Groundwater recharge amounts in areas that have an average annual rainfall threshold of 400 mm or less seem to be very low and are sometimes negligible (De Vries et al., 2000). Due to this, there is a lot of pressure on the groundwater resources by industrial development and residential growth in the area.

The West Coast National Park forms part of this area and contained within it is the Langebaan Lagoon, a RAMSAR site that holds high environmental importance as it is a biodiversity hotspot. The lagoon has estuarine characteristics and is believed to be sustained by groundwater in its most southern point known as Geelbek. Consequently, it is important to use and manage the water resources in this area sustainably to ensure the survival of both humans and ecosystems dependent on them.

1.2 SIGNIFICANCE OF STUDY

Other than water stored in glaciers and ice caps, groundwater constitutes around 97% of the earth's freshwater resources (Healy, 2010). This statistic highlights that groundwater is a significant source of fresh water all over the world. However, as the population increases, and industries expand, there is increased pressure on groundwater especially in arid and semi-arid regions. To ensure the long-term availability of this resource, effective management schemes need to be put into practice (Healy, 2010). Assessment of natural recharge is the most important aspect of hydrological systems and plays a fundamental role in the development, proper utilization, management, and protection of groundwater resources (Manna et al., 2017).

Groundwater in the West Coast of South Africa has been utilized for many years due to limited surface water resources and thus aquifer systems in this area are extremely important and need to be used sustainably. Although studies on these systems have been conducted since the late1970's, knowledge of them is still limited, particularly with regards to the natural recharge and discharge processes.

This study, therefore, aims at investigating knowledge gaps, which include groundwater flow paths and recharge mechanisms in the area. These investigations will assist in the identification of the natural groundwater recharge and discharge areas of the aquifer systems contained in the study area. This will provide better insight and understanding of the aquifer systems, which will aid in the management and protection of the resource and ecosystems that rely on them for survival.

1.3 PROBLEM STATEMENT

Groundwater in the Saldanha Bay Local Municipality area has been utilised for many years, yet the aquifer systems located within the area are still poorly understood. The specific groundwater recharge and discharge areas of the aquifers are contentious and the volume of water entering and leaving the system is yet to be investigated. These are important processes to understand especially due to the water scarcity in the area. It is therefore important to investigate these systems to optimize usage of resources in the area and to ensure optimal management and sustainability thereof.

1.4 RESEARCH QUESTIONS

The present study aims to answer the following research questions which will allow for the provision of better insight and understanding of the aquifer systems contained within the Saldanha Bay Local Municipality area:

- Where are the areas of natural recharge and discharge of the Saldanha Bay Local Municipality Aquifers?
- What are the mechanisms of natural recharge in the area?

1.5 AIM AND OBJECTIVES

1.5.1 Aim:

The purpose of the study is to identify areas of natural groundwater recharge and discharge as well as to determine how groundwater recharge is taking place to the Aquifer Systems contained within the Saldanha Bay Local Municipality area.

To achieve the above aim and ultimately answer the research questions of this study; which will ensure the success of the project; the following objectives will have to be met:

1.5.2 Objectives:

- Identify the aquifer geological layers and extent
- Delineate groundwater flow paths of the aquifer systems
- Determine groundwater recharge mechanisms taking place throughout the area

1.6 RESEARCH FRAMEWORK

The following research approach will be followed to answer the research questions of the present study and ultimately achieve the aim and objectives of the study:

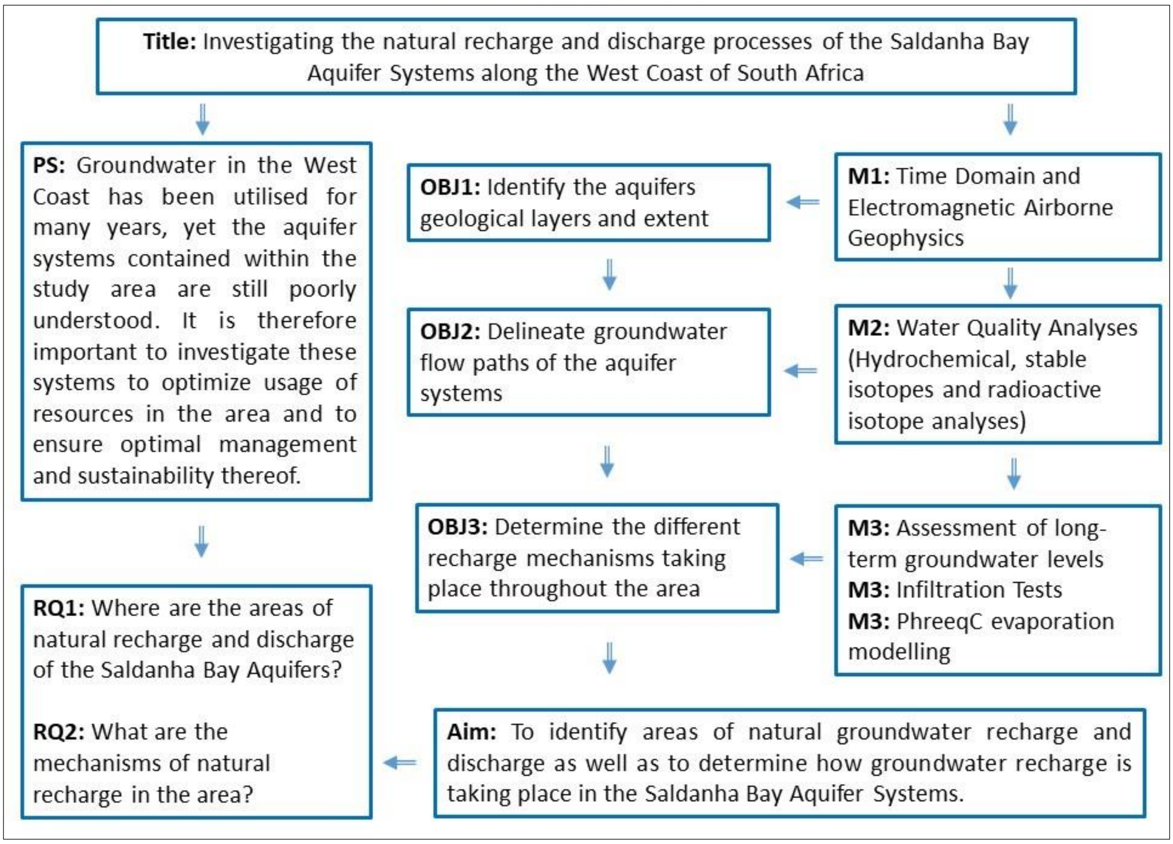

Figure 1: Flow chart of the research approach to be followed for the present study PS = Problem Statement, RQ (1, 2) = Research Question, OBJ (1, 2, 3) = Objective, M (1, 2, 3) = Methods

1.7 THESIS STRUCTURE

This research study consists of 7 chapters and is structured according to the logical progression that forms the basis of the study. The chapters are presented as follows:

Chapter 1: Provides the general background overview of the study and outlines the main aim, research objectives and significance of the research study.

Chapter 2: Reviews previous studies that were done in the area to establish what is known and unknown with regards to the aquifer systems in the Saldanha Bay Local Municipality area. It also presents an additional literature review of the following aspects: groundwater recharge in semi-arid regions, groundwater discharge, groundwater flow patterns, and appropriate methods that were used to understand these processes.

Chapter 3: Describes the study area in detail. It describes the physiographic information of the study area which includes topography, drainage, climate, geology, and hydrogeology.

Chapter 4: Outlines the experimental approaches, analytical techniques and sampling methods used in this research work to fulfil the objectives of this study, which will essentially answer the research questions of this study and achieve its aim and objectives.

Chapter 5: Displays and discusses all results of the different research methods in the form of graphs, tables, and statistical analyses of the raw data. This chapter also explains how the results can be interpreted for a better understanding of the natural groundwater recharge, flow paths and discharge of the aquifer systems.

Chapter 6: Provides a summary of the current understanding of the aquifer systems contained in the study area based on the findings of the present study in terms of natural recharge and discharge areas, groundwater recharge mechanisms in the area and groundwater flow paths.

Chapter 7: This final chapter concludes the study and provides recommendations for further research. It explains the conclusions that can be drawn from the discussion and explains to what extent the objectives of the study were achieved. The limitations encountered during this study are also highlighted within this chapter.

2. CHAPTER 2 – LITERATURE REVIEW

2.1 INTRODUCTION

Groundwater is an extremely important part of the natural hydrological system. The resource has been utilised by humans thousand years with its use increasing immensely over time. Two of the most important components in any assessment of aquifer sustainability and groundwater supply is the rate at which the system is being replenished (the rate of recharge), as well as how much water the aquifer system is losing (rate of discharge) (Healy, 2010). These components form the basis of this literature review and the study as a whole.

This chapter provides a theoretical overview of groundwater movement in aquifers in semi-arid regions. It introduces scientific concepts that will aid in understanding the natural groundwater recharge mechanisms and flow paths of the aquifer systems contained within the study area. The following scientific concepts that will assist in the present recharge study are discussed in this chapter: groundwater recharge, groundwater discharge, groundwater flow patterns, and appropriate methods that were used to understand these processes in semi-arid regions. Further, the chapter introduces the basic concepts and methodologies in groundwater recharge studies and provides a detailed discussion of the methods used in this study.

2.2 GROUNDWATER OCCURRENCE AND FLOW

The hydrological cycle is an intricate closed cycle that involves the movement of water from the oceans to continental areas, to the atmosphere and back to the ocean as seen in Figure 2. It is an interlinked cycle that governs all hydrological processes that occur and sustain life on earth. Water evaporates from surface water bodies and land surfaces to become water vapour that is carried over the earth by atmospheric circulation. Inflow to the hydrologic system arrives as snowmelt or rainfall after vapour condenses and precipitates on the land and oceans. The precipitated water may be intercepted by vegetation, become overland flow over the land surface, infiltrate into the groundwater or flow through the soil as subsurface flow. Outflow takes place as streamflow (or runoff) and evapotranspiration; a combination of evaporation from surface water bodies, evaporation from soil surfaces, and transpiration from vegetation (Freeze and Cherry, 1979).

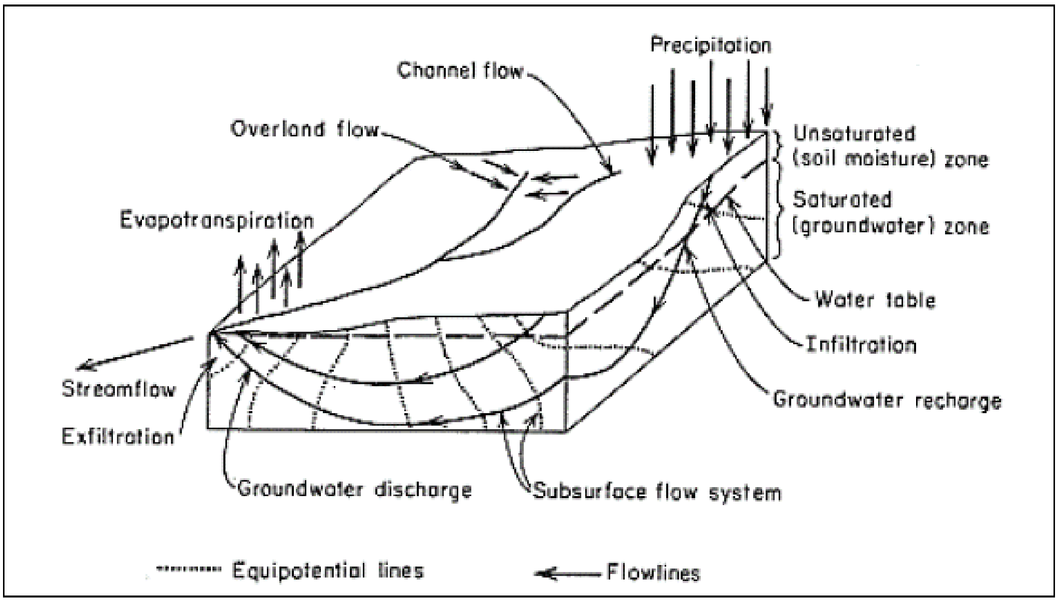

Figure 2: Schematic representation of the hydrologic cycle (Freeze and Cherry, 1979).

Groundwater flow is only one component of the complex hydrologic cycle. Groundwater is part of a dynamic flow system where water enters groundwater systems in recharge areas and moves through them, as dictated by hydraulic gradients and hydraulic conductivities to discharge areas (Heath, 1983 as cited in Peterson, 2012). It moves vertically into and horizontally through aquifers from areas of high water-level elevation to areas of low water-level elevation. The groundwater response at a given point in an aquifer depends on the distance from the recharge area and the rate at which groundwater moves through the landscape. This is dependent on the transmissivity, hydraulic conductivity and storativity of the aquifer system (Kirchner, 2003). Figure 3 shows the responses in water levels at different distances from the recharge area (Kirchner, 2003) and Figure 4 illustrates that ground-water flow paths vary greatly in length, depth, and travel time from points of recharge to points of discharge in the groundwater system (Brown et al., 2007).

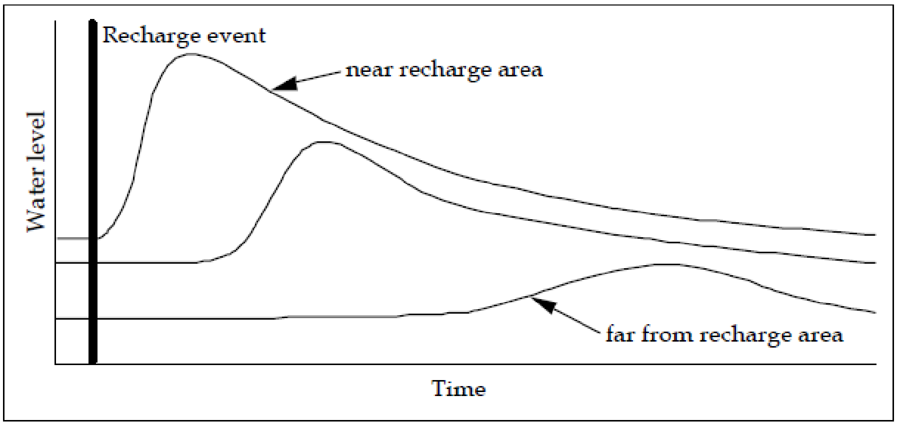

Figure 3: Responses in water levels at different distances from the recharge area (Kirchner, 2003).

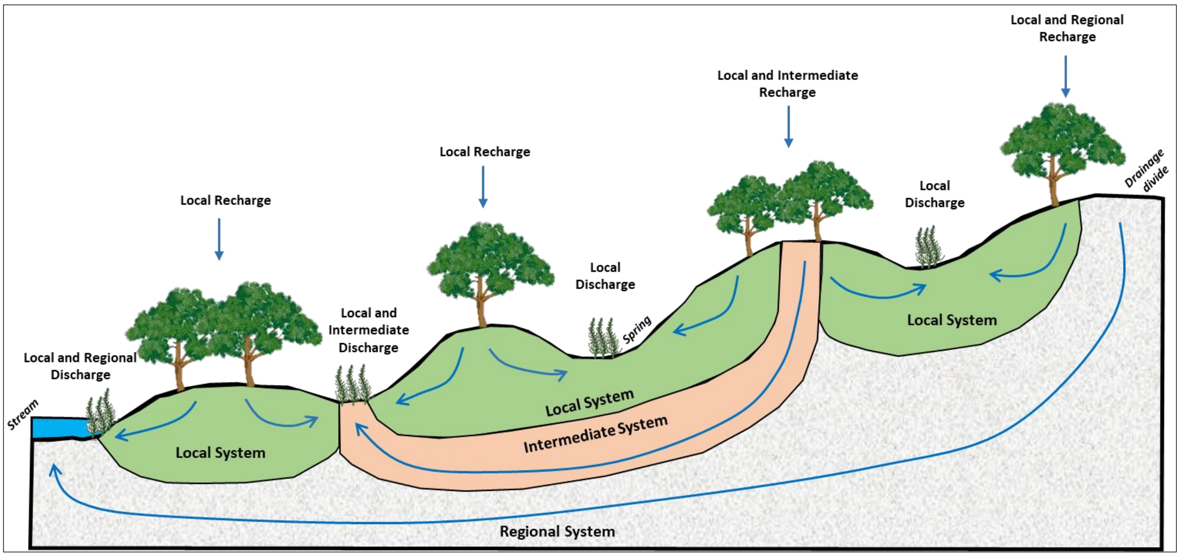

Figure 4: Local, intermediate and regional systems of groundwater flow (Adapted from Brown et al., 2007)

2.3 GROUNDWATER RECHARGE

Groundwater recharge is defined as the "downward flow of water reaching the water table, adding to groundwater storage" (Healy, 2010). Recharge can be classified as the following (Xu and Beekman, 2003):

1. According to the origin of water:
   a. Direct/local/diffuse recharge: the widespread movement of water from land surface to the water table
   b. Indirect/localised/non-diffuse recharge: accumulation of precipitation in surface water bodies, and subsequently concentrated infiltration and percolation through the unsaturated zone to a groundwater body.

2. According to flow mechanisms through the unsaturated zone:
   a. Piston/translatory flow: precipitation, which is stored in the unsaturated zone, is displaced downwards by the next infiltration/percolation event without disturbance of the moisture distribution.
   b. Preferential flow: flow via preferred pathways/macropores, which are sites (abandoned root channel, burrows, or fissures) or zones (stream beds) in the unsaturated zone with relatively high infiltration and percolation capacity.

2.3.1 Groundwater Recharge Mechanisms

Characterization of groundwater recharge is critical for sustainable management of water resources, control of subsurface contamination, and a better understanding of hydrologic and ecological variability (Ng et al., 2009). Recharge occurs through diffuse and focused mechanisms (Figure 5). Diffuse recharge generally occurs over large areas due to precipitation infiltrating into the soil and moving through the unsaturated zone to the water table, it is also known as direct recharge. A type of focused recharge is the movement from surface water (streams, lakes, canals) to an underlying aquifer. This type of recharge varies more in space and time, and as the degree of aridity in a certain area increases, focused recharge becomes more important (Xu and Beekman, 2003). Focused recharge can occur as localized recharge, which is concentrated recharge from small depressions joints or cracks. It can also occur as indirect recharge from rivers, canals, and lakes.

Groundwater systems receive both diffuse and focused recharge, but the importance of each mechanism varies from region to region or even site to site. Generally, diffuse recharge tends to dominate in humid regions and as the degree of aridity of a certain area increases, focused recharge becomes more important (Healy, 2010).

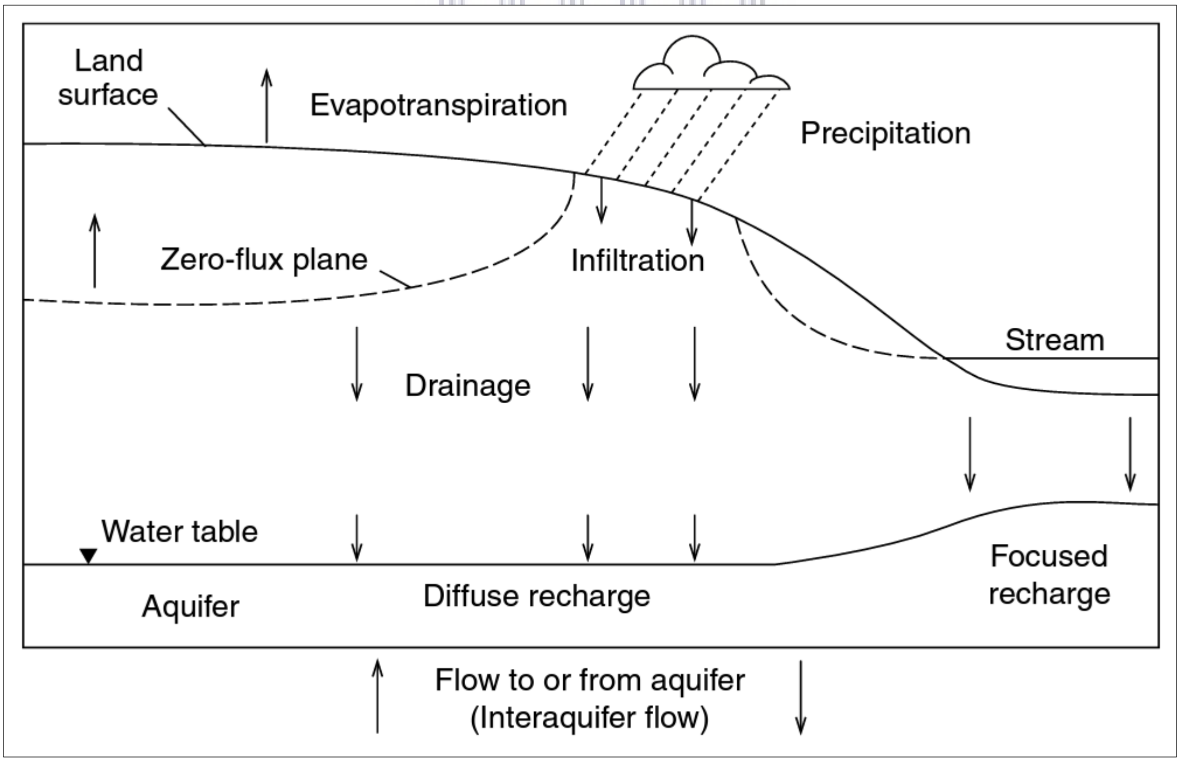

Figure 5: A vertical cross-section displaying infiltration at the land surface, the drainage through the unsaturated zone, diffuse and focused recharge to an unconfined aquifer, flow between the unconfined aquifer and an underlying confined aquifer (interaquifer flow) and the zero-flux plane (Healy, 2010).

2.3.2 Factors influencing natural recharge

The key environmental factors which control recharge are climate, soils and geology, vegetation and land use, and depth to the water table. Several factors govern groundwater recharge (Healy, 2010; Scanlon et al., 2002; Silveira and Unsunoff, 2009). These factors interact to create distinctive conditions that result in recharge.

Climate

The spatial and temporal variability of climate controls the availability of water at the land surface (Scanlon et al., 2002). Climate variability is one of the most important factors that control natural recharge as precipitation is the main source of recharge. Hence, precipitation trends such as timing, duration and intensity all affect natural groundwater recharge. Recharge is more likely to take place when precipitation rates exceed evaporation rates. In semi-arid regions, evaporation rates increase in the summer months meaning most recharge occurs during winter months when evaporation rates are lower. In humid regions, precipitation and evaporation rates are fairly uniform throughout the year and in arid regions focused recharge from ephemeral streams is often the dominant recharge mechanism. Therefore, the inter-annual variability in climate limits the time that recharge can occur throughout the year (Healy, 2010). The greater the aridity of the climate, the smaller and potentially more variable the recharge flux will be (Xu and Beekman, 2003).

Depth to water table

Semi-arid regions typically have very low rainfall amounts. This coupled with deep water tables will reduce the amount of groundwater recharge significantly. However, if the water table is shallow, which is more common in humid regions with good rainfall, it is more likely that groundwater recharge will take place.

Soils and Geology

The soil is a critical factor in the groundwater recharge process as the nature of the subsurface materials controls infiltration rates (Freeze and Cherry, 1979). Recharge is more likely to occur in areas where soils are coarse-grained as they can transmit water rapidly. This increases recharge potential as the water can quickly infiltrate downwards and drain through the root zone before being extracted by plant roots. Fine-grained soils are not very permeable but can store large quantities of water. Therefore, in areas of fine-grained soils one would expect decreased infiltration, enhanced surface runoff, increased water uptake by plant roots and decreased recharge. Permeability is also an important factor when it comes to focused recharge - stream beds that are highly permeable facilitate the exchange of surface and groundwater (Healy, 2010). The thickness of the unsaturated zone also plays a vital role in recharge as more intensive groundwater recharge is expected in areas with shallow soil profiles (Simmers, 1988).

Vegetation and Land Use

Evaporation patterns are influenced by the types and densities of vegetation in an area. A vegetated land surface typically has decreased infiltration and increased rates of evaporation resulting in less water available for recharge than an unvegetated surface under the same conditions (Scanlon et al., 2002). Distribution and type of vegetation play an important role in the uptake of water in the subsurface. Forests or areas with lots of trees for example consume more water while shrubs and grasslands use less water. The depths of plant roots also play a role in recharge as it influences the efficiency with which plants can extract water from the subsurface. Enhanced recharged rates are found in areas with shallow-rooted vegetation types. When vegetation wilts or decays, their roots shrink, which can expose cavities that can act as preferential pathways that enhance infiltration and subsequent groundwater recharge (Healy, 2010).

A study was done in the Murray Basin in Australia by Scanlon et al. (2002) where deep-rooted Eucalyptus trees were replaced by shallow-rooted crops – this change in land use resulted in an increase of natural recharge by double. The transition from vegetated land surfaces to industrial land surfaces can significantly alter recharge mechanisms and hydraulic regimes. Urbanization brings about many land surface changes that can have significant consequences for recharge processes. Most urbanized surfaces (roads, parking lots and buildings) are impermeable and do not allow any infiltration to take place, which inhibits recharge.

Topography

Land surface topography plays a big role in both focused and diffuse recharge. Steep slopes tend to have high runoff and low infiltration rates whereas flat land surfaces that have poor drainage are more conducive to diffuse recharge (Healy, 2010). Small, subtle depressions can often have a big influence on infiltration rates. Delin et al., (2000) showed that slight depressions in a uniform agricultural field caused runoff to be focused in certain areas, leading to substantially higher infiltration and subsequent recharge in those areas than the rest of the field. Along a long hillslope, apparent infiltration seems to decrease in a downwards direction, because downslope portions of the hill are exposed to runoff from upward portions as well as precipitation. Local relief, orientation and altitude of mountains are additional factors that can affect recharge processes.

2.4 IDENTIFYING GROUNDWATER RECHARGE AREAS

To ensure sustainable use of groundwater, it is essential to identify the recharge zone of the groundwater system for decision-makers to employ efficient policies for water resources management and conservation. However, it is sometimes very difficult to investigate, especially in semi-arid and arid regions, where recharge amounts are usually small in comparison with the resolution of the investigation methods (Healy, 2010). Choosing a method to assess groundwater recharge is also not straightforward as it depends on several factors, which include field constraints and the availability of field data (Conrad et al., 2004).

Several methods can be used to investigate groundwater recharge. These are dealt with exclusively in many review articles and publications (Simmers, 1988; Scanlon et al., 2002; Xu and Beekman, 2003; Silveira and Unsunoff, 2009; Healy, 2010). Scanlon et al. (2002) provided a review of methods that can be applied in different climatic regions, whereas Xu and Beekman focused on methods that are suitable for recharge estimation in semi-arid Southern Africa. According to Scanlon et al. (2002), recharge techniques are split into various types based on the three hydrologic sources, or zones, from which the data are obtained, namely – surface water, the unsaturated zone, and the saturated zone. These different zones offer recharge assessments over varying space and time scales. Within each zone, techniques are generally classified into physical, tracer, or numerical modelling approaches. Chemical and isotopic methods seem to show more promise in semi-arid regions like that of the present study (Simmers, 1988). Recharge investigations that were carried out in the present study are mentioned and explained below.

2.4.1 Physical Investigations

Physical methods attempt to determine groundwater recharge from hydro-meteoric measurements, direct estimates of soil water fluxes based on soil physics or changes in the aquifers saturated volume based on water table fluctuations.

Groundwater level fluctuations

According to Simmers (1998), physical methods rely on direct measurements of hydrological parameters, which are problematic in semi-arid regions as recharge fluxes are low and changes in these parameters will be difficult to detect. Therefore, in a semi-arid region, a rise in groundwater levels after a rainfall event is a direct consequence of precipitation, which is particularly observed in the wet seasons at higher altitudes.

Infiltration Tests

Infiltration through soil layers is one of the key elements of the hydrologic cycle as it characterizes the pathway of contribution to groundwater (Murad et al., 2019). Infiltration tests indicate the rate of recharge that will take place and are carried out in the field to measure the infiltration rate and corresponding hydraulic conductivities of soils. The tests give insight into how water will infiltrate through the topsoil in a given area, which helps to understand the type of recharge processes likely to occur in that particular area.

The unsaturated hydraulic conductivity (K_{unsat}) is measured using a tension disk infiltrometer. Tension disc infiltrometers have recently become very popular devices for in situ measurements of unsaturated soil hydraulic properties as they contain an adjustable suction (0.5 to 7 cm) where you can get additional information about the soil by eliminating macropores with an air entry value smaller than the suction of the infiltrometer. This is done by controlling the infiltration with a small negative pressure or suction. When the water is under tension or suction, it does not enter macropores such as cracks or wormholes but goes further into and through the soil as determined by the hydraulic forces in the soil (Ankeny et al., 1991).

Tension disk infiltrometers measures the unsaturated hydraulic conductivity of the medium it is placed on at different applied tensions. Flow through an unsaturated soil is more complicated than flow through continuously saturated pore spaces. Macropores generally fill with air, leaving only the finer pores to accommodate water movement. Therefore, the hydraulic conductivity of the soil is strongly dependent on the detailed pore geometry, water content, and differences in matric potential. Unsaturated soil hydraulic conductivity is a function of the water potential and water content of the soil. The decrease in conductivity as the soil dries is due primarily to the movement of air into the soil to replace the water. As the air moves in, the pathways for water flow between soil particles become smaller and more tortuous, and flow becomes more difficult. Saturated conductivity occurs when all the pores, including the large ones (such as cracks or wormholes), are filled. Macropore flow, however, is extremely variable from place to place, and thus difficult to quantify. Infiltrating water under a tension prevents the filling of the macropores and gives a hydraulic conductivity characteristic of the soil matrix, and is less spatially variable (Rose,1966; Brady and Weil, 1999).

Decagon Devices Incorporation (2016) further explains that the nature and textural changeability of the topmost layer of soil zone in areas affect the way water will infiltrate through it and cause variable hydraulic conductivity values. Soil features at the topmost zone (about 0 ~100 cm) have a vigorous role in infiltration rates. Also, the composition and textural variability of the sediments and their dryness conditions, enforce the soil to absorb more water and increase the flow to deeper layers.

2.4.2 Tracer Investigations

Environmental tracers have a variety of uses in hydrogeological studies, providing qualitative and quantitative estimates of recharge. Tracer methods are based on the distribution of natural tracers such as ^{2}H, ^{3}H, ^{18}O, ^{14}C and Cl commonly found in rainfall, the saturated and unsaturated zone.

According to Geyh (2000), tracers can be split into two types: environmental and historical tracers. Environmental tracers include ions, isotopes or gases which are soluble in water and can be detected in the atmosphere, surface water and the subsurface (Healy, 2010). These naturally occurring tracers include Deuterium, Oxygen-18, Chloride, Radon-222 and Strontium. Historical tracers are those for which high concentrations result from some historical event. They have a long time to move and are commonly used to determine the rate of movement or to estimate the recharge rate. Of the tracers mentioned above, tritium, deuterium and oxygen-18 are commonly used as they most accurately simulate the movement of water as they form part of the water molecule (Silveira and Unsunoff, 2009).

Xu and Beekman (2003) explain that the stable isotopic composition of water is modified by meteoric processes, and so the recharge waters in an environment will have a characteristic isotopic signature. This signature then serves as a natural tracer for the source of groundwater and can be used to identify zones of groundwater derived from different sources. Environmental isotopes also make a significant contribution to the understanding of groundwater flow in hydrogeological systems (Tredoux and Talma, 2009). This is because they integrate small scale variability to give an effective indication of catchment scale processes (Kendall and McDonnel, 1998).

Stable Isotopes: Oxygen-18 and Deuterium

Stable environmental isotopes are measured as a ratio of the two most abundant isotopes of a given element. For oxygen, it is the ratio of ^{18}O, with a terrestrial abundance of 0.204%, to common ^{16}O which represents 99.796% of terrestrial oxygen. Thus, the $^{18}O/^{16}O$ ratio is about 0.00204 (Clark and Fritz, 1997).

The use of stable isotopes, ^{2}H and ^{18}O, is based on the fractionation of water during phase changes. For example, $H_2{}^{16}O$ has a higher vapour pressure and diffusivity than $H_2{}^{18}O$ leading to a higher ^{18}O content in water after evaporation. Likewise, $^{2}H_2O$ and $^{1}H_2O$ also fractionate, but to a greater extent than water with different oxygen isotopes due to a larger relative mass difference (Hunt et al., 2005). The different degrees of fractionation due to different processes results in ^{2}H and ^{18}O having the widest field of application in groundwater studies (Geyh, 2000). Because they are part of the water molecule, stable isotopes ^{18}O and ^{2}H are ideal conservative tracers of water movement (Hunt et al., 2005) as long as there are no phase changes along a flow path.

Isotopic concentrations are expressed as the difference between the measured ratios of the sample and reference over the measured ratio of the reference. This is expressed using the delta (δ) notation:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \text{ ‰ VSMOW}$$

Where R is the ratio of the heavy to light isotope. As fractionation processes do not impart huge variations in isotope concentrations, δ-values are expressed as the parts per thousand or permil (‰) difference from the reference.

The isotopic compositions of $\delta^{2}H$ and $\delta^{18}O$ values are normally reported relative to an international reference standard, the SMOW standard (Standard Mean Ocean Water), or the equivalent VSMOW (Vienna-SMOW) standard. In practice, each laboratory has its own standard or set of standards that have been calibrated relative to the international standard. During the measurement, the isotopic ratio of the sample is compared to that of the laboratory standard and the result is recalculated to the VSMOW scale. A δ-‰ value that is positive, say +10‰, indicates that the sample has 10 permil or 1% more ^{18}O than the reference, or is enriched in the heavier isotope by 10‰. Similarly, a sample that is depleted in the heavier isotope compared to the reference would be expressed as $\delta^{18}O_{sample}$ = -10‰ VSMOW (Clark and Fritz, 1997).

The Global Meteoric Water Line

In 1961, Harmon Craig observed that there is a relationship between the abundance of ^{18}O and ^{2}H relative to VSMOW, represented by the equation:

$$\delta^{2}H = 8 \times \delta^{18}O + 10 \text{ ‰}$$

The above equation is known as the Global Meteoric Water Line (GMWL). The importance of the observation made by Craig (1961) is that the isotopic comparison of meteoric waters behaves predictably. The GMWL is an average of many local and regional meteoric water lines which differ from the GMWL due to varying climates and geographic factors. Local lines will differ in slope and deuterium intercept. However, Craig's GMWL provides a reference for the interpretation of the provenance of groundwaters. A key observation made by Craig was that isotopically enriched waters were associated with warm regions whereas depleted waters were associated with cold regions (Clark and Fritz, 1997). The GMWL can be used as a tool to interpret the effects of temperature and evaporation of water samples collected in any area. According to Clark and Fritz (1997) if samples have been subjected to evaporation effects the ^{18}O and ^{2}H relationship will not plot on the GMWL.

Due to fractionation, waters often develop unique isotopic compositions (ratios of heavy to light isotopes) that may be indicative of their source or of the processes that formed them (Kendall and McDonnell, 1998). It is important to understand the processes for which fractionation occurs and at what stages these processes occur within the hydrological cycle. As water moves through the hydrological cycle it is subjected to various conditions in which fractionation of the isotopes take place. The process starts with the evaporation of water from the ocean surface that has $\delta^{18}O$ and $\delta^{2}H$ values close to that of VSMOW. The evaporated water is typically isotopically lighter, or more depleted, than the water left behind. The actual $\delta^{18}O$ values of precipitation reaching the ground depend on several factors (Clark and Fritz, 1997; Kendall and McDonnel, 1998; Gat et al., 2001). Factors that influence the isotopic composition of the waters found in the Saldanha Bay region are described below:

- **Altitude Effect:** Higher altitudes, like that of mountainous regions, experience colder temperatures, which results in precipitation being isotopically depleted. This effect is caused by increased rain at higher elevations due to continuous cooling of air masses pseudo-adiabatically to below dew point in an orographic precipitation system.

- **Amount Effect:** Larger rainfall events will have more negative $\delta^{18}O$ values than small rainfall events. Rainfall events of longer duration and high intensity lead to the rainout of heavy isotopes as more vapour and cloud droplets are removed until the air below the cloud becomes saturated and colder. This reduces the evaporation effects of individual raindrops as it falls to the ground.

- **Seasonal Effect:** Greater seasonal extremes in temperature generate strong seasonal variation in isotopes of precipitation. The seasonal changes in the δ values are due to seasonal changes in relative humidity, temperature and evaporation. Colder temperatures in winter result in precipitation that is relatively depleted in $\delta^{18}O$. The seasonal effect is more predominant in inland regions whereas in coastal regions seasonal variations are small.

The above-mentioned effects will have major controls on the relationship between ^{18}O and ^{2}H of local precipitation in regional groundwater recharge studies. Diamond and Harris (1997) established a Local Meteoric Water Line (LMWL) for the Western Cape of South Africa using rainfall samples collected over 3 years. The LMWL is defined by Diamond and Harris (1997) as:

$$\delta\,^{2}H = 6.1 \times \delta\,^{18}O + 8.6\ ‰$$

The δ^{2}H and δ^{18}O values of groundwater and their relationship to the LMWL can then be used to determine if the recharge is delayed or immediate and identify possible processes that may have altered the isotopic composition of the precipitation prior to groundwater recharge.

Radioactive Isotope: Tritium (^{3}H)

Due to thermonuclear weapons testing in the late 50's and early 60's tritium concentrations in rainfall increased by up to one order of magnitude in the southern hemisphere. This tritium "peak" could be traced through hydrological systems such as groundwater (Levin and Verhagen, 2013). However, at present, artificial input of tritium to the atmosphere is not common in Southern Africa and tritium in rainfall has returned to close to natural values. Groundwater usually has lower values, depending on residence times or recharge rates. Any water labelled with artificial tritium can therefore readily be detected and traced in the Southern African environment.

Environmental tritium (^{3}H) is a very useful tracer of groundwater and has been widely used for groundwater dating in both saturated and unsaturated zones. Tritium (^{3}H) is produced naturally in the upper atmosphere through the cosmic bombardment of ^{14}N, and readily oxidized to water, in which it is a conservative tracer as it is part of the water molecule (Clark and Fritz, 1997). Natural and anthropogenic tritium enters the hydrological cycle through precipitation.

Isolated from the atmospheric source, following recharge from rainfall, no new tritium is added to groundwater and the concentration of tritium decreases with its characteristic half-life of 12.32 years as the groundwater moves through the aquifer system. This gives time-dependent information or 'ages' on fairly recently recharged groundwater (Vrba and Verhagen, 2011).

Rainwater in South Africa contains natural tritium at concentrations of approximately 3 Tritium Units (TU) (Levin and Verhagen, 2013). Therefore, it is possible to identify the recharge period of recent groundwater by comparing its tritium content with those of present-day rainfall. Measurable tritium in boreholes would indicate recharge, while zero tritium would indicate slow or no recharge of that aquifer. Tritium is thus essential in studies of aquifer dynamics.

2.5 PREVIOUS STUDIES ON GROUNDWATER RECHARGE

2.5.1 International Context

Beekman et al. (1997) conducted recharge investigations in the Kalahari Desert in Botswana between 1987 and 1996. The study used analyses of environmental tracers such as stable isotopes and tritium to determine recharge in the area. Systematic sampling of rainfall for ^{18}O and ^{2}H took place throughout the entire study period to establish relationships between rainfall amounts and intensity and groundwater recharge as well as to elucidate mechanisms of recharge for the area. Tritium input had also been analysed since 1992 and was found to range between 1.5 and 8.2 TU. In areas where high tritium values were observed about the surroundings, it indicated a significant contribution of preferential flow to groundwater recharge. Stable isotope and tritium analyses for the area helped in determining that groundwater recharge for the area is highly variable spatially and of an essentially multimodal nature with slow diffuse flow through the topsoil and relatively fast preferential flow through soil crack, root channels and fractures. The study concluded that in semi-arid regions, even under different geological and morphological conditions, groundwater recharge seems to become very low or negligible below an average rainfall threshold of 400 mm per annum.

A groundwater recharge assessment conducted on the Murray Basin in Australia was carried out by Cartwright and Morgenstern (2012). The study used high-precision Tritium concentrations together with major ion and environmental isotope geochemistry to determine recharge in the Ovens Catchment. The study found that tritium concentrations of groundwater in the catchment range from 0.02 to 3.62 TU. The tritium input for the area was measured at ~3.5 TU. Overall the tritium concentrations of groundwater in the upper Ovens were found to be higher than those in the lower Ovens at any given depth. A borehole in the upper catchment that had very low tritium concentrations was deemed to be a groundwater discharge, not a groundwater recharge area. This study illustrated that following the diminishing of the bomb pulse tritium in the southern hemisphere single measurements of tritium may be readily used to determine recharge rates in groundwater by comparing it to the natural tritium values in rainfall for the area under investigation.

Water flow through soil layers (infiltration) encompasses one of the key elements of the hydrologic cycle, where it characterizes the pathway of contribution to the groundwater aquifers. Murad et al. (2019) carried out an aquifer recharge study in the United Arab Emirates where infiltration tests were carried out in the field to measure the soil layers' infiltration rate and their corresponding hydraulic conductivity. The study area, similar to the Saldanha Bay study area, receives little rainfall (>300 mm/a) and the UAE aquifers consist of northern limestone, ophiolite, gravel, sand dune and coastal aquifers. The major fresh groundwater reserve in the UAE is available in the gravel alluvial deposits and around

74% of the total area of the UAE is covered by the sand dune aquifer that receives most of its recharge from the western side of the mountain. The Arabian Gulf and the Gulf of Oman are the main discharge area. The study found that low infiltration rates were found to be an effect of fine-grained mud cover on the topmost soil zone, which is composed of a mix of clay and silt. Accordingly, this clayey soil can be mobilized in the rainfall water and moves downward to decrease the hydraulic conductivity and infiltration capacity. It also found that in some areas the composition and textural variability of the sediments and its dryness conditions, enforce the soil to absorb more water and increase the underneath flow.

Kauer (2016) conducted a study on the Tuscan Aquifer whereby tension disk infiltrometers were used to measure infiltration and hydraulic conductivity. The study was done due to infiltration test analysis providing an opportunity to determine if the precipitation will infiltrate into the ground surface and potentially recharge the aquifer or if the precipitation will runoff and produce overland flow. The study found that undisturbed soils had a greater infiltration rate. Puddling or overland flow was observed over disturbed soils, such as eroded soils or compacted soils due to hiking and biking trails, as well as the exposed mudflow breccias.

2.5.2 Local Context

Several hydrogeological studies have been carried out in the Saldanha Bay region since the late 1970's (Vermaak et al., 2011) however, information on the natural recharge and discharge of the aquifers remain inadequate. In 1985, Timmerman carried out a few hydrogeological studies in the West Coast area to provide information on natural recharge mechanisms and the exploitation potential of water in the Lower Berg River Catchment. Timmerman delineated four aquifer systems in the area – the Adamboerskraal aquifer in the far north, the Grootwater Aquifer in the far south and Langebaan Road and Elandsfontein aquifers lying in between. The methods of the study included exploratory drilling, geophysical surveys, pumping tests, hydrochemical sampling, and groundwater level monitoring. Timmerman estimated natural recharge to the four primary aquifer units without using any method but by postulating a recharge estimate based on the calculated hydraulic conductivity data, geological and precipitation data. For all primary aquifers on the West Coast, direct recharge was estimated at 15% of annual precipitation, based on estimates calculated for the Atlantis Aquifer.

All Timmerman's studies carried out in the area provide estimates for recharge based on experience from other study areas. However, it is clearly stated in the reports that there was not enough data to quantify this for the local study area.

According to Weaver and Talma (2000), it is not possible that any sort of regional recharge could be taking place in the area due to the lack of variability in the water quality data and therefore the recharge source was a local one and the same for both the upper and lower aquifer. The study was carried out by spatially assessing different isotope concentrations (Carbon-13, Carbon-14, Oxygen-18 and Deuterium, and Chloride) across the Langebaan Road area. In the report, it was stated that the sandy plains close to Hopefield are the recharge area for the Langebaan Road Wellfield. This was due to the $\delta^{18}O$ in rainfall having the same character as groundwater and the chloride data showing no change from Hopefield to Langebaan Road. Weaver and Talma (2000) estimated recharge in the area to be 11.3% of the annual rainfall, using the chloride mass balance.

Conrad et al. (2003) estimated natural recharge for a Northern Sandveld primary aquifer in the West Coast region. Data collected in the study was assessed using several methods, which included: CMB, Saturated Volume Fluctuation (SVF), Cumulative Rainfall Departure (CRD) Method and Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hard rock (EARTH) Method. The results of the study found that previous estimates of recharge in the area were overestimated and that more realistic recharge rates for the region range between 0.2 to 3.4%.

In 2008, Tredoux and Talma conducted an environmental isotope study in the Langebaan Road area. Stable isotopes (^{2}H and ^{18}O) indicated local recharge from a nearby source that was not from the mountains in the east but somewhere nearby the Langebaan Road Well Field. Based on the ^{14}C results at the northern end of the Langebaan Road wellfield another recharge area could exist, south-south-east (SSE) of the wellfield, with high transmissivity and preferential flow causing rapid recharge. Other than this, using the above-mentioned isotopes, a general north-west piezometric level gradient and flow direction is evident for the central Langebaan Road Aquifer System. The study showed that groundwater at the Langebaan Road Wellfield is old (2– 30 pmc) and is most likely derived from pre-Holocene (>10 000 years) recharge. The study also makes mention of a possible recharge area close to Hopefield, where the clay layer is absent.

Andries (2019) researched the Langebaan Road and Elandsfontein region of the study area. The study used stable (^{2}H and ^{18}O) and radioactive (^{3}H and ^{14}C) to identify the source of recharge and residence times of the shallow, confined and bedrock aquifers based on sampling conducted during 2017 and 2018. Similar stable isotope signatures were observed in shallow and deep groundwaters indicating the same source of recharge. Bedrock groundwater with enriched isotopic signature displayed the evaporation effect indicating recharge from precipitation where clay lenses are locally absent and shallow groundwater indicated recently infiltrated water. Tritium results from this study concluded that the confined aquifer has a longer residence time as most of the samples range from 0.0 - 0.3 TU, indicating that groundwater is older than the detected age for tritium and that tritium has disintegrated due to its half-life. Whereas the variable tritium content in the upper unconfined reflect both immediate and delayed recharge to the unconfined.

Smith (2020) conducted a recharge study in the Elandsfontein region and found that local recharge processes occur via direct recharge mechanisms from surrounding granite hills and high elevated areas via runoff. Whereas a delayed recharge mechanism could be seen as the predominant source of regional groundwater flow from the Paarl and Porterville high lying area to the system. This was established using the Cumulative Rainfall Departure (CRD) method. Smith further analysed recharge in the area using stable isotopes. It was found that stable isotope ^{2}H and ^{18}O values identified both enriched isotopic values (-3.21‰ to -3.81‰; -3.08‰ -3.78‰) for $\delta^{18}O$ for direct recharge processes and depleted isotopic values (-4.50‰ to 4.43‰ for $\delta^{18}O$) for indirect recharge mechanisms within the study area.

Furthermore, Vermaak (2021) mentions that analyses of groundwater levels and groundwater chemistry done in the area shows a clear link between the Adamboerskraal and Langebaan Road aquifer, with a paleochannel running below the Berg River. A link between the Langebaan Road and Elandsfontein aquifer units was also established through the groundwater levels and the groundwater chemistry. This is possible through a break in the bedrock high – a paleochannel connecting the two units – and the shale-granite contact.

2.6 CHARACTERIZING AQUIFER SYSTEMS – GEOPHYSICAL SURVEYS

Geophysical methods are used to assess the physical and chemical properties of the subsurface (soils, rock; and groundwater). This is based on the response to various parts of the electromagnetic (EM) spectrum i.e. gamma rays, visible light, radar, microwave, and radio waves, and/or energy, or fields, such as gravity and the acoustic seismic potential of earth's magnetic field (United States Environmental and Protection Agency, 1993).

It is most beneficial to use geophysical methods early in the site characterization process, as they are typically non-destructive, less risky, cover more area spatially and volumetrically, and require less time and cost than using monitoring wells. On the other hand, great skill is required in interpreting the data generated by these methods, and their indirect nature creates uncertainties that can only be resolved by the use of multiple methods and direct observation. Consequently, preliminary site characterization by geophysical methods will usually be followed by direct observation through the installation of monitoring wells. Geophysical techniques can be used for several purposes in groundwater investigations and are particularly important to the present study as they can:

- Characterize the subsurface geology: which includes the identification of types and thicknesses of strata, the topography of the bedrock surface below unconsolidated material, and generating fracture or paleochannel maps.
- Characterize the aquifer system: this includes depth to water table, water quality, hydraulic conductivity, and fractures within the subsurface.

2.6.1 Geophysical methods applied in the study area

Direct Current Electrical Resistivity

The electrical resistivity of a rock depends on the physical properties of the rock and the fluids it contains in the pore spaces, the salinity of that fluid, and how the pore spaces are interconnected (Keys and MacCary, 1971). Resistivity investigations are therefore used to identify zones in the subsurface that has different electrical properties.

The electrical resistivity method involves the placement of electrodes on the earth's surface for the injection of an electrical current into the ground. The current stimulates a potential response between two other electrodes, called potential electrodes, that is measured by a voltmeter (Figure 6). Resistivity (measured in ohm-meters) can be calculated from the geometry and spacing of the electrodes, the current injected, and the voltage response (Keys, 1990).

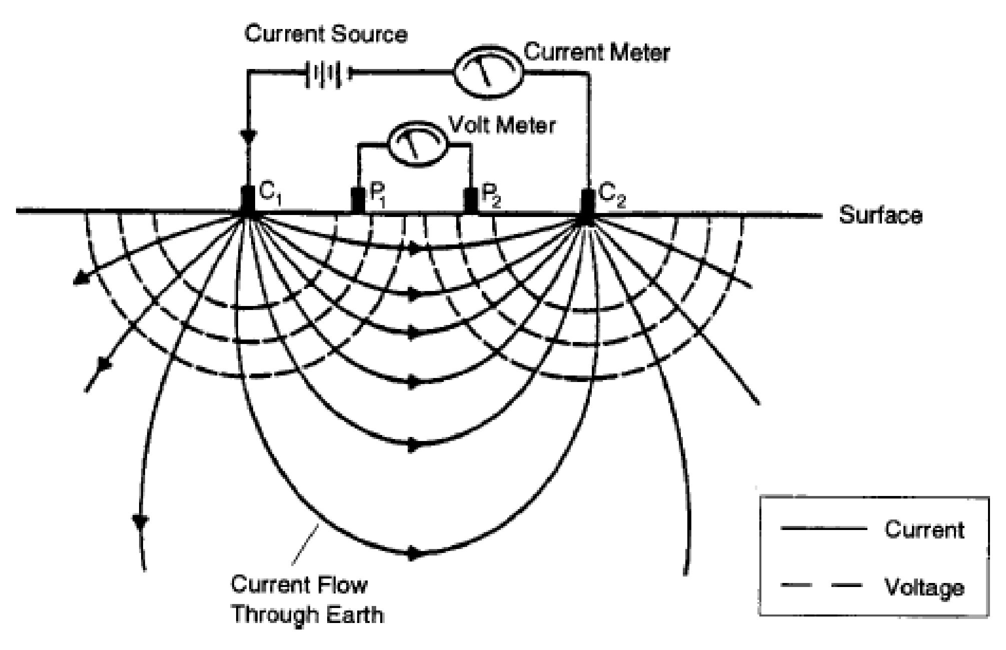

Figure 6: Basic concept of resistivity measurement (Benson et al., 1984).

Smith (1982) conducted a resistivity survey that covered the Langebaan Road and Elandsfontein areas to determine the nature, thickness and distribution of the local Cenozoic deposits in the area. Using ground resistivity geophysical methods, Smith (1982) found the presence of a northern paleochannel (running through Langebaan Road) and southern paleochannel (running through Elandsfontein). The northern paleochannel was found to transect from the Berg River valley, through Langebaan Road, to inner Saldanha Bay. Smith (1982) refers to the paleochannel as a pre-Cenozoic trough following a meandering course with the greatest thickness of unconsolidated sediments occurring at sites of cut-off meander features.

The southern paleochannel identified in the study was found to stretch from the Groen River and joins on the farm Elandsfontein, changing direction and exiting into the end of the Langebaan Lagoon. Smith (1982) also suggests that there is no connection between the southern and northern sedimentary deposits. An example of a profile of the geophysics done by Smith (1982) is displayed in Figure 8, which shows a trough of sand that is assumed to be evidence of the northern paleochannel in the Langebaan Road region.

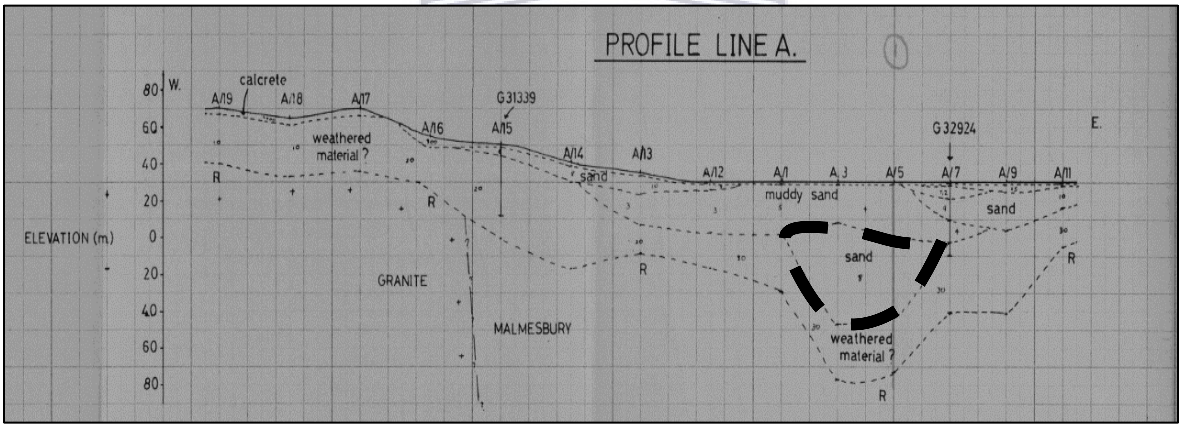

Figure 7: Profile Line A from Smith (1982) showing evidence of a portion of the Berg River paleochannel (black dashed line)

Nel (2019) conducted a ground resistivity geophysical survey over the Hopefield Reserve. The purpose of this investigation was to identify drilling sites for the Hopefield wellfield as part of an emergency water supply scheme, as well as to form part of the long-term water supply to Saldanha Bay Local Municipality. The resistivity profiles and drilling that came from these surveys (Figure 8) show the presence of a thick clay layer, with no confined lower aquifer beneath the clay.

According to drilling logs obtained from Nel (2019) for boreholes drilled along Traverse 2 (Figure 8), it was found that HPF2-3 and HPF2-4 produced very low yields due to them being drilled into clay lithologies. Therefore, a further 4 boreholes were drilled into regions with lower resistivity (33.2 ohms) to achieve higher yields. All boreholes drilled in the Hopefield reserved had no evidence of a lower confined aquifer beneath the thick clay layer, suggesting that only a shallow aquifer unit is present in the Hopefield area. It is for this reason that the aquifers discussed in this thesis will be referred to as upper and lower aquifers rather than confined and unconfined aquifers.

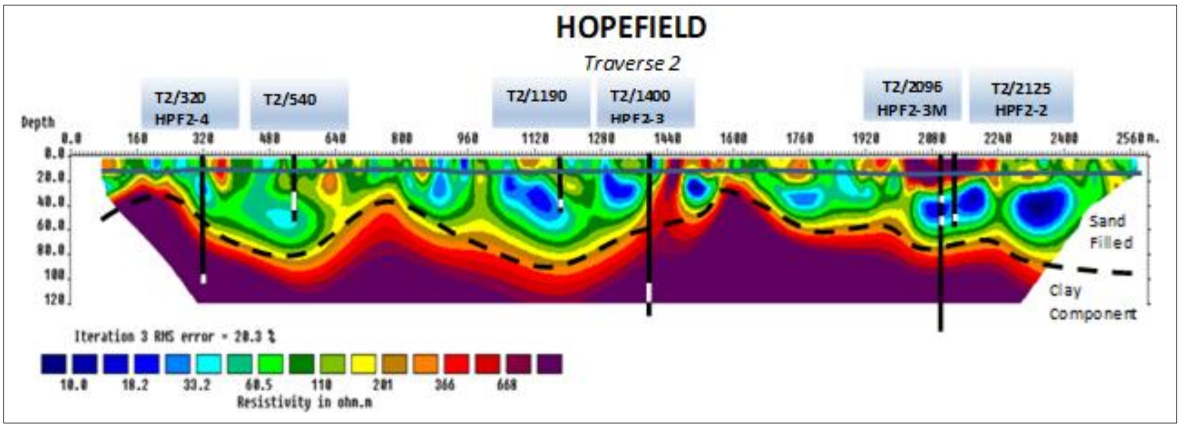

Figure 8: An example of a resistivity profile carried out by Nel (2019).

<u>*Time Domain Electromagnetic (TDEM) Airborne Geophysics*</u>

Time Domain Electromagnetic (TDEM) geological mapping involves equations for calculating the value of electromagnetic fields that are time-dependent. Geological data is then inferred from the electromagnetic field data based on resistivity factors (Morrison et al., 2007). The method was originally designed for mineral investigations but over the last two decades, the TDEM method has become increasingly popular for hydrogeological purposes as well as general geological mapping (BurVal Working Group, 2006).

Due to the dependency of the electrical conductivity on both the clay content of the host material and the mineralisation of the water, airborne electromagnetics is suitable for providing information on groundwater resources, water quality, aquifer conditions and protection levels (Siemon et al., 2011). Airborne electromagnetic surveys are also very cost-effective and data acquisition is extremely fast especially where sites are inaccessible and where large areas need to be evaluated.

The TDEM method involves generating a periodic magnetic field pulse that penetrates the earth surface. Turning off this magnetic field at the end of each pulse causes an appearance of eddy currents in geological space. These currents then gradually decay and change their disposition and direction depending on the electrical resistivity and geometry of geological bodies. The electromagnetic fields of these eddy currents are then measured above the earth surface and used for mapping and geological interpretation. The common technical means to generate magnetic field pulses is a known transmitter generally consisting of a loop of wire or a multi-turn coil connected to the output of a known electrical current pulse generator or transmitter driver. Generally, the bigger the transmitter coil diameter the stronger its magnetic moment, which then results in deeper and more accurate investigations. Received signals are digitised by a known analogue to digital converter and processed and stored by computer (Morrison et al., 2007).

Airborne TDEM geophysical methods have been successfully used in groundwater exploration studies over the last two decades. Basheer et al. (2014), Campbell et al. (2006), Masrom and Samsudin (2012) Brown et al. (2016) and Rey et al. (2020) conducted studies that found that the use of airborne time-domain electromagnetic (TDEM) surveys was an efficient method for identifying the subsurface structure of the different geological formations present in the respective study areas, within the range of 0 – 200 m below the earth's surface.

Flores Avilés et al. (2020) investigated the hydrogeological functioning of the Katari-Lago Menor Basin aquifer located in the semi-arid Altiplano in Bolivia using TDEM surveys along with groundwater level data, geochemical data and geological, lithological, and topographical information. Using the abovementioned combination of methods, the investigation successfully resolved the spatial limits of the aquifer, the vertical and lateral continuity of the Quaternary deposits, bedrock depths and revealed a general overview of the dynamic behaviour of the aquifer in terms of groundwater flow. This study is an example of how an aquifer can be characterized successfully using TDEM surveys and other hydrogeological investigations, which is an important step in identifying the natural groundwater recharge and discharge processes of the aquifers being investigated in the present study.

3. CHAPTER 3 – STUDY AREA

3.1 INTRODUCTION

This chapter describes the physiographic information of the study area which includes topography, drainage, climate, geology, and hydrogeology. These physiographic features control where and when recharge will take place and are therefore extremely important to understand. Geological and hydrogeological information is key to understanding the occurrence of groundwater and recharge processes in the area.

3.2 LOCATION, TOPOGRAPHY AND DRAINAGE

The aquifer systems under investigations are located within the Saldanha Bay Local Municipality area, along the West Coast of South Africa between Vredenburg and Moorreesburg, approximately 100 km north of Cape Town (Figure 9).

Aeolian dunes that overly wave-cut terraces dominate the topography of the Langebaan area. Sand covered plains, fixed dunes and surface limestone ridges form the visible landscape with intrusive granitic plutons responsible for the raised highlands and koppies, which reach heights up to 450 mamsl. The regional topography is generally flat to slightly undulating and does not reach elevations beyond 120 m. The Aurora-Piketberg Mountain Range is situated in the north-eastern section of the study area and reaches an elevation of about 400 m.

Situated in the same area is the Langebaan Lagoon, declared a RAMSAR site in 1998, which is a biodiversity hotspot and falls within the West Coast National Park. The Langebaan Lagoon is an extension of the Saldanha Bay, and the southernmost point of the Lagoon is known as Geelbek.

The Berg River is the only perennial river that runs through the study area. The river lies in a broad, flat flood plain with an elevation of less than 20 mamsl. The Berg River drains in a north-westerly direction and discharges into the Atlantic Ocean near Velddrif. The Groen and Sout Rivers are tributaries that feed into the Berg River and are situated on the eastern boundary of the study area. The Papkuils River is a non-perennial river situated in the north-eastern part of the study area and runs through the Aurora-Piketberg Mountain Range.

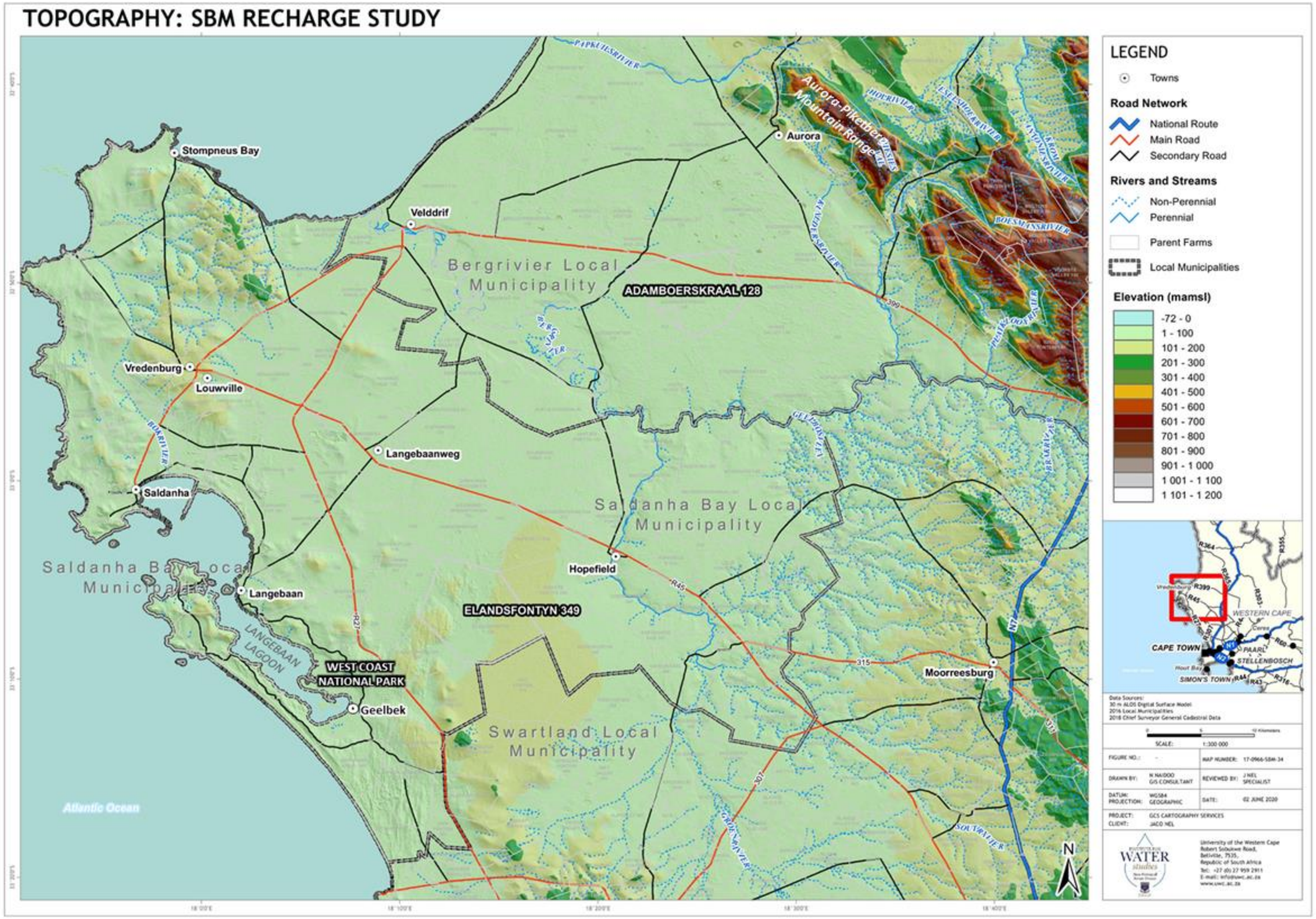

Figure 9: Location of the study area along West Coast of South Africa.

3.3 CLIMATE

The study area has a Mediterranean climate, meaning hot dry summers and cool wet winters. The region is considered semi-arid with the highest measured temperature is in February. The area receives winter rainfall with June to August being the wettest months of the year. Summer months in the study area range from November to late March. Precipitation is generally in the form of frontal rain approaching from the Atlantic Ocean. The highest rainfall is experienced in the mountain ranges (Aurora-Piketberg and Franschhoek Mountains) where the mean annual precipitation can reach 3000 mm per annum, while the mean annual precipitation for the inland areas is around 300 mm per annum.

The locations of rainfall stations in the study area are shown in Figure 10. Inter-annual variability and variability in rainfall between weather stations are significant, this is seen when comparing rainfall data from a South African Weather Services (SAWS) weather station at the coast (Geelbek) to one that is about 15 km inland (Langebaanweg) and one situated in Malmesbury, southeast of Langebaan Road. The differences in rainfall and minimum and maximum temperatures between the coastal and inland areas are shown in Figure 11, Figure 12 and Figure 13.

Rainfall data for the Aurora-Piketberg Mountain Range was provided by DWS. The highest amount of rainfall occurs in this region of the study area (Figure 14). The coast (Geelbek) experiences the second-highest amount of rainfall, with inland areas (Langebaanweg and Malmesbury) receiving the least rainfall. Areas that receive higher rainfall have an increased chance for recharge from rainfall to occur.

Figure 10: Location of rainfall stations in the study area

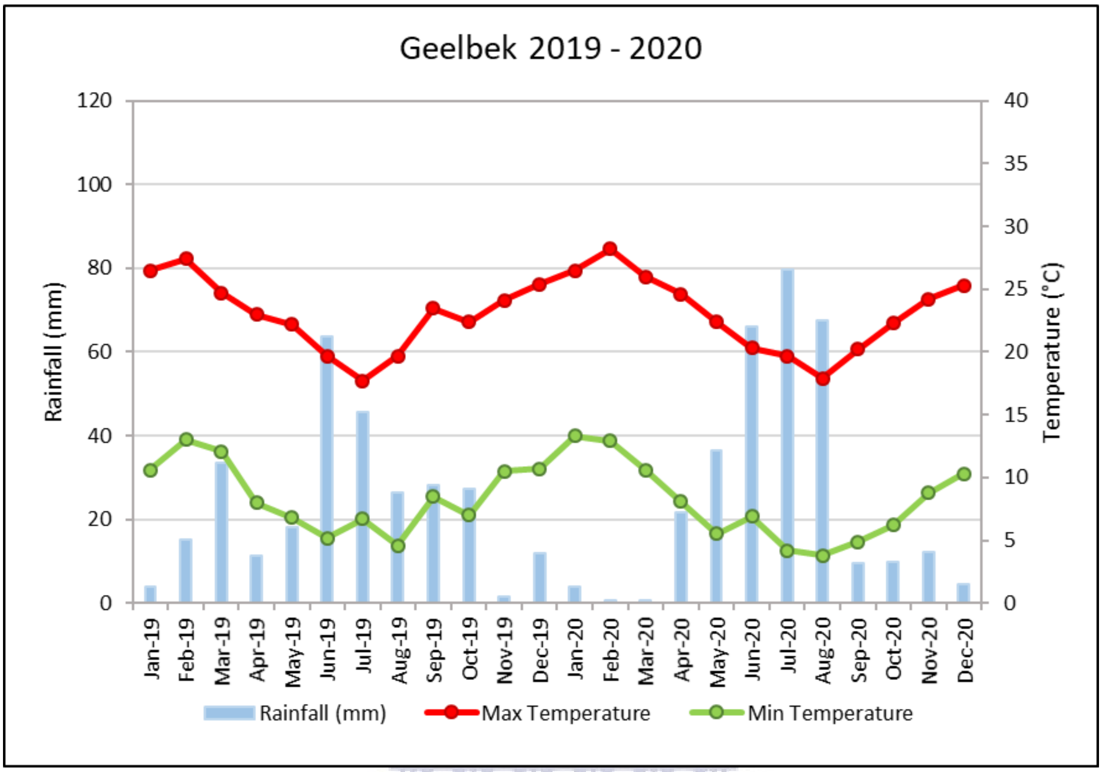

Figure 11: Rainfall, minimum and maximum temperatures at Geelbek for 2019 – 2020 (SAWS)

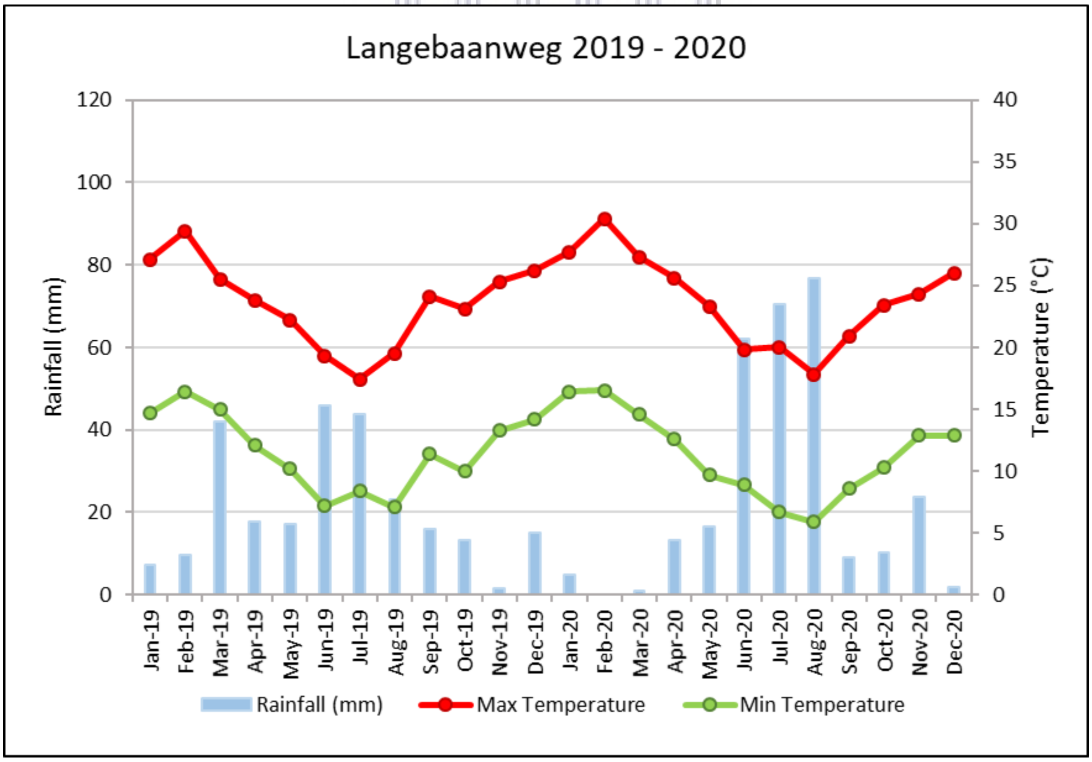

Figure 12: Rainfall, minimum and maximum temperatures at Langebaanweg for 2019 – 2020 (SAWS)

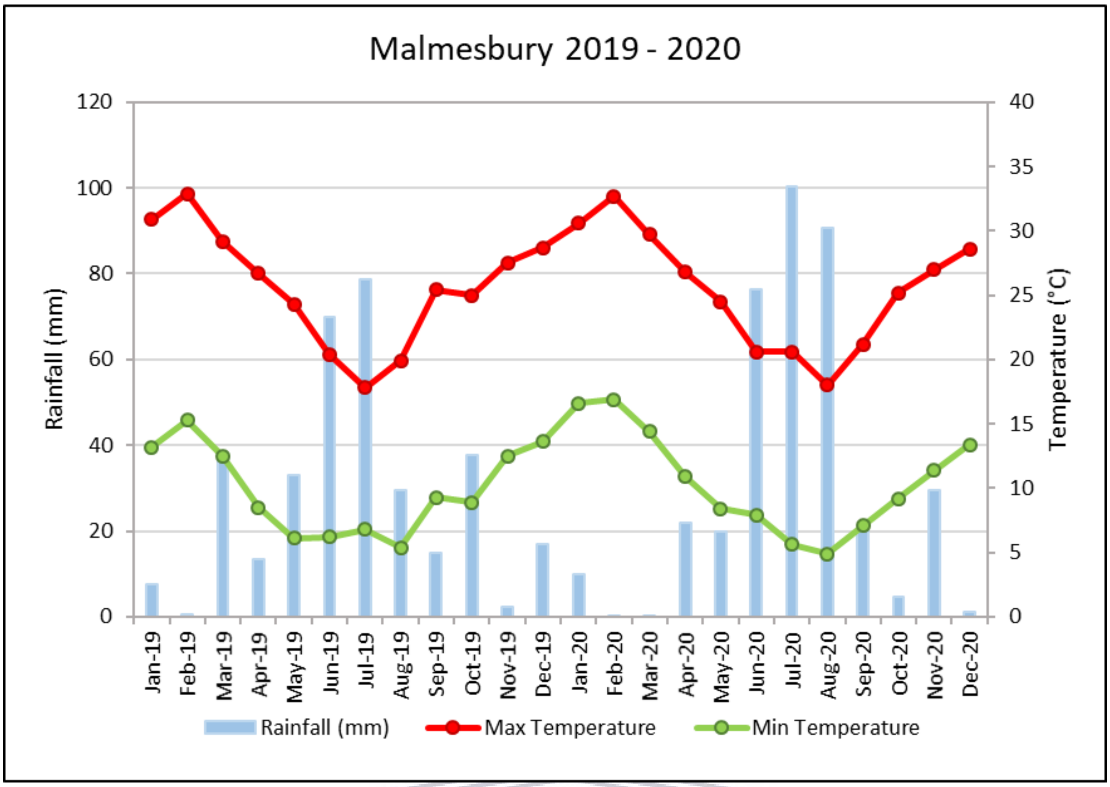

Figure 13: Rainfall, minimum and maximum temperatures at Malmesbury for 2019 – 2020 (SAWS)

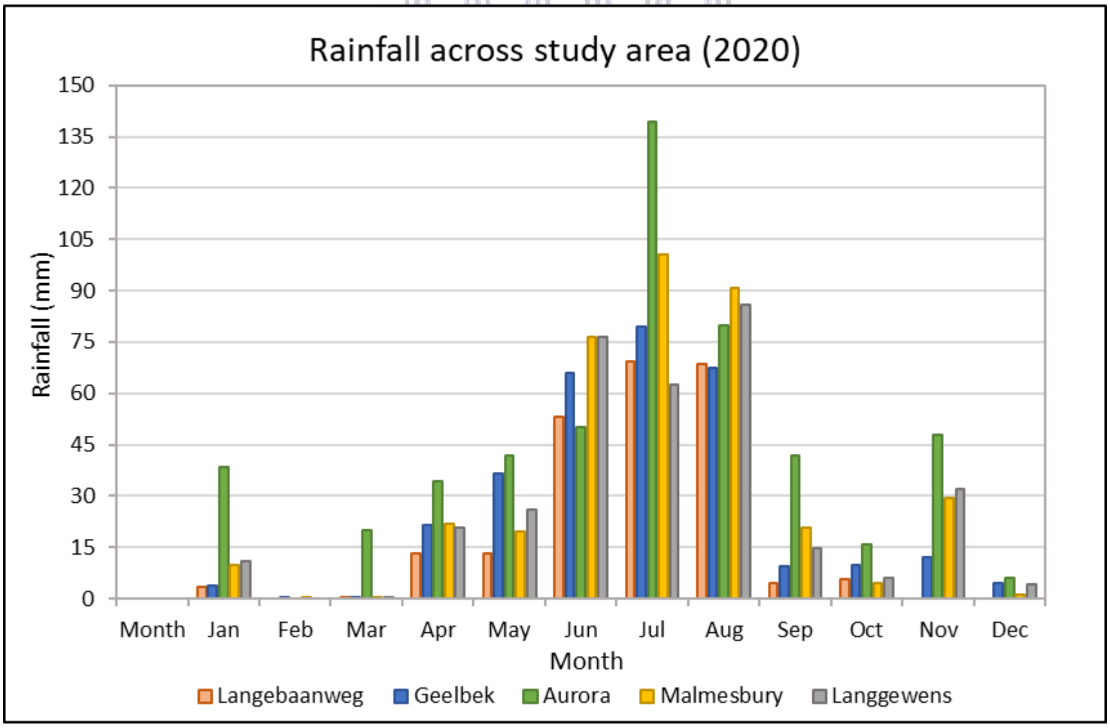

Figure 14: Rainfall (mm) occurring across the study area for the year 2019 (SAWS; DWS)

3.4 VEGETATION AND LAND USE

The dominant vegetation in the study area is open shrubland and low fynbos with cultivated land (large commercial farms) being the major land use. Most of the built-up areas occur in the small towns around the area, which include Saldanha, Langebaan, Velddrif, Hopefield and Aurora. Industrial areas occur in the centre of Saldanha Bay and near Langebaan Road. Farming concentrates in the area just south of the Berg River with wheat, barley, and dairy farming prominent in the Langebaan Road and Velddrif area. Most of the upper Berg region extending from Velddrif to Aurora consists of heavily cultivated land.

West Coast Strandveld occurs along with the entire coastal plain and most of the rest of the area is covered with Coastal Macchia. Vegetation of the Granite and Malmesbury hills are Renosterbosveld but due to most of the area being under cultivation, only remnants of the Renosterbosveld are seen (Timmerman, 1985b). The composition of vegetation is strongly controlled by the different soil sources of unconsolidated and consolidated aeolian sands, limestone, and granites.

At discrete points along the Langebaan Lagoon shoreline area, reeds (*Phragmites australis* and *Typha capensis*) dominate. Growth of these reeds at the Lagoon provides clear evidence of the significant influx of groundwater to the Lagoon because these plants can only survive in water or damp soil and can only tolerate salinity levels up to a maximum of 20 - 25 ppt. The salinity of the lagoon water is around 35 ppt (Clark et al., 2017).

3.5 GEOLOGY AND HYDROGEOLOGY

3.5.1 Regional

The regional geological setting of the study area is shown in Figure 15. Geological features that are salient to the hydrogeology in the Langebaan region are semi- to unconsolidated Cenozoic sediments that unconformably overlie basement rocks. The basement rock is dominated by deeply weathered shales of the Malmesbury Group, with Cape Granite intrusions occurring in certain parts along the coast (Clark et al., 2017). Granitic outcrops or hills can be seen in the Vredenburg, Saldanha Bay and Darling areas (Roberts and Siegfried, 2014). The basement Cape Granite and Malmesbury Group rocks that underlie the unconsolidated sediments of the Sandveld Group (consisting of Springfontyn, Langebaan, Varswater, and Elandsfontyn Formations) extends from False Bay to Saldanha Bay. The Malmesbury Group is of Pre-Cambrian age and outcrops in the valley of the Modder River and Berg River. The Darling and Vredenburg granitic plutons are two successive intrusions of the early Cambrian age.

The thickness of the Cenozoic sediments varies between 0 and 120m, with the greatest thicknesses occurring between Langebaan Lagoon and Hopefield (Timmerman, 1985b). These overlying sedimentary deposits, especially of Quaternary age, vary greatly in composition and grain size; from peaty deposits (with a high clay and mud component) to course, well-rounded sand and gravel deposits. Where these coarse-grained deposits occur, and especially where they have been deposited in eroded valleys, reaching largely saturated thicknesses, they have resulted in the occurrence of very high aquifer yields. These high yielding aquifers include the Elandsfontein and Langebaan Road aquifers, which are specifically encountered close to the Hopefield area. Borehole yields from certain portions of these aquifers can be extremely high – in excess of 20 ℓ/s. The Malmesbury Groups in general do not have high groundwater potential, but where fracture/fault systems are well developed the groundwater potential is very high. In favourable geological settings borehole yields from these groups can be 5 ℓ/s and even higher.

North-west of the Langebaan region, about 20 km east of Moorreesburg, small greenstone bodies of the Bridgetown Formation are exposed along the course of the Berg River as elongated lenses and dykes within metasediments of the Malmesbury Group. The exposed Bridgetown Formation is an NNW trending lensoid outcrop, about 15 km long and 3 km wide. It consists of a sequence of greenstones, intruded by a mafic dyke; chert and dolomite (Slabber, 1995). Generally, the dolomite is light grey to cream, fine-grained, massive, and quite pure. Small veins and inclusions of chert are present in the dolomite. Small chert bodies in the greenstone are associated with dolomite. The cherts vary considerably in colour, texture, and degree of deformation.

The Bridgetown Formation weathers relatively easily, and its position is probably determined by the course of the Berg River in this area (De Villiers, 1969). Outcrops are restricted to the banks of the Berg River and are sometimes exposed in small streams. The transition between the Bridgetown Formation and adjoining formations (Moorreesburg and Porterville Formations), which consists mainly of phyllites, is gradational. The Dolomites are known to have more effective recharge rates and higher yields than most other aquifers and the Bridgetown Formation have the potential to contribute significantly to the aquifer systems in the study area via regional recharge and long groundwater flow paths.

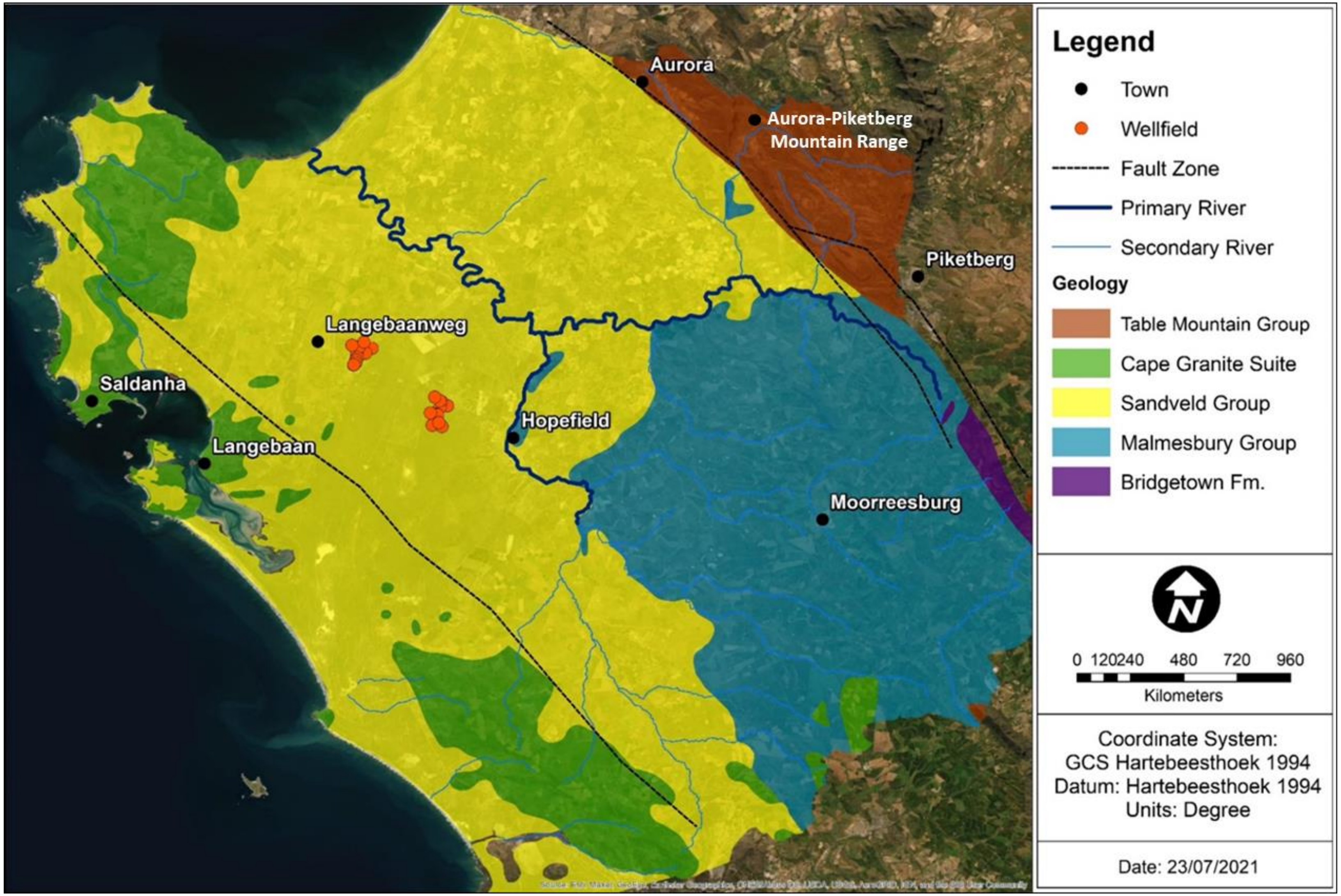

Figure 15: Surficial geology of the study area

3.5.2 Local Geology and Hydrogeology

The coastal plain between the Berg River and the Aurora-Piketberg Mountain Range, also known as the Adamboerskraal Aquifer System, consists of fine to coarse sands of the Table Mountain Group that are discrepant in relation to the underlying Malmesbury sediments. The Aurora-Piketberg Mountain Range borders the region in the north-eastern part of the study area. The mountain range forms part of the Table Mountain Group (TMG). The TMG comprises of thick layers of sandstone that varies between quartz arenite, silty and feldspathic arenites, accompanied by minor interbedded conglomerate and shale. The aquifer consists of three paleochannels correlating with old river courses of the Berg-, Kulders and Papkuils Rivers (Timmerman, 1985). North of the Berg River the basal Elandsfontyn Formation is absent in a 3 – 4 km wide zone along the coastline but attains a thickness of 40 m inland. Few Malmesbury outcrops occur in the area except in the south-eastern section along the Berg River.

The Langebaan Road and Elandsfontein Aquifer Systems are situated in the lower Berg River region and have very similar geology. The coarse Elandsfontyn Formation sands and gravels were deposited in several paleochannels, which can be correlated with old courses of the Kulders-, Berg- and Groen Rivers (Timmerman, 1985b). The thickness of the Cenozoic sediments (shown in Table 1 below) varies between 0 and 120 m, with the greatest thicknesses occurring between Langebaan Lagoon and Hopefield (Timmerman, 1985b). These Cenozoic deposits unconformably overlie the metamorphosed shale of the Malmesbury group and the granites of Cape Granite Suite.

The hydrogeological characteristics of these aquifer systems are extremely complicated due to the complex nature of the regional geology. The transmissivity (T) of the lower Langebaan Road Aquifer is said to vary between 10 and 4 000 m^2/day with its storage capacity is calculated to be 21,9 x 10^6 m^3, and the total groundwater in the area estimated at 1 035 x 10^6 m^3 (Roberts and Siegfried, 2014).

The transmissivity of the Elandsfontein aquifer is lower than that of the Langebaan Road area, according to Roberts and Siegfried (2014). It is estimated that its T is 5 – 250 m^2/day with its confined storage is calculated to be 15.5 x 10^6 m^3, with total groundwater in the area amounting to 750 x 10^6 m^3. The semiconfined to unconfined aquifer system occurs in the Varswater and Langebaan Formations above the Elandsfontyn Formation. The highest transmissivities were recorded in sandy zones of the Varswater Formation at 50 – 100 m^2/day. The total volume of groundwater stored within these aquifers is estimated to be around 2 400 x 10^6 m^3 (Roberts and Siegfried, 2014).

Table 1: Stratigraphy of the Cenozoic (65 Ma to present) sediments of the Saldanha Bay area (Adapted from Roberts and Siegfried, 2014; Roberts et al., 2011; Timmerman, 1985; Timmerman, 1985b)

GROUP	AGE RANGE (million years ago)	FORMATION	ORIGIN	DESCRIPTION
Sandveld *Summary*: *Basal gravel overlain by clay, overlain by various sands with peat /clay layers.*	0-2.5	*Bredasdorp	Aeolian/Marine	Calcareous and shelly sands. Also has a component of silica and muddy sands in some areas
		Witzand	Aeolian	Semi-consolidated calcareous dune sand
		Springfontyn	Aeolian	Clean, quartzitic sands, a decalcified dune sand that dominates in the coastal zone
		Langebaan	Coastal Aeolian	Consolidated calcareous dune sand. Accumulated during the last glacial lowering of sea level when vast tracks of un-vegetated sand lay exposed on the emerging seafloor.
		Velddrif	Marine	Beach sand. Associated with the last interglacial sea-level rise to 6–7 m above the present level
	2.5 - 25	Varswater	Estuarine/ Marine/ Marsh/ Fluvial	Deposits include a coarse basal beach gravel member, peat layers, clay beds, rounded fine-to-medium quartzes sand member and palatal phosphate-rich deposits.
		**Elandsfontyn	Meandering Fluvial valley fill	Coarse fluvial sands and gravels deposited in several paleochannels filling depressions. The deposits were subsequently covered by clays and peat.
// MAJOR UNCONFORMITY //				
*Table Mountain Group	>340	Sandstones		
Malmesbury Group	>495	Franschhoek	Feldspathic conglomerate, sandstones and weathered shales	
		Porterville	Phyllite shale, schist and greywacke with dark grey limestones	
		Moorreesburg	Greywacke, phyllite with quartz schist lenses and limestones	
		Bridgetown	Greenstones with dolomite and chert lenses	
Cape Granite Suite		Granites		

*Only present in the upper Adamboerskraal region of the study area

**Not present at Hopefield wellfield

4. CHAPTER 4 –METHODS

4.1 INTRODUCTION

This chapter describes the methodology that was applied to achieve the aim of this study, and in turn answer, the research questions posed. The purpose of this chapter is to demonstrate the research setup, which aided in the conceptualization of the natural groundwater recharge processes taking place in the study area. The methodology explained in this chapter includes a description of the desktop study conducted, field procedures and techniques in which the raw data was acquired as well as the analyses methods employed to analyse and interpret the raw data.

4.1 DESKTOP STUDY

Before field investigations took place, a desktop study was conducted to review the hydrogeological information that was available in the study area to get an understanding of the current knowledge of the aquifer systems within the study area.

Previous hydrogeological studies were reviewed. These consisted of borehole siting in the area using geophysical methods and pumping tests as well as isotopic methods to characterize the aquifer systems. The National Groundwater Archive (NGA) was used to access geological logs for boreholes drilled in the area to determine which boreholes would be best to use for the present study investigations. All information was sourced from various reports including Departmental GH reports, theses and publications that were carried out in the study area.

Previous work done in the area along with the geological logs assisted in selecting boreholes that would be part of the recharge study. Boreholes were chosen in the suspected recharge areas and along its possible flow paths which were based on previous studies whereby paleochannels were delineated (Smith, 1982; Timmerman, 1985b). Figure 16 displays the locations of all the boreholes investigated in this recharge study.

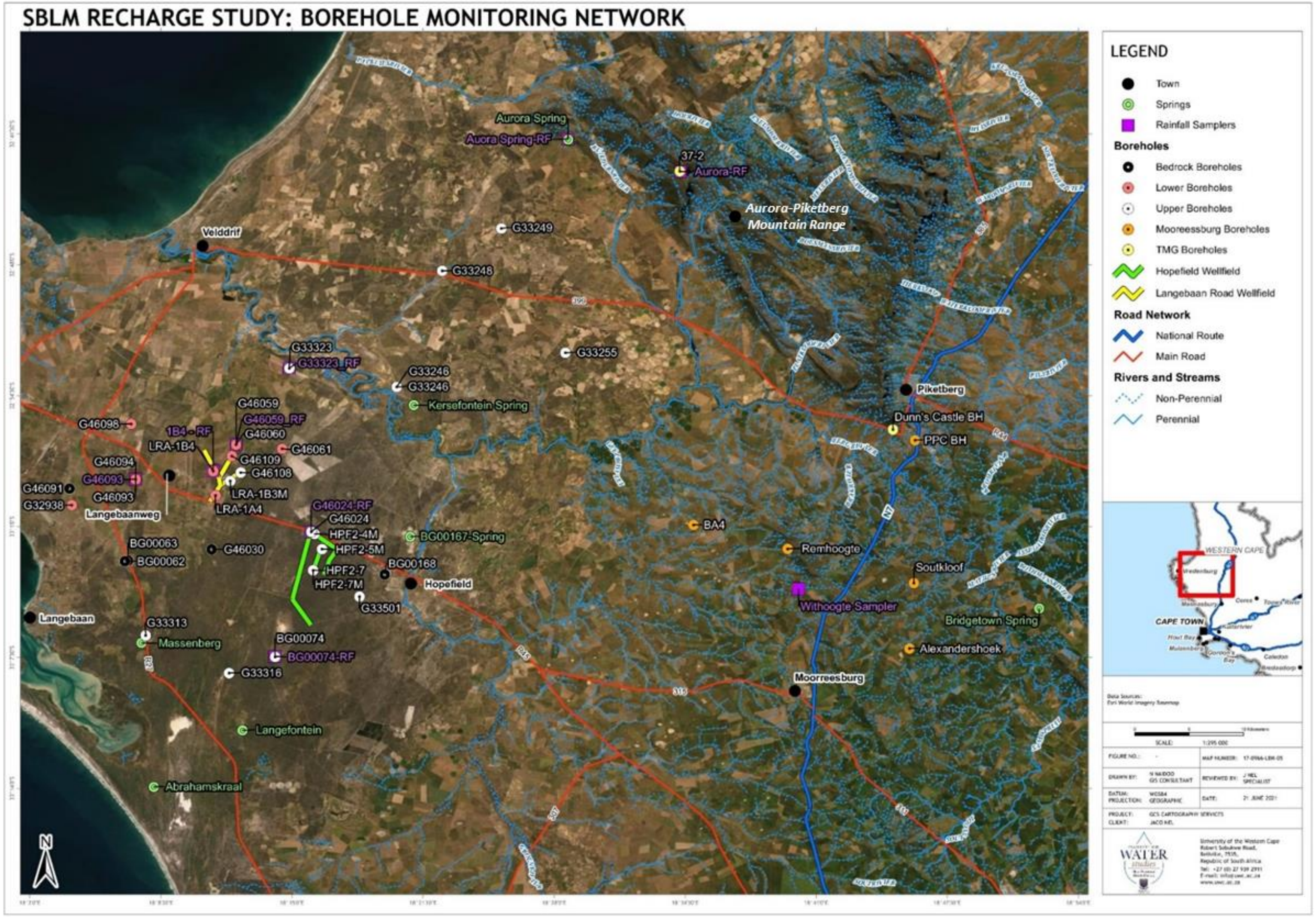

Figure 16: The selected borehole monitoring network for the present study.

4.2 IN-SITU DATA COLLECTION METHODS – FIELD PROCEDURES

4.2.1 Groundwater

Groundwater level monitoring

Monthly water levels, both static water level and data logger readings were measured at selected boreholes, as set out by the WRC 2017 groundwater level measurement field procedure. Static water level readings are measured using a water level meter (dip meter). The instrument consisted of a sensor attached to the end of a double connector wire. When the sensor comes into contact with water, there is a spike in mV on the meter reader. Depth to water levels is then taken directly from the tape/wire at the top of the borehole casing. Groundwater level readings were measured from August 2019 until November 2020.

Field Parameter readings

Electrical conductivity, pH and dissolved oxygen were measured in the field using the handheld YSI multiparameter probe. For electrical conductivity readings, the instrument was standardized against standard conductivity solution of conductivity 0-3999 µS/cm, resolution 1 µS/cm, accuracy ±2% F.S. EC readings were reported in micro-Siemens/cm. The pH meter measurements range from 0.00 to 14.00, resolution 0.01 pH, accuracy ±0.05. The pH meter was standardized using pH 4.0, 7.0 and 9.0 buffer solutions. Once standardized, the combination sample/reference pH probe is stored in a receptacle of deionized water. After use, the probe is rinsed with distilled water dipped in pH 4.0 buffer and replaced in its protective cover.

The borehole water was pumped into a bucket using a submersible pump (traditional pumping). The probe was then placed in the bucket. Once parameter readings stabilized on the screen of the YSI, they were recorded onto a field sheet. The stabilization of the field parameters also helped indicate when to take a sample at boreholes sites. When field parameters stabilized, it meant that all the stagnant water had been removed and that the borehole water being pumped at that point was representative of the aquifer.

Down-the-hole (DTH) borehole parameter logging

The objective of the Down-the-hole (DTH) logging was to assess the borehole to confirm that the borehole screen is open and well connected to the aquifer. Before logging the borehole, the depth of the borehole was checked to confirm that the borehole had not collapsed and to verify the depths of boreholes for which no information was available. This was done by attaching two heavy weights to the bottom of a Solinst Tag Line. The tag line was then lowered into the borehole until the weights could no longer be felt. The measurement at the top of the borehole's casing was read off the tag lines wire/tape and recorded. This procedure was repeated at all boreholes to verify the depth, which ensured that the borehole was correctly logged.

Down-the-hole borehole logging of groundwater EC and temperature was conducted using a down-hole logging protocol with the YSI multiparameter Sonde, lowering it at a rate sufficiently slow to obtain 30 to 50 cm interval data points down the hole. The multiparameter Sonde is an instrument with specific conductivity, temperature and depth logging capabilities. Attached to the end of it. As it is lowered down the borehole, these probes took measurements every 2 seconds and readings are logged to a single file. A manual downward logging protocol was used with the Sonde set at a two-second logging interval as set out by Nel (2011).

Down-the-hole profiles provided information on the hydrogeological processes of the aquifer such as flow through the hole, geological layers within the borehole, and insight into groundwater-surface water interaction taking place. EC gave an indication of residence times and water-rock interactions. These logs will also confirm borehole construction (screen and casing positioning), which ensured a representative groundwater sample was collected on every sampling run.

Water Quality Sampling

Time series data of groundwater samples were collected every quarter to understand how the water chemistry in the aquifer changed over time. Groundwater samples from various boreholes representative of the aquifer systems contained within the study area were collected. Before sampling, the selected boreholes were traditionally purged according to the procedures set out by Groundwater Sampling Manual (WRC, 2017) as outlined in Weaver et al. (2007). Once it was certain that water being discharged from the borehole was that of the aquifer (when the standing volume of water calculated was removed and key water quality parameters such as pH, EC and temperature were stabilized), a sample was taken. The standing volume of water was calculated using the following formula:

$$V = \pi \times d^2 \left(\frac{h}{4000}\right)$$

Where d is the diameter of the inner casing in mm and h is the water level in meters subtracted from the depth of the borehole.

For major anions and cation sampling (Calcium, Magnesium, Sodium, Potassium, bicarbonate, chloride and sulphate), a 500 ml Teflon bottle was rinsed thrice with the aquifer water as a form of precontamination of the sample bottle, to ensure that only water from that sampling point is contained within the sample bottle. The bottle was then filled, sealed tightly with an inverted cap as to prevent oxidation and any gas exchanges that might take place. The bottles were then labelled before being placed onto ice in a cooler box. For isotopes, a 50ml Teflon bottle with an inverted cap was rinsed and filled ensuring that there are no air bubbles for any sort of evaporation to take place. Once the sample was secured, it was placed on ice in a cooler box (0 – 6 °C). Samples were then transported and stored in a fridge (as per storage guidelines) until analysis could take place. For quality control, a duplicate sample was taken at every 10 boreholes.

At sites where the diameter of the borehole was too small to fit a pump, grab samples were taken using a Teflon bailer according to the standard grab sampling procedure set out by WRC (2017).

Figure 17: Sampling for major ions at production borehole HPF2-7 in the Hopefield Wellfield

4.2.2 Rainfall Sampling

Rainfall was sampled using the DWS Cumulative Rainfall Collectors (CRC) spread across the study area (Figure 18). These samplers had already been set up across the area prior to the present study and were chosen based on which samplers would spatially provide the best data across the study area. The samplers chosen for this study were: G46024-RF, G46059-RF, G46092-RF and G33323-RF. Three new isotope samplers were set up around the region in 2019 to include the Aurora and Moorreesburg regions of the area (Figure 19). These samplers were set up on top of the Aurora-Piketberg Mountain Range, at the Withoogte water treatment plant and in the Langebaan Road area at borehole G46093. Rainfall samplers were used to collect rainfall across the study area for the analysis of Deuterium and Oxygen-18 content. The advantages of both samplers are that it is time integrating, inexpensive, the collectors can be left unattended and thus have a low servicing cost, and the collectors do not need a power source (Weaver and Talma, 2007). The samplers are an inexpensive tool capable of yielding valuable information for groundwater investigations regarding the chemical and isotopic signature of rainfall and thus the recharge to aquifers. The set-up and design of the CRC and newly installed isotope samplers are shown in Figure 18 and Figure 19, respectively. All essential features and explanations on how the CRC functions can be found in Weaver and Talma (2007).

Samples are collected from isotope samplers and CRC's using a 100 ml Teflon bottle with an inverted cap to prevent evaporation. It is ensured that no bubbles are contained within the sample bottle when collecting the water. The samples were stored in a cooler box before being delivered to the lab.

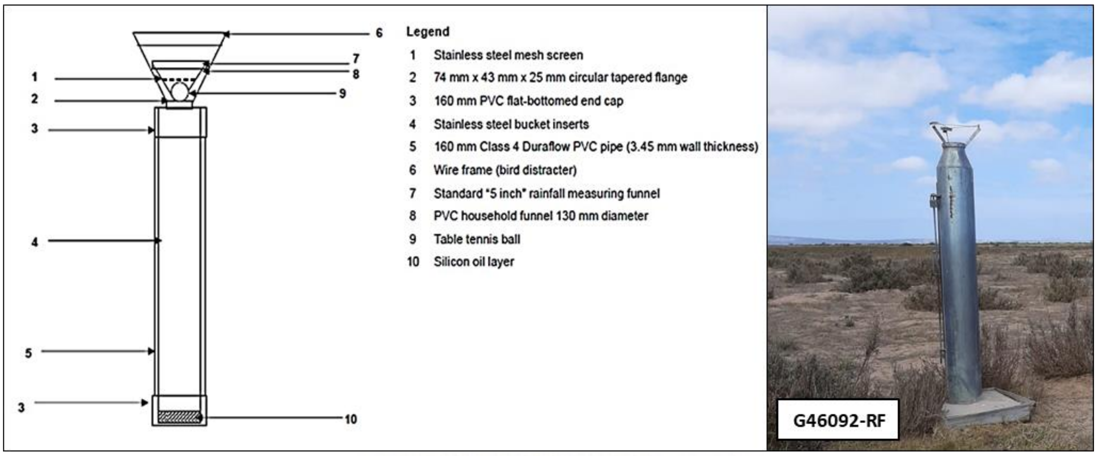

Figure 18: Diagram showing the critical design elements of the cumulative rainfall collector (left) (Weaver and Talma, 2007) and a picture of the CRC in the field (right)

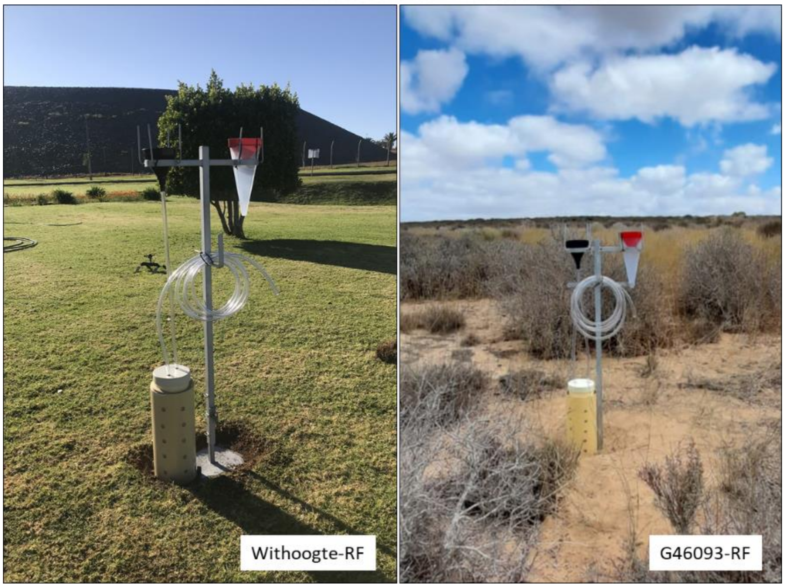

Figure 19: Newly installed isotope samplers

4.2.3 Surface Water

Isotope samples were collected directly from the Berg River using a plastic Teflon bailer. The river was sampled along the course of the river close to borehole G33246 (near Kersefontein Farm) as well as the Misverstand Weir. The bailer was lowered into the Berg River and weir and pulled up when it was filled. Each sample bottle was rinsed with the sampling water before taking the samples. The water collected was then poured over into a Teflon sampling bottle carefully to avoid any air bubbles, labelled and stored in a cooler box.

4.2.4 Airborne Geophysics

Time Domain Electromagnetic (TDEM) and Magnetic geophysical methods were used to survey Sadhana Bay and surrounding areas. Airborne electromagnetic surveys are advantageous as they are non-invasive and very cost-effective. The survey was conducted in the area between Yzerfontein and the Aurora-Piketberg Mountain Range (Figure 20). Before the airborne survey commenced, a trial survey was conducted over the existing water supply wellfields where there were existing groundwater data available including borehole lithology from drilling and ground geophysics data. The existing borehole lithology data and ground geophysics data were then compared to the resistivity data from the trial airborne survey.

In Figure 20 below, the yellow bolded lines indicate trial lines and the green lines indicate flight lines from the main survey. The trial lines were conducted over the existing Saldanha Bay Local Municipality water supply wellfields and 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 line data. The main survey was carried out after the data from the trial survey were analysed and confirmed to be representative of the known conditions along the trail lines. The vertical survey lines were flown 1 kilometre apart and the horizontal lines 10 kilometres apart over the greater survey area. At the wellfields, the survey lines were flown 100 m apart to obtain more detailed data. A 200 m line spacing along the Elandsfontein area towards Geelbek was flown. The survey began on 21 May 2020 and concluded at the end of June 2020.

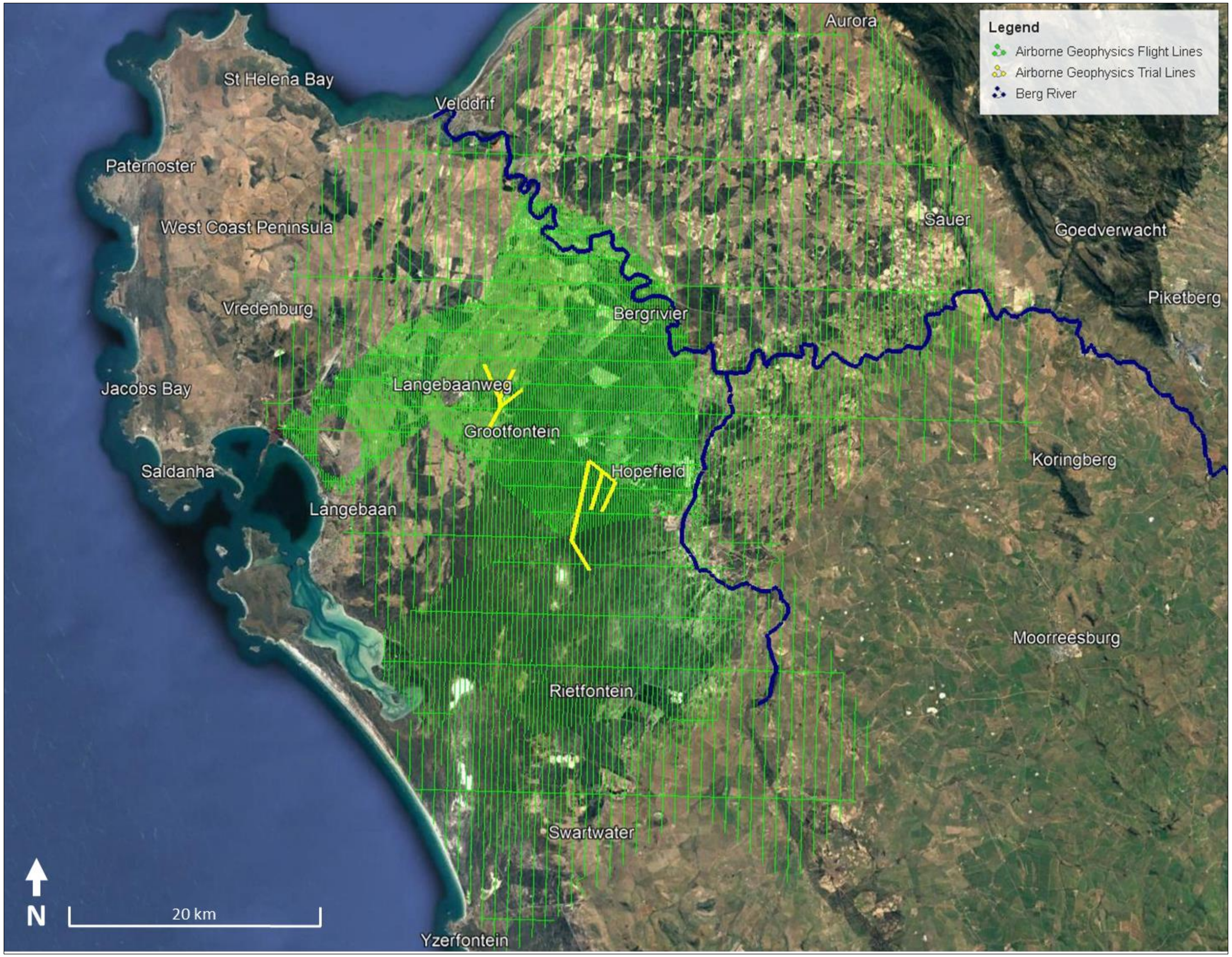

Figure 20: Area covered by the airborne geophysical survey carried out in study area

The SkyTEM helicopter system was selected for this study as it provides the sufficient accuracy necessary for groundwater investigations. Figure 21 displays the set-up of the SkyTEM system.

The SkyTEM system was developed for groundwater investigations by the HGG group at the University of Aarhus, Denmark. The transmitter and receiver coils, power supplies, laser altimeters, inclinometers, a global positioning system (GPS), electronics, and data logger are carried as a sling load on the cargo hook of the helicopter. BurVal Working Group (2009) provides a more in-depth explanation of how each part of the system operates.

Data quality checks form part of the standard field procedures. Repeated datasets are measured at a local control site every time the helicopter refuels (every 1.5 – 3 hours). The repeated measurements when corrected for the geometrical parameters such as altitude and inclination are expected, generally, to be within 5%.

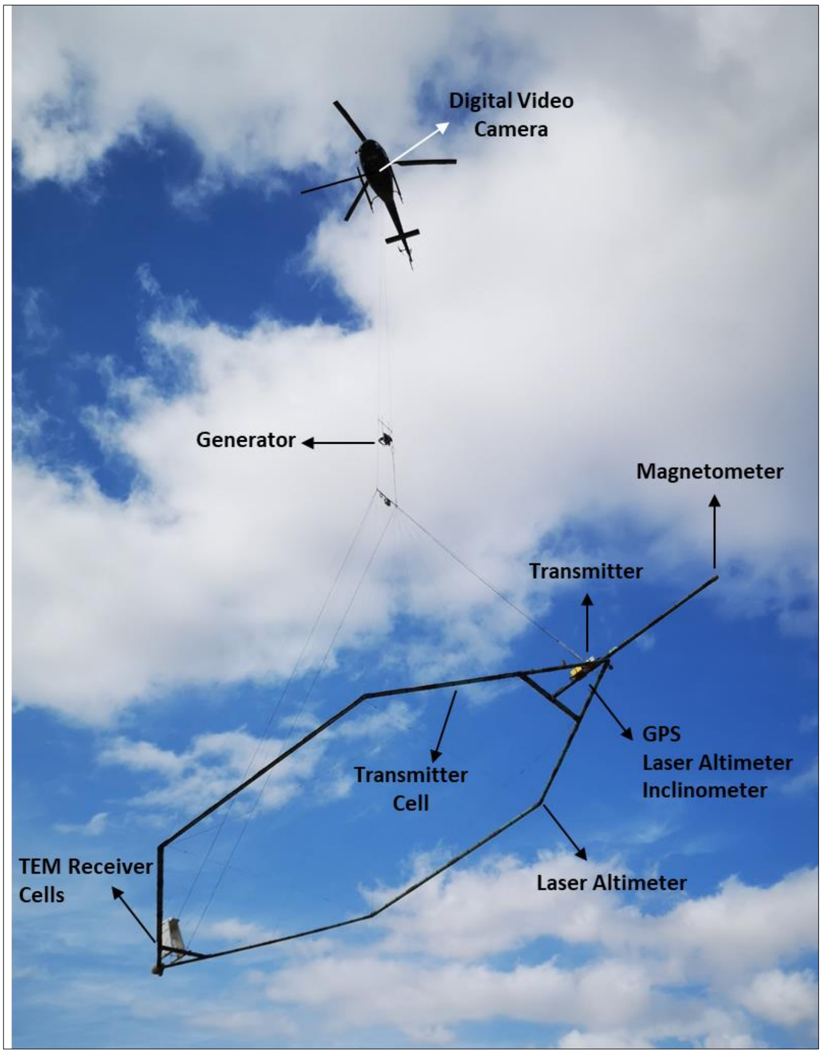

Figure 21: Set up of SkyTEM's airborne geophysical survey system in operation

4.3 DATA ANALYSIS METHODS

4.3.1 Hydrochemical Groundwater Analysis

Laboratory analysis of groundwater samples from selected boreholes was done to acquire basic water chemistry information. These included analyses for major ions: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^- and CO_3^{2-} and SO_4^{2-} as well as pH, alkalinity and electrical conductivity (EC). Hydrochemical analyses took place at Vinlab (Pty) Ltd Laboratory, which is a SANAS accredited lab. The concentrations of major ions were analysed using ICP-MS, Titrimetric method and Auto analyser method with conformance to ISO 17025 standards.

Schoeller and Piper diagrams were used to plot groundwater quality for analyses. According to Fetter (1994), the major ionic species in most natural waters are Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^- and CO_3^{2-} and SO_4^{2-}. These diagrams show the percentage composition of the ions and analyses are plotted based on the percent of each cation (or anion).

As water flows through an aquifer, it assumes a chemical composition as a result of interaction with the lithology. The term hydro-chemical facies are used to describe the bodies of groundwater, in an aquifer, that differ in their chemical composition. The facies are a function of the lithology, solution kinetics and flow patterns of the aquifer. Hydro-chemical facies can be classified based on the dominant ions in the facies using the Schoeller and Piper diagrams.

4.3.2 Stable Water Isotopes (^2H and ^{18}O)

The stable isotope analyses were performed at the Department of Earth Sciences at the University of the Western Cape, Bellville. Analyses of groundwater samples were conducted using the off-axis integrated cavity output spectroscopy (OA-ICOS) method with an LGR DLT-100 liquid water isotope analyser (model 908-0008-2010). The analyser measured the abundance of $^2H/H$ and $^{18}O/^{16}O$ ratios in the water samples using laser absorption. According to the manufacturer specifications the isotope analyser provides a 1-sigma precision below 0.6‰ and 0.2‰ for δ^2H and $\delta^{18}O$, respectively.

Before lab analysis, preparation of the samples was done by filtering them using a 0.25-micron (µ) filter to a vial of 1.5 mL, which is then sealed with a vial cap and placed into a vial tray. The analysis procedure made use of LIMS (Laboratory Information Management System). The LIMS procedure employs a distribution layout of several occurrences of two laboratory standards (high-δ and low-δ), a control standard, and 5 – 10 unknown samples situated in between these lab standards. Every run commenced with a dummy sample to prime the flow with deionized water to clean the syringe.

A 2-point normalization is done using two laboratory standards W-31 (high standard) and W-32 (low standard) and they were calibrated using VSMOW2 and SLAP2 reference materials using assigned values of 0±0.3 and 0±0.02, and -427.5±0.3, -55.5±0.02, for δ2H and δ18O, respectively. The δ-values for laboratory standards W-31 and W-32 are -11.9±0.7, -74.11±0.6, -3.54±0.1 and -9.92±0.1 ‰ for δ2H and δ18O, relative to VSMOW, respectively. All values are expressed in the standard delta notation in the permil (‰).

For data normalization, the two standards were calibrated directly against VSMOW and SLAP2 standards. These isotope δ-value results are graphically displayed along the Global Meteoric Water Line (GMWL) by Craig (1961) and along a Local Meteoric Water Line (LMWL) by Diamond and Harris (1997).

4.3.3 Tritium (^{3}H)

All 1-litre groundwater, surface water and rainwater samples were sent to iThemba labs for tritium (δ^3H) analysis. On arrival at the lab, the samples were distilled and subsequently enriched by electrolysis. iThemba labs explained that the electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is made of mild steel with a special surface coating. About 500 ml of the water sample, having first been distilled and containing sodium hydroxide, is introduced into the cell. A direct current of 10 – 20 amperes is then passed through the cell, which is cooled because of the heat generation. After several days, the electrolyte volume is reduced to around 20 ml. The volume reduction of 25 times produces a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) are run in one cell of each batch to check on the enrichment attained.

For liquid scintillation, counting samples are prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. 10 ml of the distilled water sample is mixed with 11 ml Ultima Gold and placed in a vial in the analyser and counted 2 to 3 cycles of 4 hours. Detection limits were 0.2 TU for enriched samples.

4.3.4 Infiltration Tests

Infiltration tests for the unsaturated zone were conducted across the study area using a Mini-disk infiltrometer by Decagon Devices Inc (2016). The Mini Disk Infiltrometer measures the hydraulic conductivity of the medium it is placed upon. Due to the Infiltrometer having an adjustable suction (0.5 to 7 cm) additional information about the soil is obtained by eliminating macropores with an air entry value smaller than the suction of the infiltrometer. This is done by controlling the infiltration with a small negative pressure (suction). When the water is under suction, it does not enter macropores such as cracks or wormholes. The tests give insight into how water will infiltrate through the topsoil in a given area, which gives an understanding of recharge processes likely to occur in that particular area.

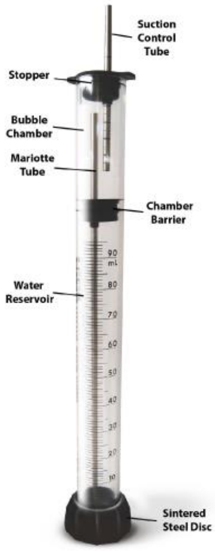

Figure 22: Decagon Mini-Disk Infiltrometer via Decagon Devices Inc. (2016)

The mini disk infiltrometer was prepared according to the Decagon Devices Mini Disk Infiltrometer manual (Decagon Devices Incorporation, 2016). When making use of the infiltrometer the upper and lower chambers of the Infiltrometer are both filled with water, with the top chamber controlling the suction. The lower chamber contains a volume of water that infiltrates into the soil at a rate determined by the suction selected in the bubble chamber. A suction rate of 2 was chosen for the soils in the study area. The bottom of the Infiltrometer has a porous sintered stainless-steel disk that does not allow water to leak in the open air. 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 contacted the soil surface correctly (Figure 23). Once the Infiltrometer was placed on a soil, water begins to leave the lower chamber and infiltrate into the soil at a rate determined by the hydraulic properties of the soil. As the water level drops, the volume of water left in the lower chamber was measured at specific time intervals. The time intervals as to when measurements were taken once the tests began were determined by the soil type. If the soil was very dry and porous time intervals were generally 5 – 20 seconds. If the soil was wet and/or compact time intervals varied between 30 seconds and 1 – 5 minutes. Decagon then provides a Microsoft Office spreadsheet where data gets inputted, and the hydraulic conductivity is automatically generated using a formula. These tests were repeated 3 – 4 times at each site.

Figure 23: Conducting infiltration tests using the Mini Disc Infiltrometer

4.3.5 Airborne Geophysics

The airborne geophysical survey began on 21 May 2020 in the area between Langebaan Lagoon and the Aurora-Piketberg Mountain Range. The survey was concluded at the end of June 2020. The area covered by the airborne survey included the potential recharge area along the Aurora Mountains, the faults from Porterville and Malmesbury, as well as all the potential flow paths from the recharge areas to the Langebaan Lagoon Ramsar discharge area.

Time Domain Data Processing

The conductivity data of the geological formations that were obtained from the airborne geophysics survey are interpreted in reducing resolutions with depth. The top layers were interpreted at about 2 m intervals, to 10 m and ultimately to 20 m resolution layers at a 150 m total depth. The conductivity layers were overlain with the surface topography of the area to incorporate features such as bedrock highs, clay layer depth and paleochannel depths.

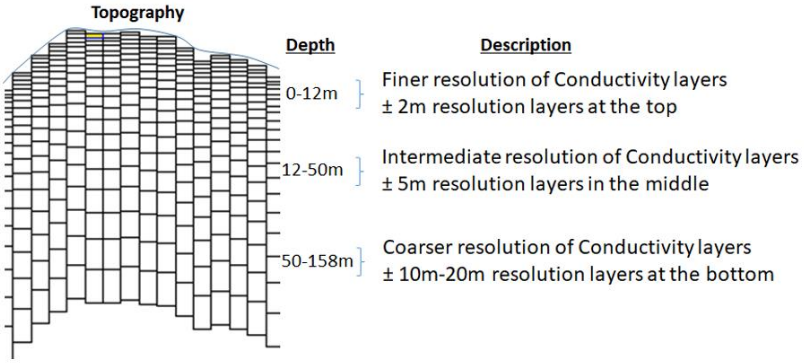

Figure 24: Conceptualization of conductivity layers at depth correlated with the surface topography.

Ground-truthing

The trial data was interpreted to determine if the airborne geophysical results provided an accurate representation of the subsurface layers. Figure 25 (trial line 900040) and Figure 26 (trial line 900070) below show an example of two trial lines that were flown over the Hopefield Wellfield and Langebaan Road Wellfield, respectively.

Trial line 900040 was flown in a north easterly direction above traverse 3R, which was a resistivity line from the ground geophysics conducted at the Hopefield wellfield (Figure 25). Trial line 900070 (Figure 26) was flown in a south westerly direction over three production boreholes (of which the lithology is known) at the Langebaan Road Wellfield. The data from the trial lines confirmed the findings of the ground geophysical survey at Hopefield are supported by the lithological logs from boreholes that were drilled along those flight lines at both the Hopefield and Langebaan Road Wellfields.

The SkyTEM resistivity depth profiles (Figure 25 and Figure 26) show the following data:

- Flight elevation of the helicopter is shown as a line above the surface.
- The red colour near the surface indicates unsaturated sands.
- The green and yellow colours indicate saturated sand material.
- The blue lenses are an indication of the presence of clay, and
- The bottom grey colour represents bedrock.

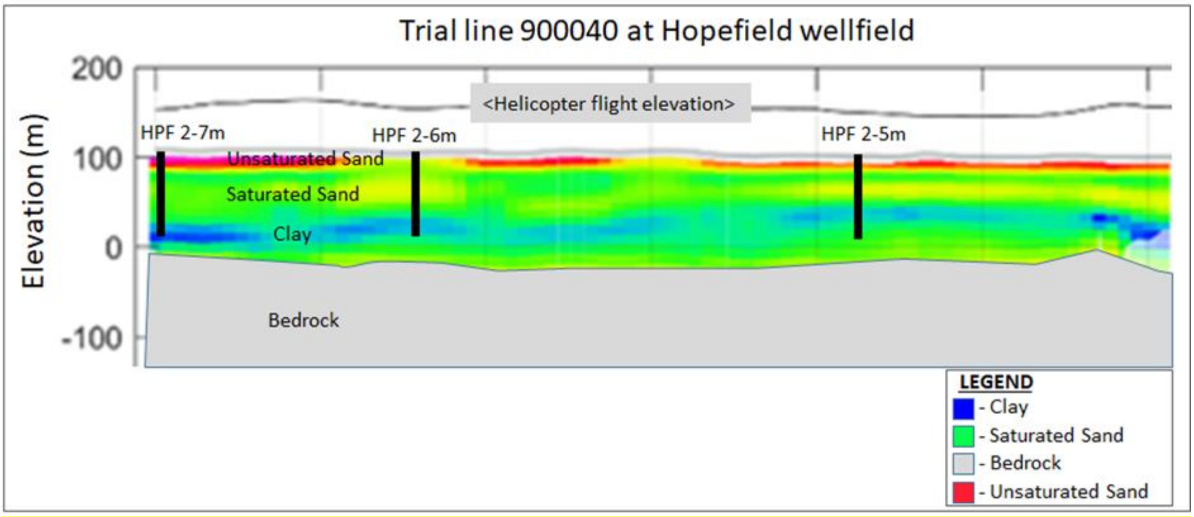

Figure 25: Airborne geophysical trial line 900040 at the Hopefield Wellfield over traverse line 3R

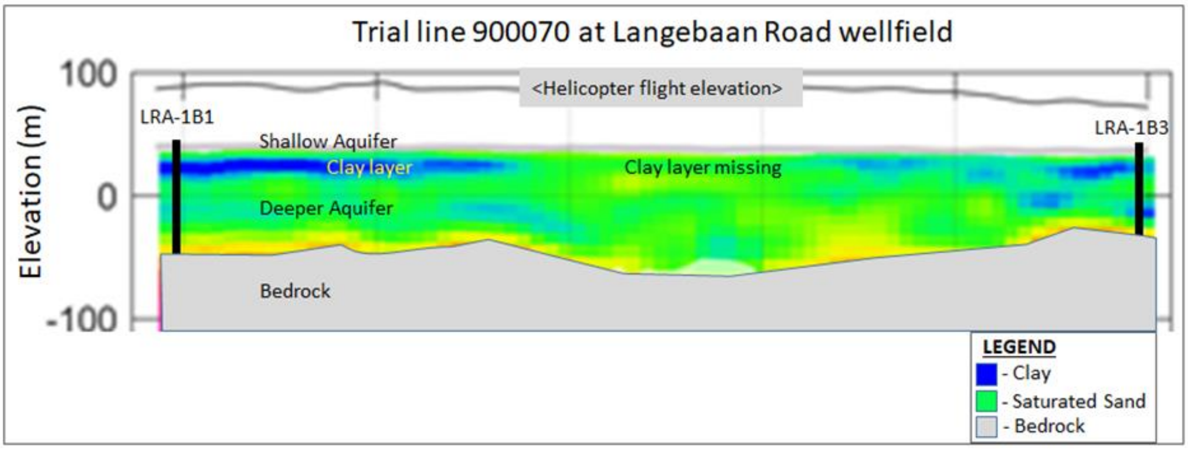

Figure 26: Airborne geophysical trial line 900070 at Langebaan Road Wellfield

4.3.6 PHREEQC Evaporation Modelling

PHREEQC is a computer program that is designed to perform a wide variety of aqueous geochemical calculations. PHREEQC is based on an ion-association aqueous model and has capabilities for (1) speciation and saturation-index calculations, (2) reaction-path and advective-transport calculations involving specified irreversible reactions, mixing of solutions, mineral and gas equilibria, surface-complexation reactions, and ion-exchange reactions, and (3) inverse modelling, which finds sets of mineral and gas mole transfers that account for composition differences between waters, within specified compositional uncertainties (Parkhurst, 1995).

The evaporation feature (which uses inverse modelling) was used to evaporate the lower aquifer water at Langebaan Road to check if it would resemble the upper aquifer water quality at any point in the evaporation process. PHREEQC accomplishes this by removing water from the chemical system. The software simulated the evaporation process in twenty-three (23) steps. Step one represented 4% evaporation and step 23 represented 100% evaporation. After each step was complete, the software generated a concentration in moles for the elements - Boron, Carbon, Calcium, Chloride, Iron, Potassium, Magnesium, Manganese, Sodium and Sulphur. The values were then converted to mgl/L using the following formula:

$$\frac{(Moles \times Molar\ Mass)}{1000}$$

Although mostly accurate, a limitation of the software is that it models ideal conditions, which is not always the case in real-life scenarios.

5. CHAPTER 5 –RESULTS: PRESENTATION AND DISCUSSION

This chapter displays all results derived from recharge investigation methods used in the present study. Infiltration tests, Groundwater level assessments, water quality analyses (chemical, stable and radioactive isotopes) as well as the airborne survey results are displayed, explained, and discussed in detail within this chapter.

5.1 UNSATURATED HYDRAULIC CONDUCTIVITY (KUNSAT) AND GROUNDWATER LEVELS

Infiltration tests for the unsaturated zone were conducted across the study area using a Mini-disk infiltrometer. The infiltration tests were conducted to measure infiltration rates and vertical unsaturated K-values for the wet season (August). These values aided in the identification of potential groundwater recharge areas as soils that had high K-values would allow water to infiltrate and reach the water table at a faster rate.

Observations in the field showed that when the topsoil at Langebaan Road came into contact with water, it stuck together and became malleable, which slowed down infiltration (Figure 26). This is due to the topsoil in the area being predominantly fine sands (Figure 28), which do not allow for quick infiltration due to the soil being extremely compact.

Figure 27: Malleable, very fine sands in the Langebaan Road area

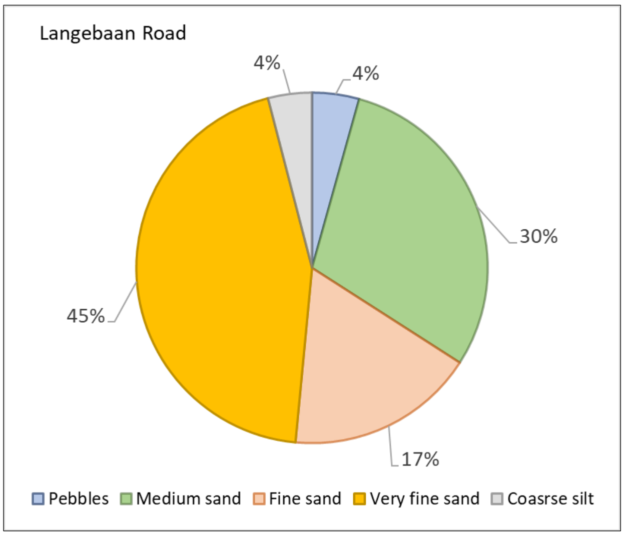

Figure 28: Soil distribution in the Langebaan Road region of the study area

Infiltration rates of the topsoil's in the Langebaan Road, Hopefield area and TMG Sands on the Aurora-Piketberg Mountain Range area are shown in Figure 29. Results indicated that infiltration at Hopefield and Aurora-Piketberg Mountains are much higher than those at Langebaan Road.

The K$_{unsat}$ values for Langebaan Road ranged from 0.37 – 1.21 m/day and K$_{unsat}$ values at Hopefield ranged between 3.46 - 8.64 m/day. The average hydraulic conductivity of the Table Mountain Group (TMG) sands near Aurora were around 2.17 – 3.03 m/day. Preferential recharge via fractures is expected within the TMG. The combined higher rainfall, fracture flow and high infiltration via the sands result in this area being favourable for recharge.

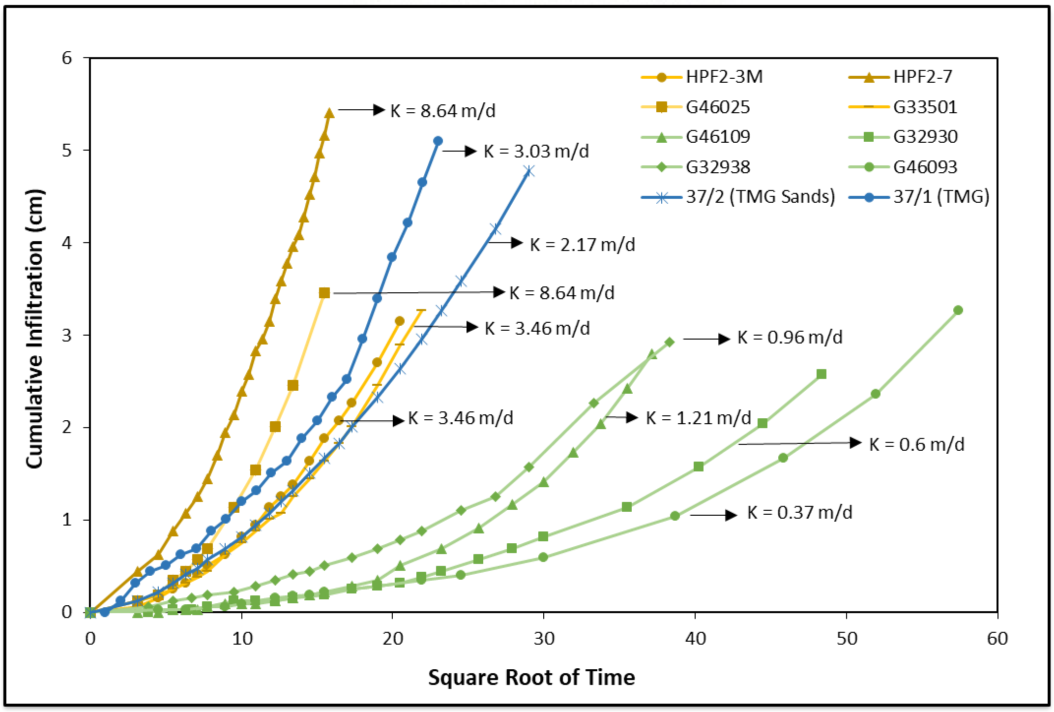

Figure 29: Infiltration rates of soils in the Langebaan Road (green), Hopefield (orange) and TMG (blue) areas

Analyses of water level trends at boreholes 37-1 and 37-2, situated at the top of the Aurora-Piketberg Mountain Range (Figure 30), show an almost immediate response to rainfall events occurring on the mountains, suggesting seasonal winter recharge. This correlates well with the infiltration test results which showed higher infiltration rates for the TMG.

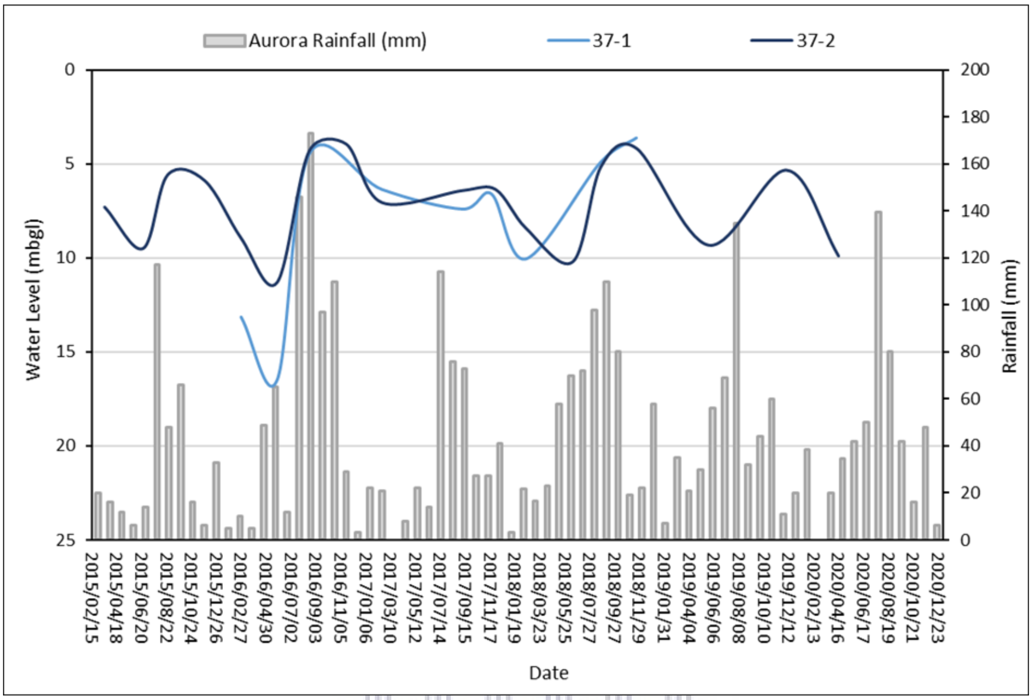

Figure 30: Water level responses to rainfall on the Aurora-Piketberg Mountain Range

Boreholes displayed in the Langebaan Road (Figure 31) and Hopefield (Figure 32) water level graphs were chosen to demonstrate the general trend in water levels seen in all boreholes that were part of the present study. Fluctuations in groundwater levels at borehole G46093 and LRA-1B1M in Figure 31 are from the local Langebaan Road wellfield abstraction.

Groundwater levels in both the Langebaan Road and Hopefield area show almost no response to local rainfall in the area, suggesting an indirect, regional recharge source of groundwater for the aquifer systems in the study area. Although the sands at Hopefield have higher infiltration rates, unsaturated zones in this region of the study area are also very thick and have water levels of approximately 8 – 15 mbgl (Figure 32). These factors coupled with very low rainfall (~300 mm/annum) show that it is unlikely that recharge through local rains take place in the Hopefield region. In the Langebaan Road area, there are shallow water levels but low infiltration rates, solid calcrete and saline waters, which also suggests that direct recharge from local rains does not take place.

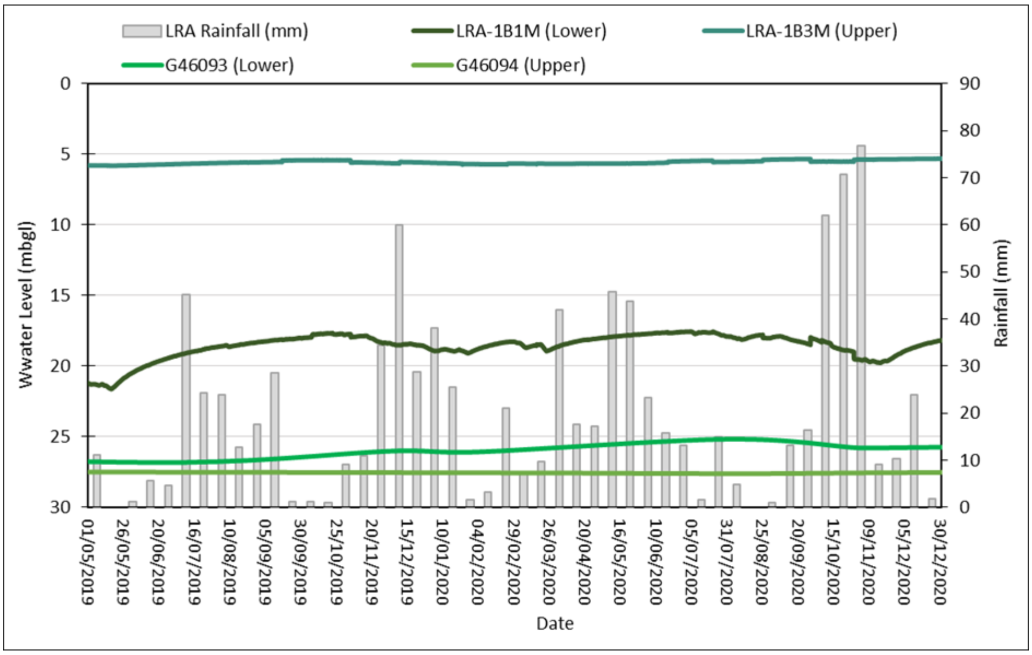

Figure 31: Langebaan water level responses to local rainfall in the Langebaan Road Area

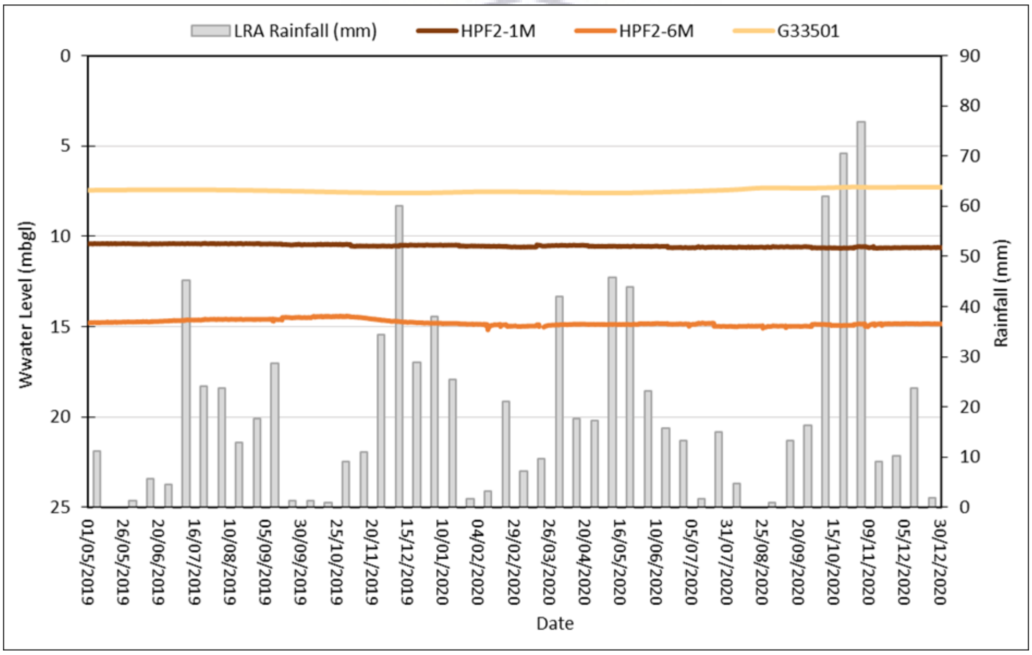

Figure 32: Hopefield water level responses to local rainfall in the Langebaan Road Area

5.2 TIME DOMAIN ELECTROMAGNETIC (TDEM) AIRBORNE GEOPHYSICS

The geophysical survey provided an improved resolution and characterisation of the subsurface in the study area compared to previous geophysical surveys conducted in the area, which supplemented the interpretation of recharge and groundwater flow occurrence. Due to the dependency of the electrical conductivity on both the clay content of the host material and the mineralisation of the water, airborne electromagnetics is suitable for providing information on groundwater resources, water quality, aquifer conditions and protection levels (Siemon et al., 2011). The following information was gained from the geophysical survey:

- Unsaturated sand thickness – indicating areas where infiltration is likely and where it is unlikely,
- saturated sand thickness – indicating areas where there is available groundwater (thick sands),
- groundwater quality – the TDEM waves propagate differently in saline water compared to freshwater. Relative water quality could therefore be inferred – this aided in the identification of saline areas that are more likely to be discharge areas, as well as
- bedrock depths and pre-Cenozoic topography – airborne magnetic and electrical methods provided information on the bedrock geology underlying the sand, which was important to evaluate the regional groundwater flow paths and characteristics.

5.2.1 TDEM Interpretation: Paleo-Lagoon, paleochannel, Clay, Saturated and Unsaturated Material

Frames A to F in Figure 33 depict the conductivity of the subsurface at varying depths. The airborne survey results along with the results of previous geophysical surveys done in the area as well as lithological logs were used to determine what the conductivity ranges of the airborne survey results represented. The different conductivity ranges and colours represent the following (Figure 33):

- Red (>200 mS/m): high salt content areas.
- Blue (40 – 200 mS/m): south of the Berg River, the clay layers are presented in this colour, whereas the blue colour north of the Berg River is represented by saturated sands due to the higher salt content in the groundwater.
- Yellow (12 – 30 mS/m): south of the Berg River, this colour represents the saturated sand and north of the Berg River it represents unsaturated sand.
- Orange (1 – 12 mS/m): this colour represents unsaturated sand and also bedrock at depth.
- Brown (<1 mS/m): represents the bedrock.

Frame A: Conductivity layer at a depth between 105.7 and 121.2m

This frame exhibits the deepest sand (yellow) deposits demarcated with the black line surrounded by bedrock in an old lagoon-like shape. It appears that this is the deepest part of the greater aquifer displaying a hallway like structure towards the Langebaan Lagoon. This structure contains some deep sand deposits, which are also present in the Aurora-Piketberg Mountains (blue colours). There are also signs of a deep paleochannel running north to south from the Velddrif area towards Saldanha Bay, the conductivity of that paleochannel suggests a saline environment.

Frame B: Conductivity layer at a depth between 91.9 and 105.7m

The bedrock becomes wider at this depth, resulting in the expansion of the quaternary sands with some signs of clay deposits in the middle of the aquifer. There seem to be no significant other changes at this depth over the total area when compared to frame A.

Frame C: Conductivity layer at a depth between 68.8 and 91.9 m

It is visible that the aquifer extent becomes greater at this depth, with a significant expansion of the clay deposits (demarcated with a black line). The bedrock becomes less prevalent, suggesting the expansion of the aquifer. The saturated sands in the Aurora area also exhibit some expansion at this depth.

Frame D: Conductivity layer at a depth between 30.6 and 68.8 m

The saturated sand becomes more predominant over the entire study area in this frame, with some of the bedrock outcrops visible towards the north at Aurora, East in the Moorreesburg area, West in the St. Helena Bay area and in the South West (close to the coast) where the granite hills are situated. It is also noteworthy that the salt below the Berg River becomes prevalent, with some salt patches between the Berg River and the Aurora-Piketberg Mountain Range in the north. The thick unsaturated sand (orange colour) in the area becomes visible towards the south in the vicinity of the Langebaan Lagoon.

Frame E: Conductivity layer at a depth between 20.7 and 30.6 m

In this frame, it is notable that the salt patches (red colour) in the northern region of the study area become more visible, with some expansion of the unsaturated sands in the south and around Hopefield and Langebaan Road.

Frame F: Conductivity layer at a depth between 2 and 20.7 m

Most of the aquifer area is covered by unsaturated thick sands (orange), with shallow saturated sand (yellow) present around the edges of the thick dry sand. The red (>200 mS/m) and blue (40 – 200 mS/m) indicate saline areas that are characteristic of discharge points of the aquifer. Salts are confined to these areas of discharge due to the large-scale evaporation that takes place. There are some bedrock hills still visible in this frame, which is represented by the brown colour (<1 mS/m).

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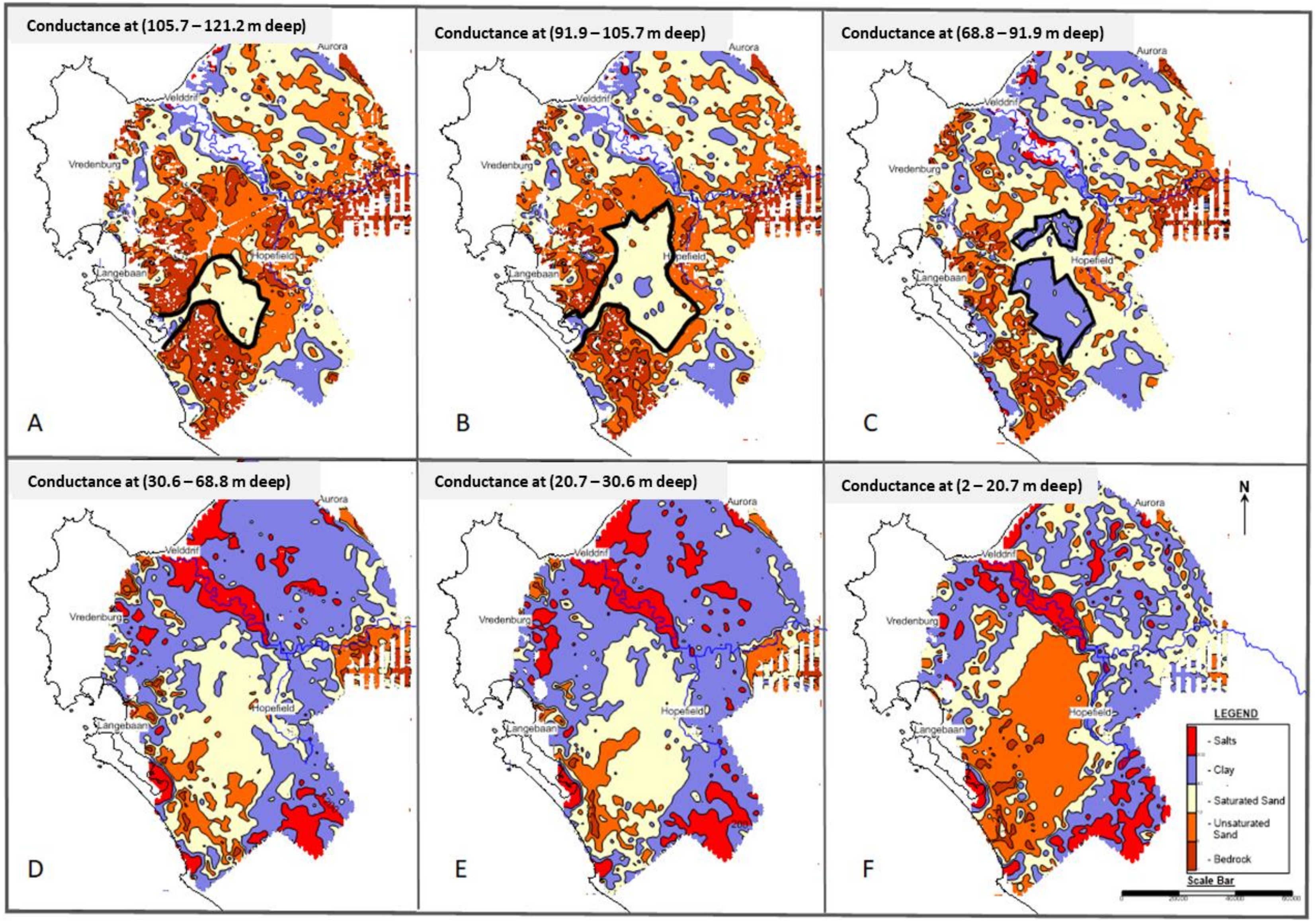


Figure 33: Examples of conductivity distribution derived from the geophysical survey of the geological material at depth in the study area.

5.2.2 Bedrock Topography

The depth to bedrock and the topography of the study area was derived from the airborne geophysical survey data. In Figure 34 below, Frame A depicts the depth of bedrock below the surface whereas Frame B illustrates the topography of the area. The blue to dark blue colours shows that the deepest bedrock depths are located in the greater Elandsfontein aquifer, west of Hopefield with depths greater than 100 m. Some deep patches of up to 100 m deep are also seen towards Velddrif and Aurora. Frame B illustrates the elevation of the surface above sea level and the blue colour delineates the surface elevation of 20 m and lower. The gold colour shows the surface elevation between 20 m and 70 m, with the darker brown colour depicting the areas with an elevation of more than 70 meters above mean sea level.

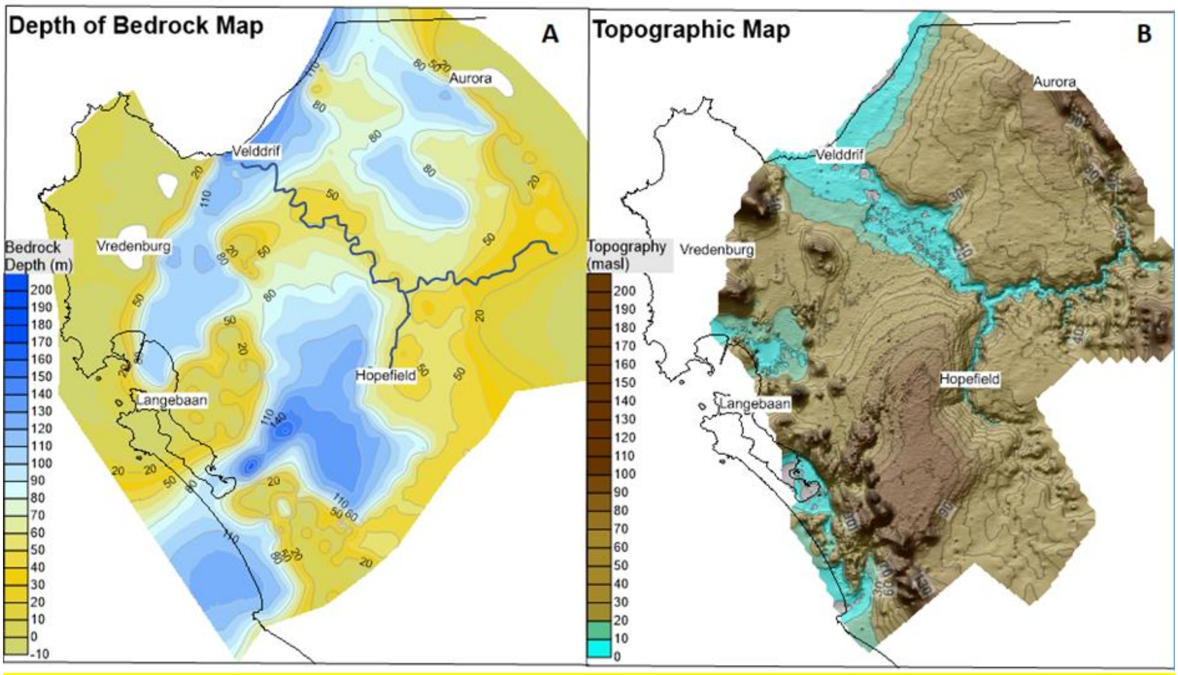


Figure 34: Maps showing the depth of bedrock (frame A-left) and topography (frame B-right) in the study area.

The bedrock depth layers that were derived from the conductivity data of the airborne survey was subtracted from the topography layer. This was done to obtain the depth of the layers relative to the surface topography. The bedrock topography was interpreted from the contact between the sand and the bedrock in each layer and then combined to form a single dataset. The bedrock depth was then combined with the topography to provide a bedrock elevation map (Figure 35). The yellow colour on the map depicts the higher elevated areas such as the mountains north of Aurora, Moorreesburg and the granite hills along the western part of the study area.

The deepest bedrock elevations which are represented by the dark blue colour in Figure 35 and occur in the southwestern part of the Elandsfontein aquifer towards the Lagoon, between the Lagoon and Yzerfontein and in the northwestern side of the map, where a deep paleochannel is located in a northeasterly to southwesterly direction along the coast, passing through Velddrif towards Saldanha Bay. These bedrock depths (dark blue) are approximately 100m below sea level.

There are also some deep bedrock patches found in the Langebaan Road wellfield vicinity and between the Berg River and Aurora with depths up to 60 m below sea level. Overall, the blue coloured area is where sands were deposited over time and make up the aquifer structure in the area. The bedrock depths at the Hopefield wellfield ranges 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 from the Hopefield wellfield to the Langebaan Road wellfield. Results of the geophysical survey showed that the upper and lower aquifers are connected.

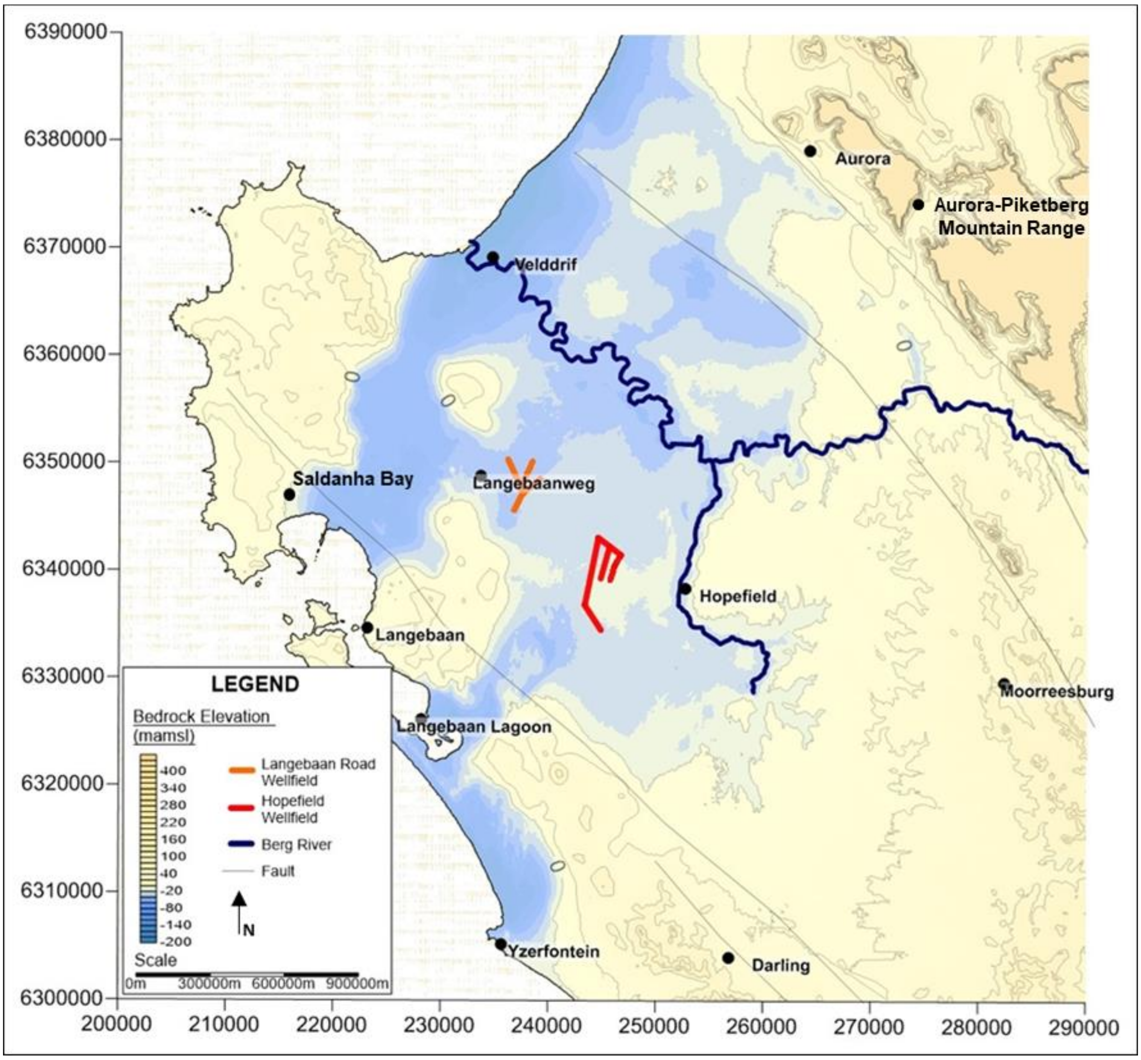


Figure 35: Bedrock elevation map of the Saldanha Bay Local Municipality area.

5.2.3 Clay Layer

The Time Domain Electromagnetic (TDEM) properties (40 – 200 mS/m) that represent the clay were overlaid on top of each other to provide information regarding the extent of the clay layer in the study area (Figure 36). Each layer is represented by a slightly opaque blue layer, increasing in darkness as the different clay layers overlay each other. Thicker clay layers are thus characterized by darker blue zones.

Northeast of Langebaan Road, there is no indication of a confining clay layer up to 80 m below the surface. Similarly, at Hopefield, the clay layer seems to be non-existent to the west, north-east, east and south-east of the wellfield, suggesting that in these regions, recharge from the upper aquifer to the lower aquifer is possible. Clay is also missing around the granite outcrops southwest of Langebaan Road, along the coast.

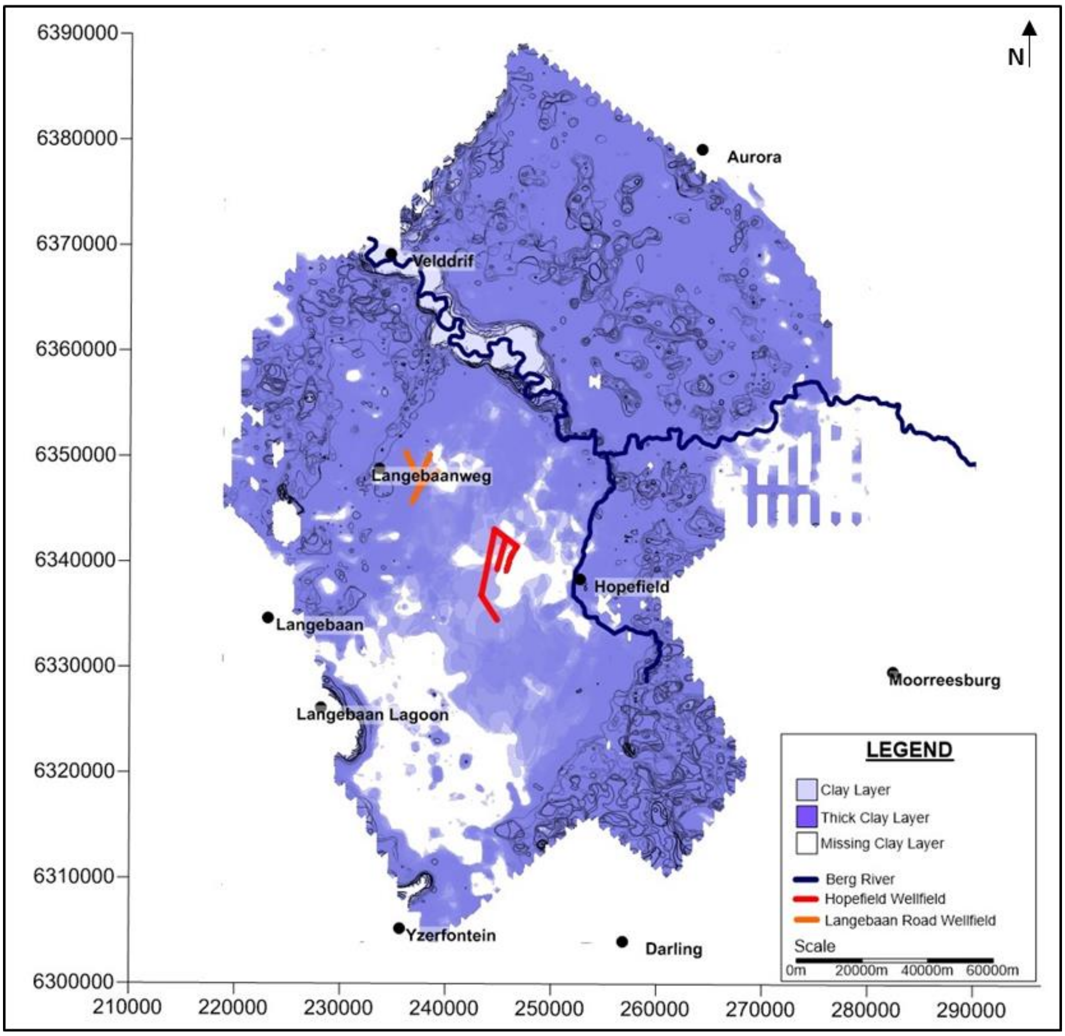


Figure 36: Extent of the clay layers across the study area

5.2.4 Groundwater recharge and flow direction

Groundwater recharge and flow directions are discussed in this section using geophysical cross-sections that were generated from the airborne geophysics results. These cross-sections aided in the identification of recharge to the aquifers contained within the study area. The locations of the cross-sections are shown in Figure 37 and Figure 38 below. Locations of the cross-sections were chosen based on where the suspected recharge and discharge areas were.

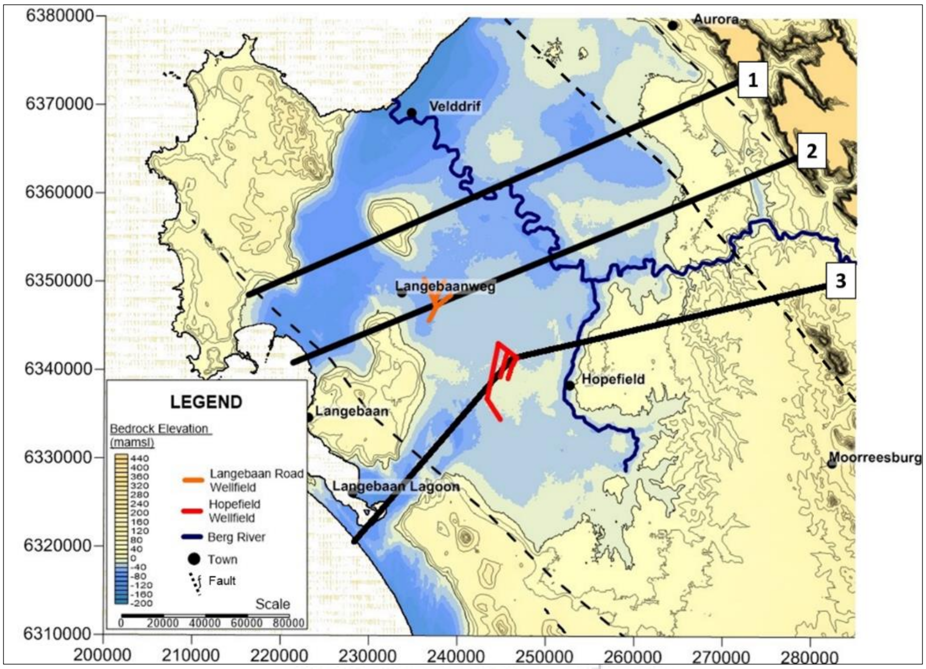


Figure 37: Traverses for which cross section 1, 2 and 3 were generated

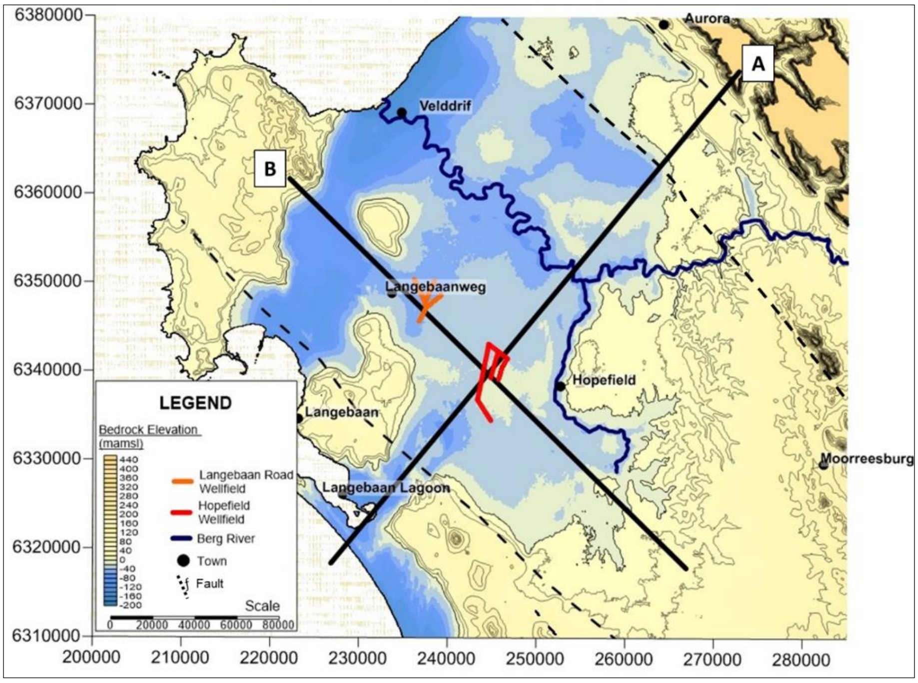


Figure 38: Traverses for which cross section A and B were generated

Cross-section 1

Geophysical results displayed on cross-section 1 (Figure 39) indicate thin sand cover and rock outcrops at 5000 m and 20000 m on the profile, which are expected to be favourable for local recharge. This supports the findings of Smith (2020) who conducted a recharge study in the area and found that boreholes located near granite hills indicated direct recharge from local rains. The cross-section suggests that groundwater flows from either side of the granite koppies towards the Berg River and Saldanha Bay. The bedrock valley between 5000 m and 20000 m on the profile advocates that a subsurface flow occurs perpendicular to the cross-section. It is also likely that the faults are seen at 52000 m and 60000 m on the cross-section contribute to the groundwater in the area however, this requires further investigation.

Areas of high salinity are shown in the valley at 10000 m on the profile. The Berg River is saline (indicated by the colour red) and is underlain by very thick clays (blue colour). This suggests that recharge from the Berg River to the aquifer system below it is not possible. The Berg River is situated at the lowest topography on the profile with evaporation of the surface water body increasing the salt concentration – suggesting that it is not a recharge area but rather a discharge area for the aquifers.

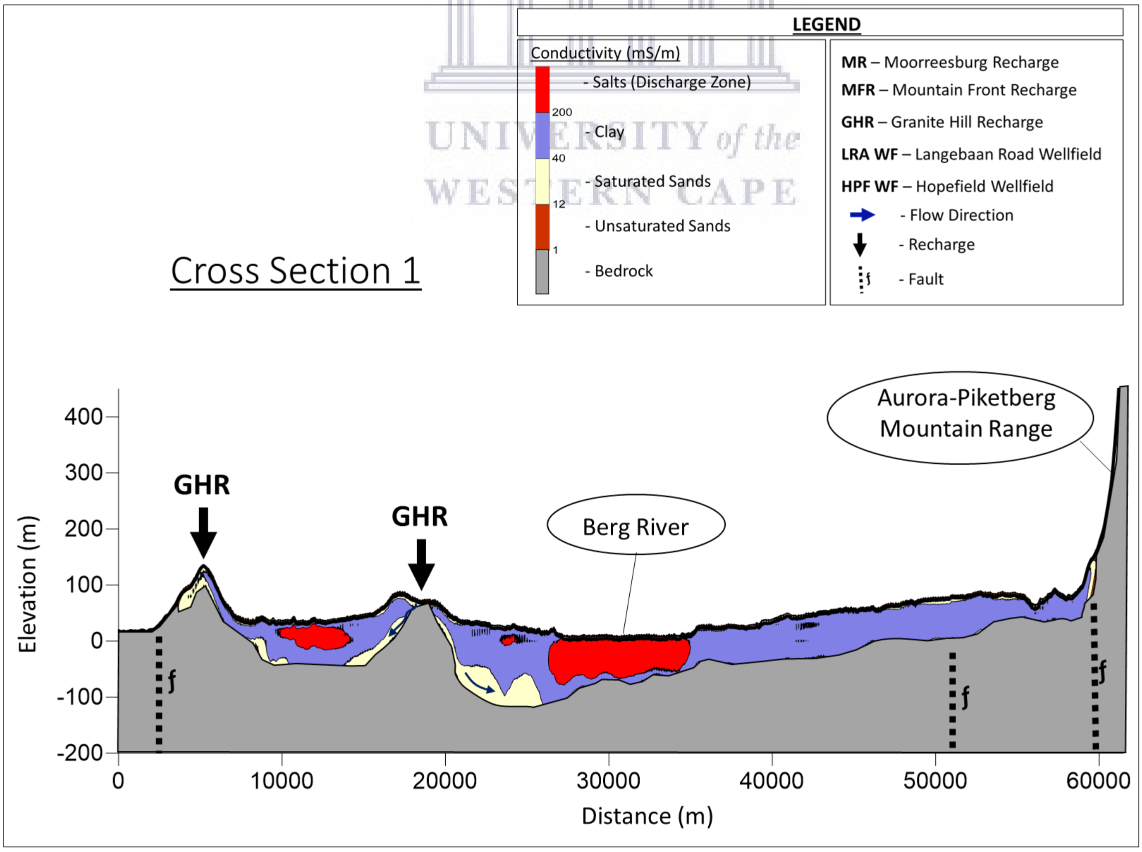


Figure 39: Cross Section (1) from the Aurora-Piketberg Mountain Range to Saldanha Bay

Cross-section 2

The cross-section suggests that groundwater flows from the higher elevated Aurora-Piketberg Mountain Range under the Berg River and towards the Langebaan Road Wellfield. Mountain front recharge at the foot of the Aurora-Piketberg Mountain Range and granite hill recharge at the granite outcrops nearer to the ocean in the Langebaan Road can be seen in Figure 40 at 10000 m and 60000 m, respectively. This profile, like cross-section 1, suggests that the Berg River is a discharge zone in the area and that recharge from surface water to groundwater in this area is not possible due to the thick clays underneath the Berg River.

What should be noted is that data displayed in cross-section 2 clearly shows a direct (local) recharge component at the foot of granite outcrops in the area. At 10000 m on the profile, it shows that the lower Langebaan Road aquifer gets recharged by local rains accumulating at the foot of granite hills. Groundwater then flows from the higher elevated granite hills towards the Langebaan Road Wellfield and then discharges into the Berg River.

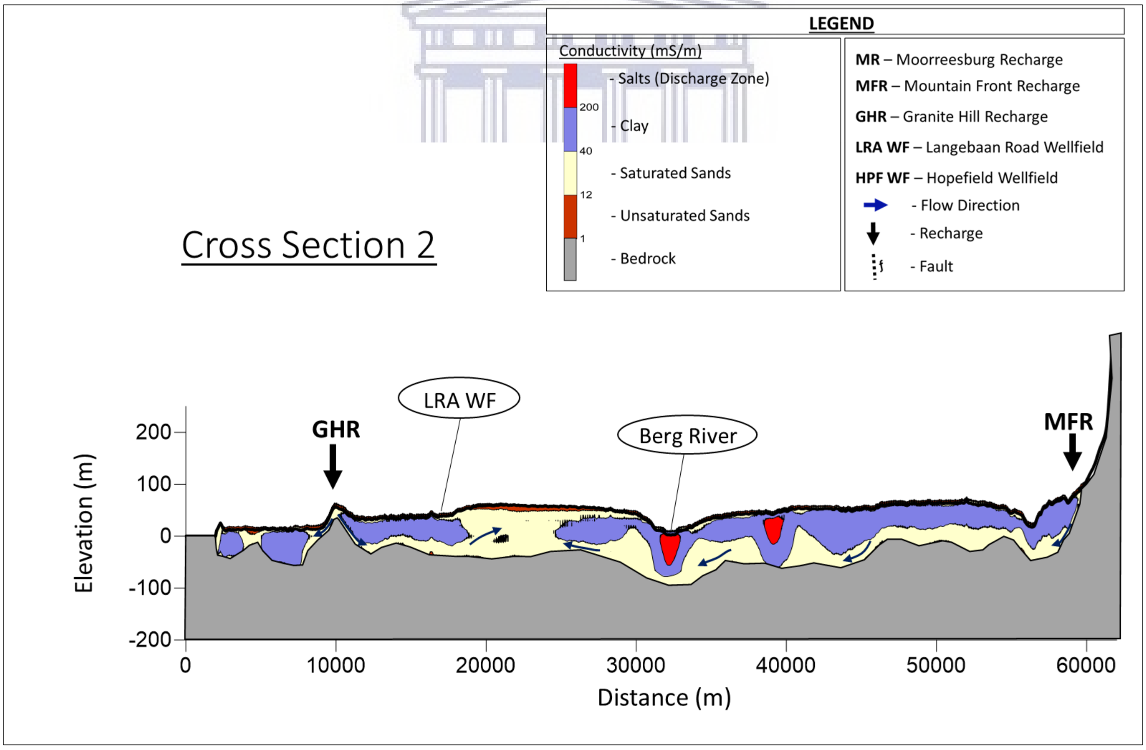


Figure 40: Cross-section (2) from the Aurora-Piketberg Mountain Range to Saldanha Bay

Cross-section 3

Regional recharge from the Moorreesburg area is shown in Cross-section 3 (Figure 41). Smith (2020) conducted a recharge study in the Elandsfontein area and found that it was most likely that the regional source of recharge was around Moorreesburg/Porterville area. Bedrock elevation suggests that groundwater flows from the Moorreesburg recharge area, underneath the Sout River towards Hopefield wellfield and then discharges into the Langebaan Lagoon. This is likely a very long flow path under high pressure (confined conditions) due to the think clays below the Sout River.

The 10-meter thick unsaturated zone in the Hopefield area (between 20000 and 30000 m on the profile), indicated by the dark orange colour, indicates that recharge from local rainfall is very unlikely as the limited rainfall received in the area cannot infiltrate such thick, dry sands. Between 6000 m and 17000 m on the profile, an 80-meter thick saturated zone can also be seen. Recharge from local rains in this area is also improbable.

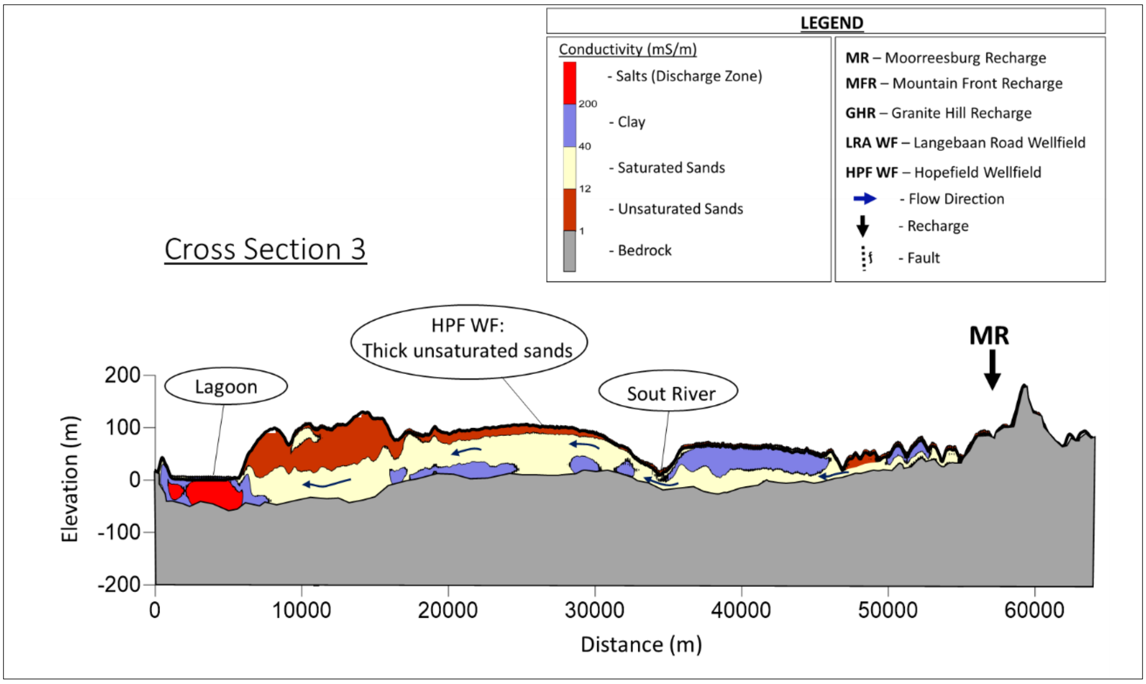


Figure 41: Cross-section (3) from the Moorreesburg area to Langebaan Lagoon

Cross-section A

The TDEM data displayed in Figure 42 shows evidence of a deep layer of saturated sands extending between the Hopefield Wellfield towards the Langebaan Lagoon. This cross-section displays that the main discharge zone in the Elandsfontein portion of the aquifer is the Lagoon (8000 m on the profile).

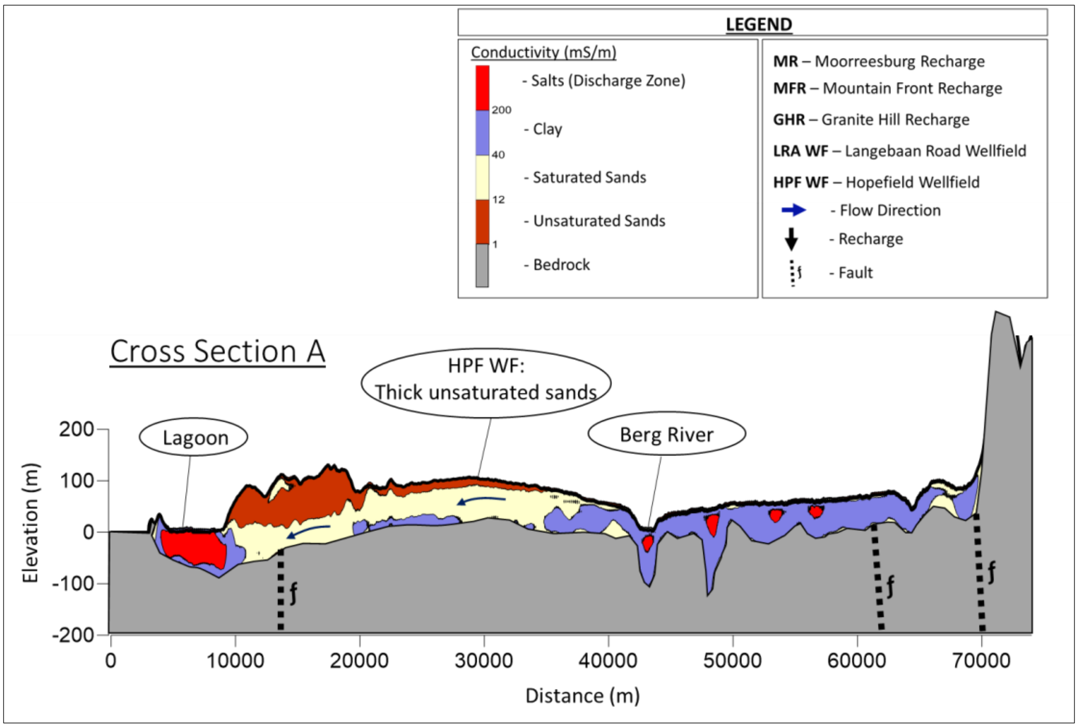


Figure 42: Cross Section A from the Aurora-Piketberg Mountain Range to the Langebaan Lagoon

<u>*Cross-section B*</u>

Recharge to the Langebaan Road Wellfield (Figure 43) is seen to come from the flow that passes through the Hopefield Wellfield. This is most likely a deep recharge flow path from the Moorreesburg recharge area. Data in the Moorreesburg area was limited and it is therefore recommended that further studies be conducted in the area to confirm the Moorreesburg recharge zone.

The TDEM data displayed in cross-section B displays that the aquifer systems between Hopefield and Langebaan Road are connected and suggests that inter-aquifer flow takes place above and below the clay layers (30000 m on the profile).

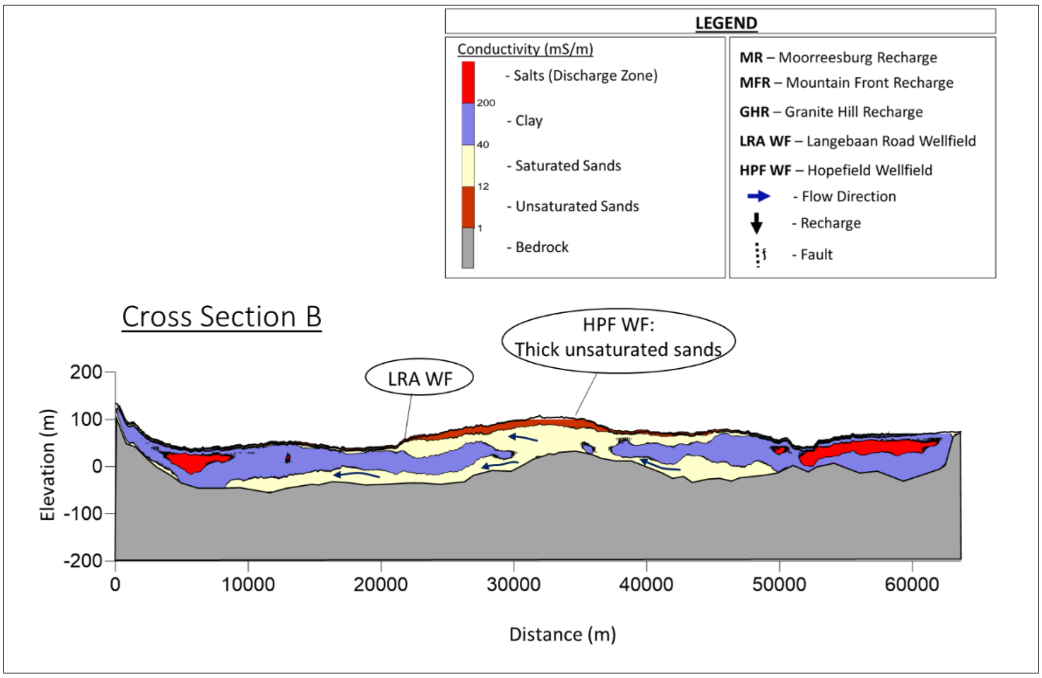


Figure 43: Cross Section B from the Hopefield Wellfield to the Langebaan Road Wellfield.

To better display the potential recharge sources and processes as well as groundwater flow directions in the Saldanha Bay area, all generated cross-sections (Figure 39 to Figure 43) were combined and put into a 3-dimensional format (Figure 44).

From the assessment of all the geophysical survey data, it is postulated that regional recharge sources contribute a large amount of groundwater to aquifer systems. These sources include recharge from the high lying Moorreesburg area and mountain ranges that surround the study area. Thin layers of saturated sands near granite hills promote the occurrence of direct groundwater recharge from local rains. Interaquifer flow is seen in the Langebaan Road area where groundwater flow is seen to take place above and below the clay layer (Figure 43). The main discharge from the aquifer most likely occurs at southern end of the Langebaan Lagoon at Geelbek, with some groundwater discharge occurring at the Berg River and north of the Berg River where salt pans are present.

In addition to the geophysical survey results discussed in this section and the infiltration test results discussed in Section 5.1, further investigations were carried out (these are discussed in Section 5.3 below) which supported the findings of the geophysical survey.

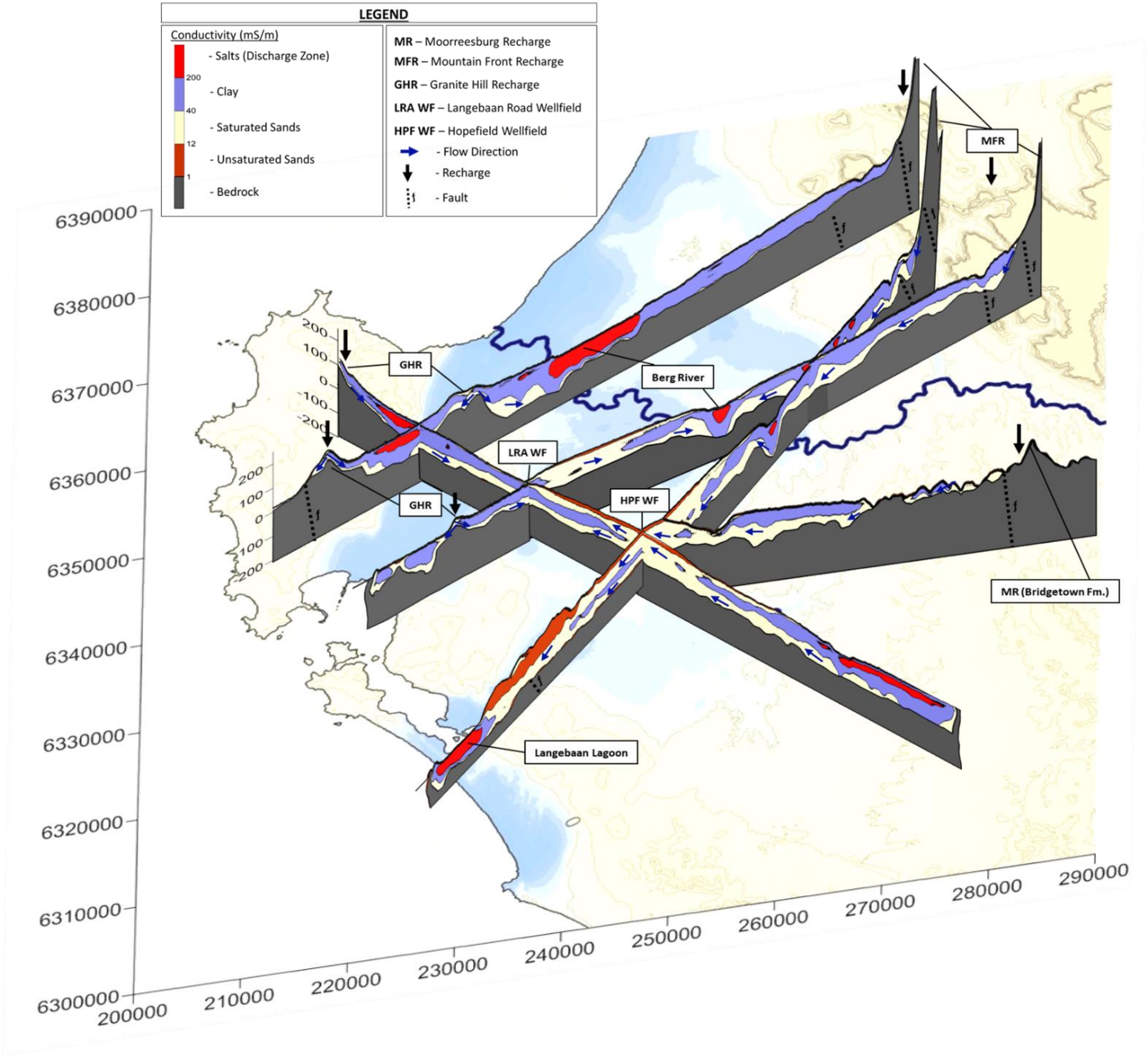


Figure 44: Combined 3D geophysical cross section superimposed on the study area

5.3 WATER QUALITY RESULTS

Water quality analyses were used to supplement the geophysical data to confirm the postulated recharge and discharge zones. All boreholes were sampled for both major anions and cations as well as stable isotopes (Oxygen-18 and Deuterium) and a radioactive isotope, Tritium. The first sampling run was conducted in February – March 2020 (dry season) and the second run was in August 2020 for the wet season. The Covid-19 Pandemic limited field trips and in turn, sample collection. It is for this reason that only one wet and one dry sampling run took place during 2020.

5.3.1 Chemical Analysis

A Schoeller diagram showing the relative concentrations of anions and cations in groundwater samples collected for the present study is shown in Figure 45 and Figure 46, respectively. Groundwater samples from different boreholes were plotted on the diagram to determine if there were similar patterns in the ratios of certain anions and cations. The relative ion concentrations are a function of the groundwater geochemistry and the chemical composition of the aquifer rock material. The patterns may be used to distinguish common or different source areas of water pumped from different boreholes. Similar waters exhibit similar patterns on the diagram.

In Figure 45 the ions concentration is represented in mg/l and show a tendency of Na>Ca>Mg and $Cl>SO_4>HCO_3$. The dominant water type in the samples was Na-Cl, which is typical of the local sand and quartzite groundwater systems and is also due to the coastal rainfall that the area receives. Both diagrams suggest that all the boreholes that were selected to be part of the present study were likely to have the same water source.

A Schoeller diagram displaying the ion concentrations of TMG boreholes are shown in Figure 46. Although the quality of these boreholes is similar to those shown in Figure 45, they have considerably lower cation and anion concentrations, very similar to that of rainwater, which is an indication of shorter residence times and characteristic of a recharge zone.

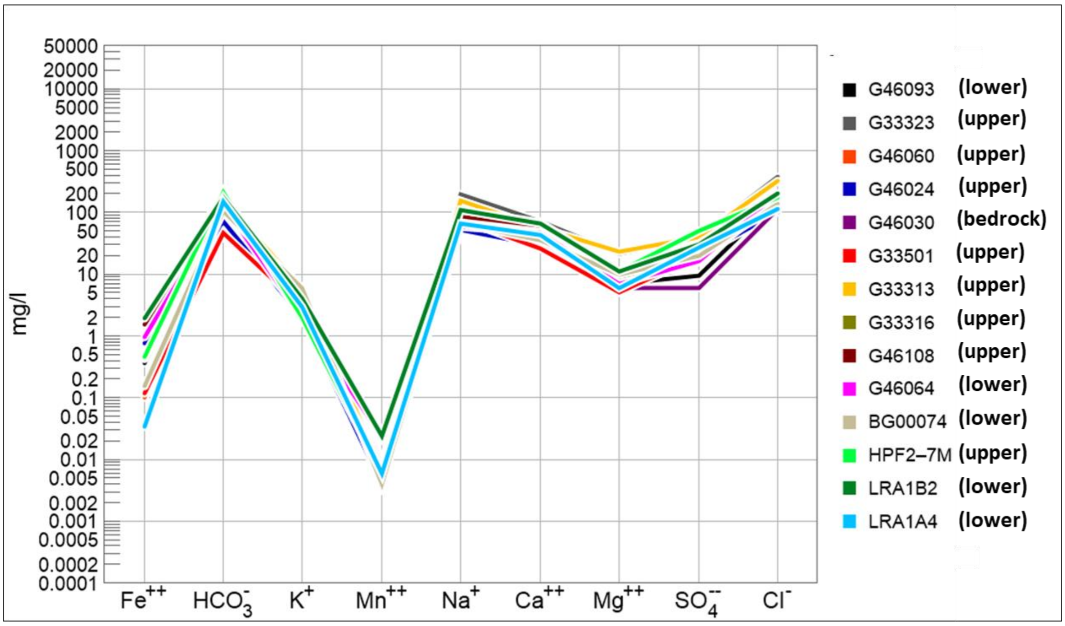


Figure 45: Schoeller diagram of some boreholes selected for the study

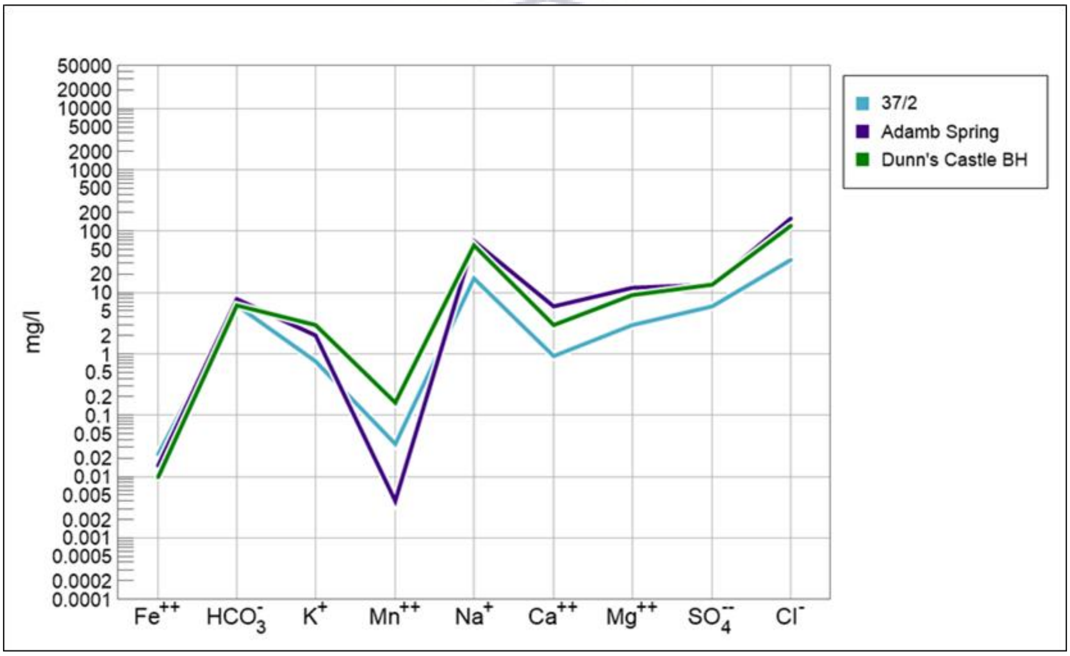


Figure 46: Schoeller diagram of boreholes drilled into the TMG aquifer – a possible recharge zone

5.3.2 Down-the-hole electric conductivity and temperature logging

Groundwater sources and movement of groundwater through a borehole can be identified by down-the-hole logs due to water from different aquifers having different temperatures and conductivities. Seasonal recharge to the ground-water system may be reflected in cyclic-temperature fluctuations, and the vertical movement of water in the unsaturated zone can be investigated with temperature sensors (Stallman, 1965). Temperature and electrical conductivity (EC) logs may also provide evidence of possible recharge zones. For example, downhole profiles with cool temperatures and low EC's are usually an indication of recharge.

Borehole 37-2 (TMG)

Borehole 37-2 is situated at the top of the Aurora-Piketberg Mountain Range (Figure 47). At this borehole, EC values were seen to be extremely fresh when compared to the EC's of other selected monitoring boreholes used in the study. The construction and geology of this borehole are not known. However, examination of the logs shows that this borehole was likely screened between 15 and 35 m due to gradient changes in the EC and temperature profiles. Gradient changes in both profiles indicated that there is a single inflow into this borehole at around 15 m (12.5mS/m and 16.2°C). The top 25 m displayed active through flow from rainfall.

Low-temperature values were due to the cooler ambient temperatures of the high-altitude mountain recharge processes. Low EC, Na-Cl type dominated water is typical of the TMG water in the well-leached recharge areas, where the rainfall Na-Cl characteristics are maintained. Both low EC and temperature readings were an indication that the Aurora-Piketberg Mountains was an indirect, regional recharge zone for the aquifer systems within the Saldanha Bay Local Municipality area.

G46094 (Upper Aquifer Borehole)

According to EC measurements recorded at upper aquifer boreholes selected for the study, it was found that high salinities are characteristic of the upper aquifer in the Langebaan Road area. G46094 (Figure 48) is an example of a low yielding, upper aquifer borehole. At this borehole, the electrical conductivity of the groundwater became more saline post-pumping. The gradient change at 37 m was an indication of water with an increased EC value (800 mS/m) entering the borehole at the top of the screen.

G46093 (Lower Aquifer Borehole)

An example of a high yielding, lower aquifer borehole can be seen in Figure 49 (G46093). When assessing the down-the-hole logs, it was observed that the upper aquifer boreholes chosen for this study were considerably more saline (EC = 92 – 800 mS/m) than the lower aquifer boreholes (EC = 9 - 105 mS/m). This was an indication that the two aquifers are recharged through different processes. The low salinity of the lower aquifer water suggests that it is unlikely that local rainfall is passing through the more saline upper aquifer and recharging the lower aquifer.

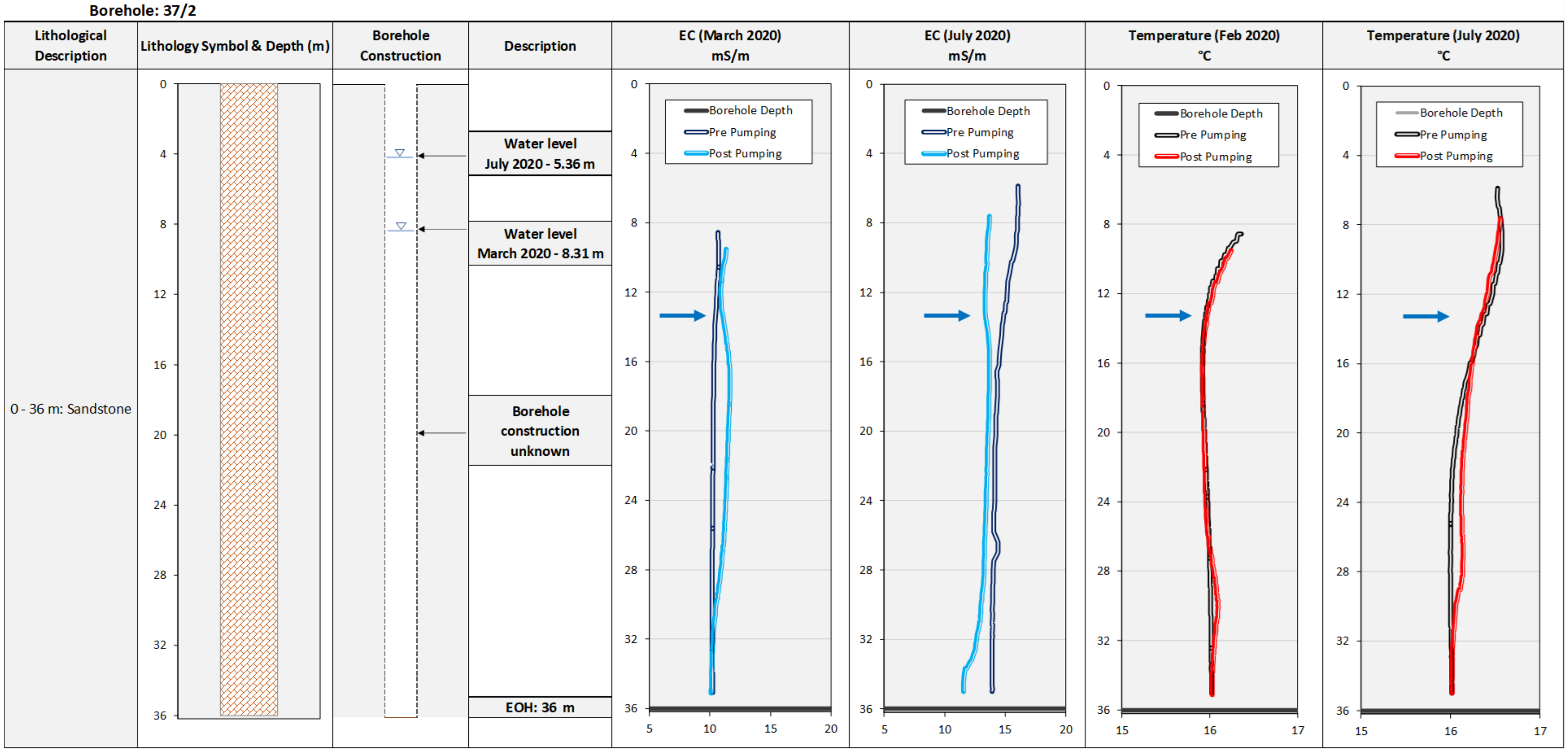


Figure 47: Down-the-hole EC and Temperature log of borehole 37-2 at the top of the Aurora-Piketberg Mountain Range (possible recharge area)

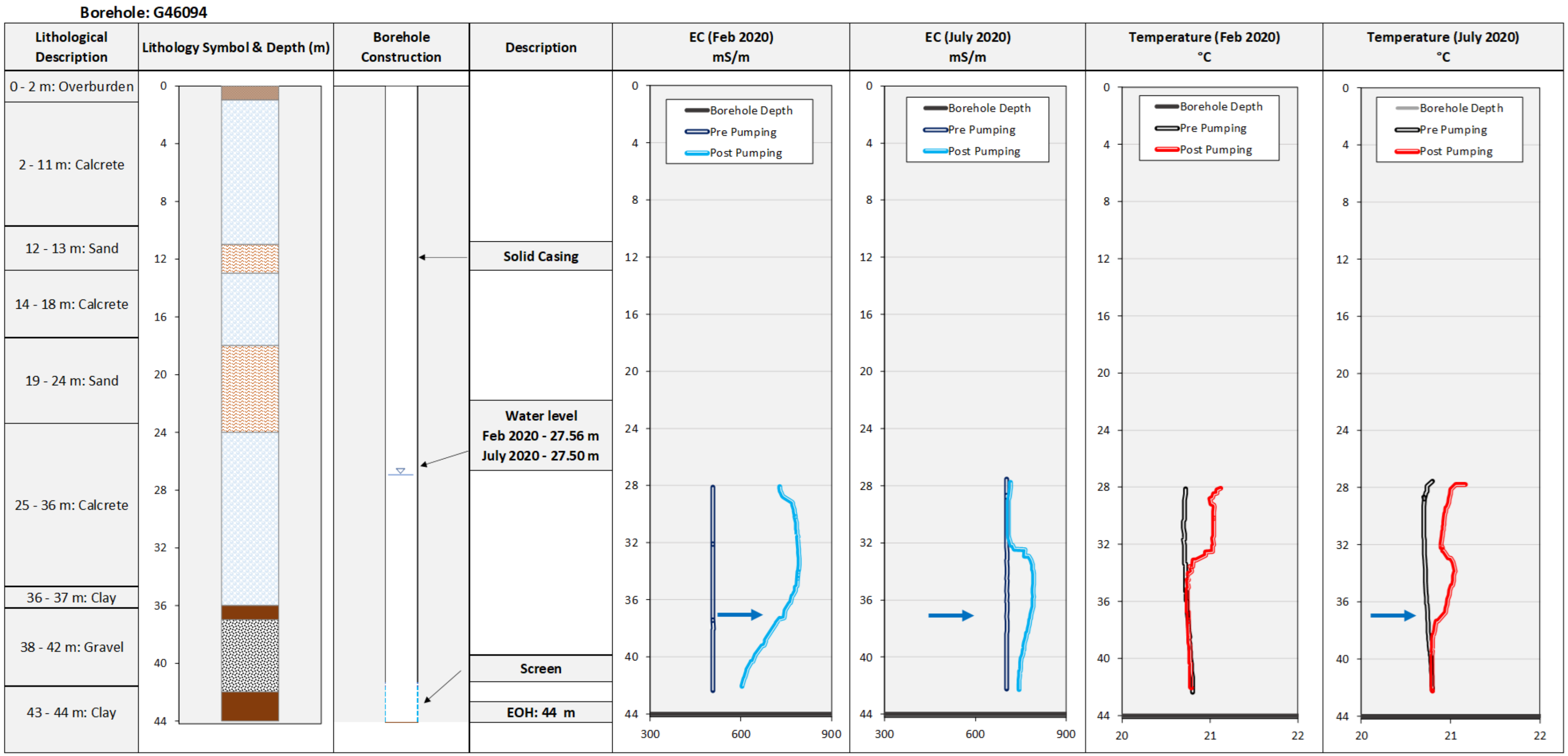


Figure 48: Down-the hole EC and temperature logs for G46094, an upper aquifer borehole at Langebaan Road

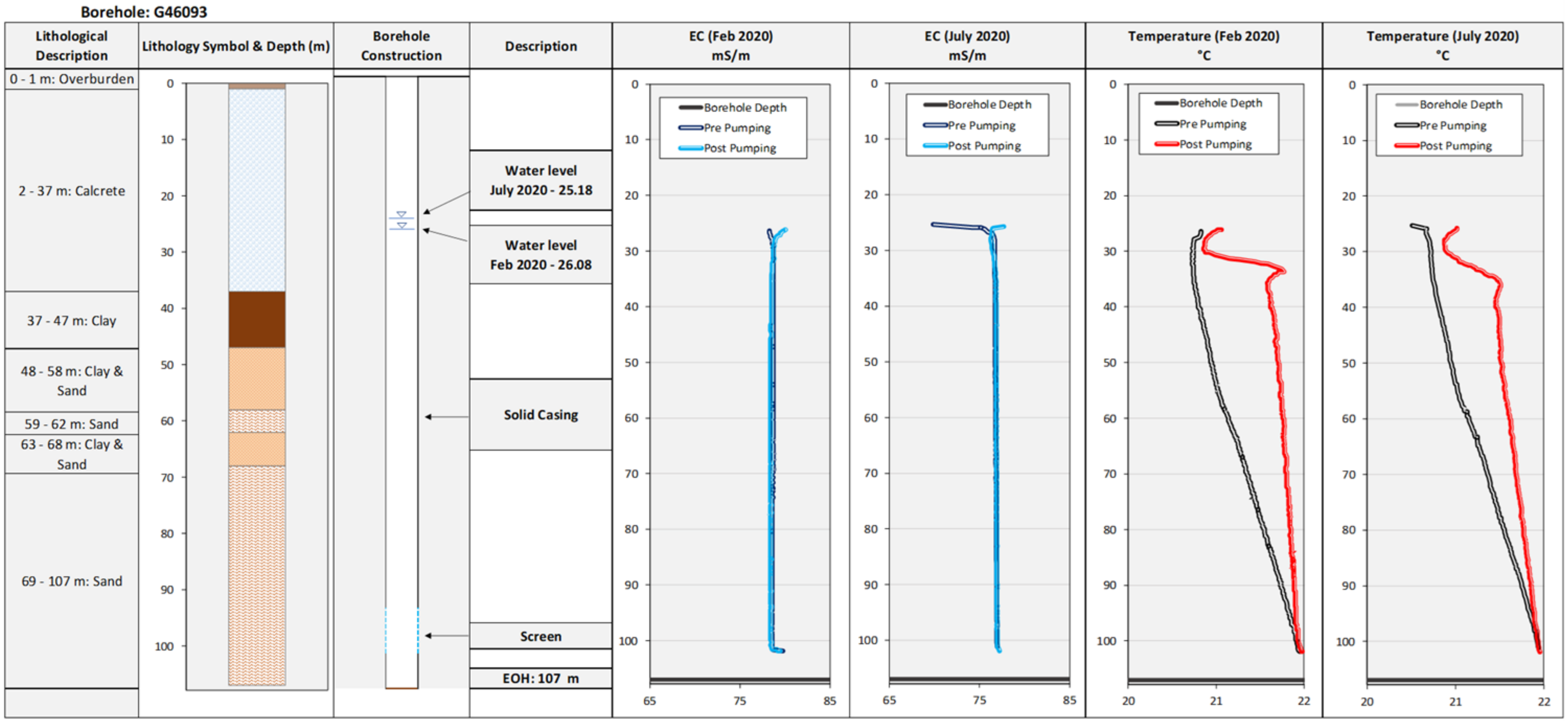


Figure 49: Down-the hole EC and temperature logs for G46093, a lower aquifer borehole at Langebaan Road

5.3.3 Isotope Analysis

Isotope analysis includes measurements of isotopes that form water molecules, such as oxygen isotopes (e.g. oxygen-18) and hydrogen isotopes (deuterium, and tritium). These isotopes are ideal tracers of water sources and movement because they are integral constituents of water molecules. Water isotopes can be useful tracers of water flow paths, especially in groundwater systems, as different sources of water will have different isotope signatures due to undergoing different processes before recharge takes place (Kendall and McDonnell, 1998).

Isotope analyses are used to support the chemical analysis of water samples. Results of the stable isotope analyses for samples collected during the February – March 2020 (dry season) and August 2020 (wet season) field trips are displayed in Figure 50. During the dry season field trip, boreholes in the Langebaan Road and Hopefield areas were sampled. The sampling area was extended for the wet season after the preliminary geophysical results became available, which showed that a regional scale recharge process from the Moorreesburg area may be taking place.

Stable Isotopes (δ^2H and $\delta^{18}O$)

Very little variation in stable isotope signatures was seen between wet and dry seasons and as a result of this were plotted together in Figure 50. Most groundwater samples have a depleted signature and plot in the lower left quadrant of the graph, aside from 2 springs samples that plot in the upper right quadrant.

Surface water, indicated by the blue diamond-shaped markers in Figure 50, as well as springs show a more enriched isotopic signature. It is evident from the isotopic composition of the surface water and springs that there has been some degree of evaporation (indicated by the dashed arrow). Surface waters are typically associated with an evaporative trend, which may not be evident due to the lack of surface water data. Due to the surface water bodies being so much more enriched than the groundwater samples in the area, it is improbable that groundwater is recharged by surface water in the area.

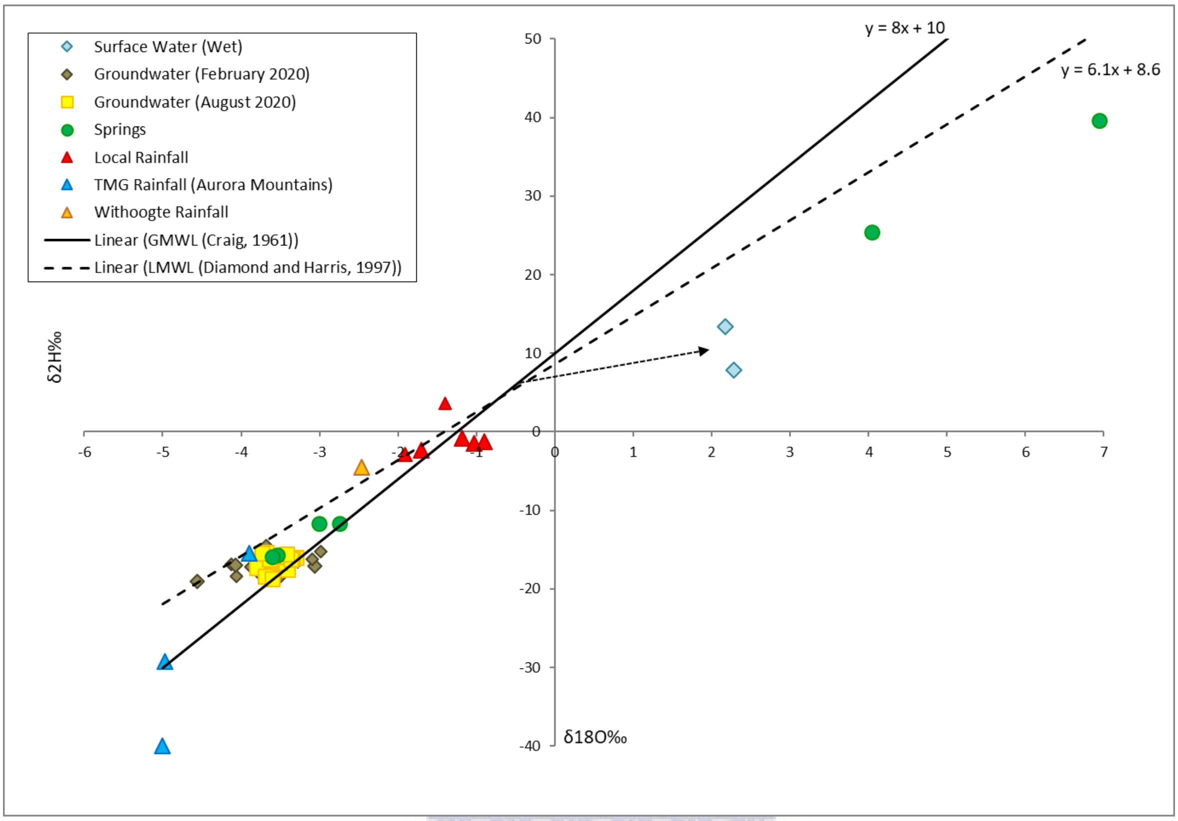


Figure 50: Stable isotope results of surface, groundwater and rainfall samples collected throughout 2020

Due to most of the samples plotting in the lower left quadrant of the graph, this section of the graph was zoomed into and is displayed in Figure 51. Isotope signatures of groundwater samples cluster together indicating that groundwater in the area is recharged by the same source.

All local rainwater samples had relatively enriched isotopic signatures compared to regional rainfall which had a very depleted signature. Regional samples were collected from high lying areas and are more depleted due to the altitude effect. This effect is caused by increased rain at the higher elevations due to continuous cooling of the air mass pseudo-adiabatically to below the dewpoint in an orographic precipitation system, whereby isotope fractionation removes the heavier isotopes from the air mass leaving it more depleted (Kendall and McDonnell, 1998).

Isotopic signatures of groundwater show a different range to that of all local rainfall samples, aside from the sample collected from the rainwater collector on a granite hill (BG00074-RF). The isotopic signature of BG0074-RF has a similar isotopic signature to two springs, which is an indication that those springs ate fed through local rainfall. The springs in the study area are situated topographically higher than the regional groundwater flow elevation and are consequently not part of the regional system, but rather fed through recharge from local rains in the area.

The majority of the local rainfall samples did not show a similar signature to the groundwater and was an indication that groundwater in the area is not a result of modern precipitation but rather an indication of longer residence times and indirect recharge from a regional source. It is most likely that the source of recharge to the study area is from rainfall occurring on the mountain ranges and high lying areas that surround it. This can be deduced as regional rainfall (TMG and Withoogte) samples, specifically, the TMG sample taken at the base of the Aurora-Piketberg Mountain Range has a very similar isotopic composition to the groundwater in the area.

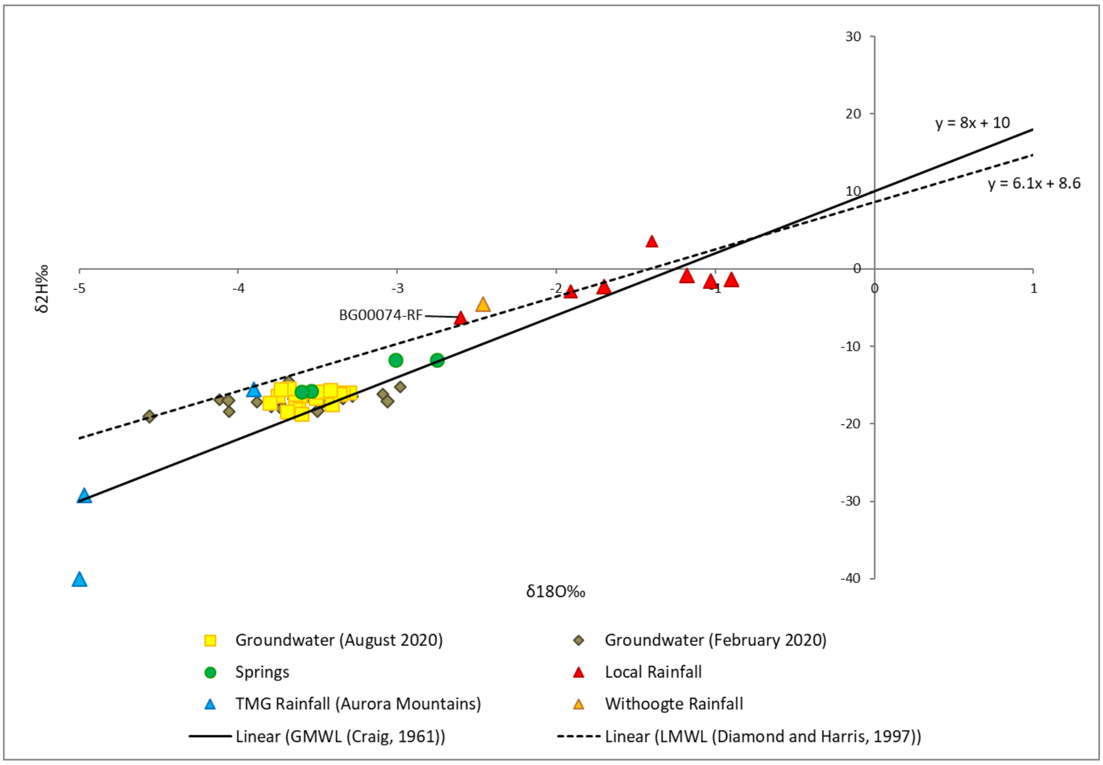


Figure 51: Lower left quadrant of the graph shown in Figure 49 showing the stable isotope results of groundwater and rainfall samples collected during the wet and dry seasons (2020)

Radioactive isotope Tritium (^{3}H)

Tritium enters the groundwater system through precipitation. Isolated from the atmospheric source, following recharge from rainfall, no new tritium is added to groundwater and the concentration of tritium decreases with its characteristic half-life of 12.32 years as the groundwater moves through the aquifer system. Measurable tritium in boreholes that are close to the present-day tritium input would then indicate recent, local recharge, while zero tritium would indicate slow or no modern recharge of that aquifer.

On average, rainwater in the study area was found to contain a natural tritium concentration of approximately 1.6 tritium units (TU). The tritium input was measured at the Withoogte rainfall sampler, at the rainfall sampler close to the Langebaan Road Wellfield (G46093-RF) and at the top of the Aurora-Piketberg Mountains as these were the only isotope samplers containing enough water for a 1-litre sample to be taken. Results showed that Tritium values for the groundwater of the aquifer systems in the study area were very low compared to the tritium input, indicating older waters and longer flow paths (Figure 52). This, again, reiterated that groundwater in the study area is most likely fed through indirect, regional recharge processes.

Samples on Figure 52 that plot close to the tritium input value was an indication of recent, local recharge while samples plotting closer to zero suggest much older water. Evidence of local recharge is seen in the tritium signatures of borehole 37-2, situated on the Aurora-Piketberg Mountain Range, and the dolomitic borehole at PPC De Hoek as they are relatively close to the tritium input.

Boreholes G46108, G33313 and BG00074 are all situated on granite hills in the area and have values that are close to the tritium input (0.8, 1.1 and 0.9 TU respectively), indicating a recent recharge source, which is most likely fed through granite hill recharge supporting an efficient local recharge mechanism. Spring samples were also found to have a tritium signature that was comparable to the tritium input, which similar to the stable isotope analysis, is an indication that they form part of the local groundwater system and are most likely fed through modern precipitation.

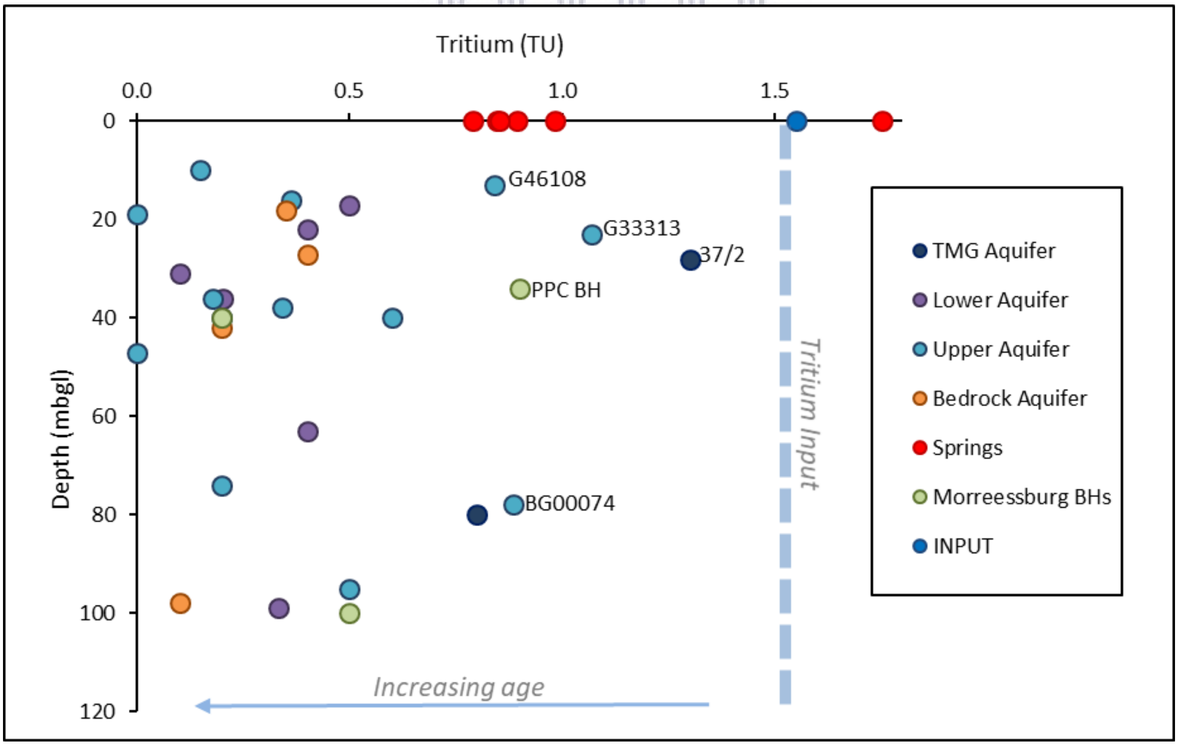


Figure 52: Tritium values of groundwater samples collected throughout the study area

Summary of Water Quality Results

All water quality measurements, (stable isotope and tritium values, EC's and temperature readings) of groundwater samples collected throughout the study area are displayed on the map below (Figure 53). Water quality data discussed in previous sections are brought together in Figure 53 and provide an overview of the results obtained through all water quality investigations.

According to the major anion and cation analyses as well as the down-the-hole logs, it was found that upper aquifer boreholes in the area are generally more saline than lower aquifer boreholes. This suggests that piston recharge from rainfall is highly unlikely in the area, as recently recharged water would have a lower EC value due to shorter residence times and less interaction with the subsurface. Boreholes G46094, G46060 and G46023 are the only upper boreholes with an EC value characteristic of the lower aquifer – these boreholes are likely situated along a recharge flow path

Stable isotope signatures were found to be similar for most boreholes in the study area and for this reason, was not included in the combined map. The similarity in isotopic signatures for groundwater throughout the study area is an indication that the groundwater in the study area is coming from the same source. However, stable isotope signatures of the springs in the area suggest that they are most likely fed by local rains as they have a similar range to local rainfall signatures and are located topographically higher than the regional groundwater flow and are therefore part of the local groundwater system.

Tritium values also suggest that springs in the area are more recently recharged as they have tritium values very close to the present-day tritium input for the area (1.6 TU). Boreholes situated close to granite hills have a higher tritium signature than the rest of the groundwater in the area suggesting recharge from local rains that accumulate at the foot of these hills. The low tritium values of the rest of the groundwater in the area point to a longer groundwater flow path, indirect recharge mechanism and regional recharge source.

The lowest groundwater temperature (16 °C) was measured at the top of the Aurora-Piketberg Mountain Range at borehole 37-2 (Figure 53). Lower temperatures are characteristics of recharge areas – the low temperature of borehole 37-2 supports the evidence of the Aurora-Piketberg Mountain Range being a regional recharge zone for the aquifer systems under investigation. The rest of the groundwater temperatures in the area are relatively similar with the lower aquifer boreholes being slightly warmer than upper aquifer boreholes.

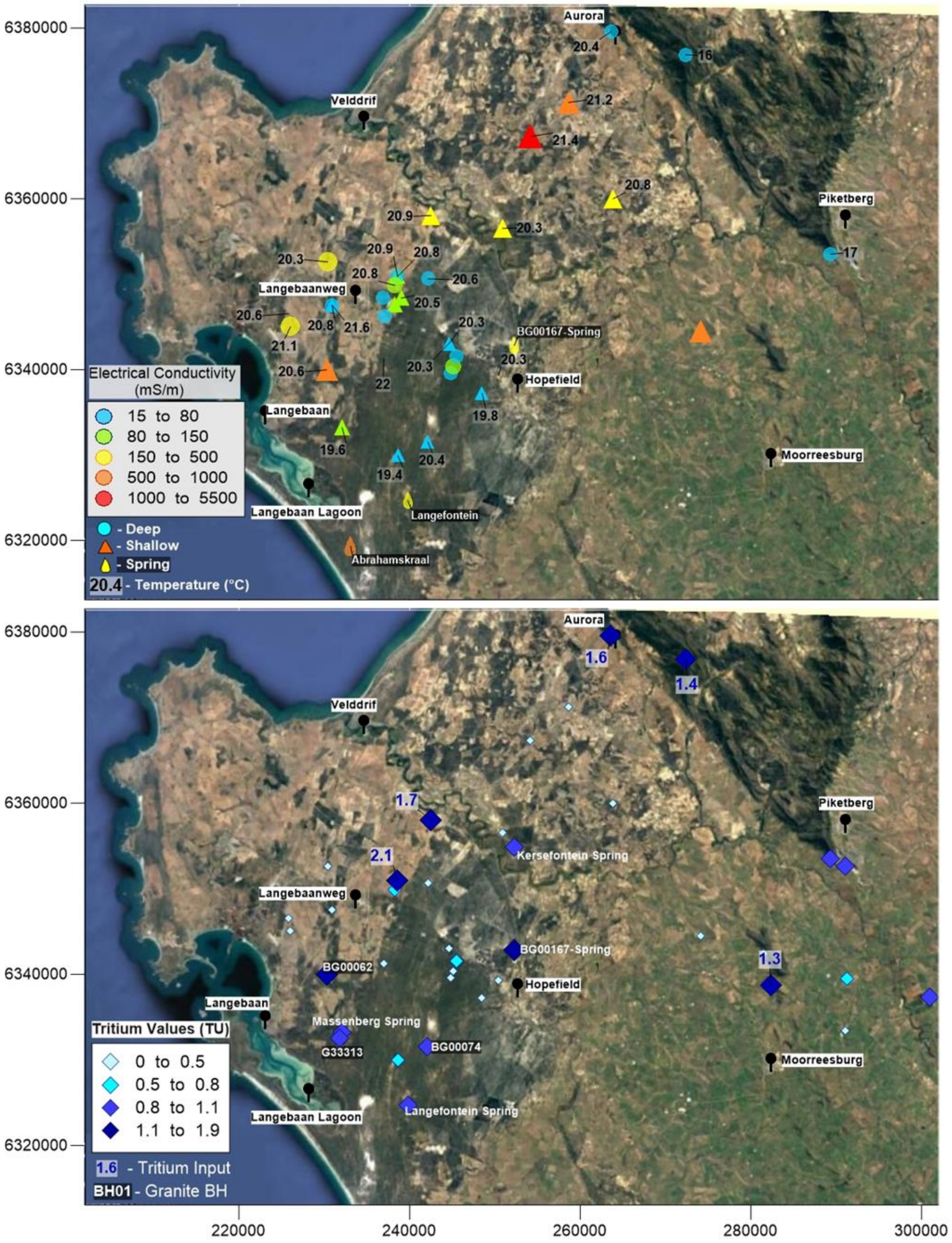


Figure 53: Map of water quality measurements (Tritium, EC and groundwater temperature) of groundwater samples taken throughout the study area.

5.3.4 PhreeqC Evaporation Modelling

The Langebaan Road area has extensive calcrete (rich in calcium and magnesium) layers close to the surface (Figure 53), which are overlain by windblown sands of the Springfontyn Formation. This formation is described as clean quartzose sands with low mineral concentrations (Roberts and Siegfried, 2014). Local rains also contain very little mineral concentrations, which do not allow for the precipitation and formation of calcretes in the area.

It was therefore postulated that groundwater from the lower aquifer containing measurable concentrations of calcium and magnesium is most likely discharging into the upper aquifer, after which evaporation takes place resulting in the mineral over-saturation, and precipitation of calcrete. This process also increases the salinity of the groundwater. The geophysical results indicated that the upper and lower aquifer systems contained within the study area are connected, with the flow sometimes occurring above the clay and sometimes below clay, which allowed for this process to take place. PhreeqC modelling was then undertaken in an attempt to prove this by determining if at any point the lower aquifer begins to resemble the upper aquifer during evaporation and which minerals precipitate out during this process.

Figure 54: A thick calcrete layer visible below the Springfontyn Formation in Langebaan Road Wellfield.

The geochemical modelling was completed for the following lower aquifer boreholes: LRA-1A1, LRA-1A4, LRA-1B2, LRA-1B2M, G46093 and G46061. The water quality parameters that were input into the PhreeqC software included: temperature, pH and, major anion, and cation concentrations. Inverse modelling within the software, which aims to decipher the reactions and mixtures which have led to a given water quality, was then used to model the change in the lower aquifer water quality under different percentages of evaporation.

PhreeqC results indicating the elements which precipitate during evaporation of the lower aquifer water are displayed in Figure 56 and Figure 57. Elements that precipitate out are characterized by an increase in molality and moles of solid (above 0), with an increase in the concentration factor. Whereas, dissolution is characterised with a decrease in molality and moles of solid, with an increase in the concentration factor. All modelled boreholes indicate magnesium (Mg), Sodium (Na) and Chloride (Cl) precipitation during evaporation. Precipitation of calcium is seen at all boreholes aside from G46093 and LRA-1A4.

Although the PhreeqC evaporative modelling does not show calcium evaporation at LRA-1A4 and G46093, geological logs confirm the formation of calcretes in the first few subsurface layers in both boreholes (Figure 55). This discrepancy in results is due to the PhreeqC software modelling ideal conditions, which is not always the case in real life circumstances. The geological logs for LRA-1A4 and G6093 as well as the modelled results for LRA-1A1, LRA-1B2, LRA-1B2M and G46061 confirm the formation of calcretes through discharge of the lower aquifer, which are consequent of evaporative processes.

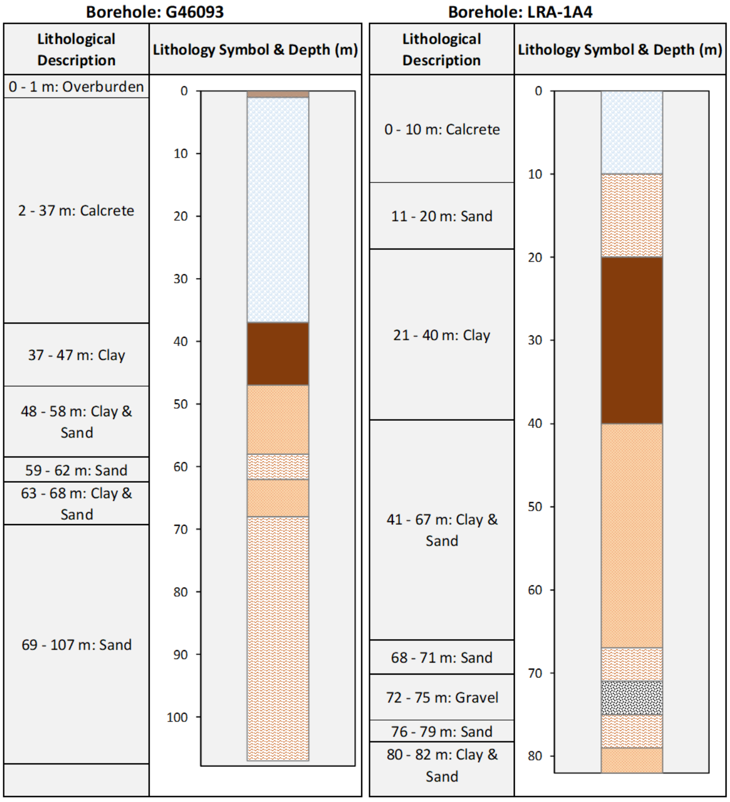
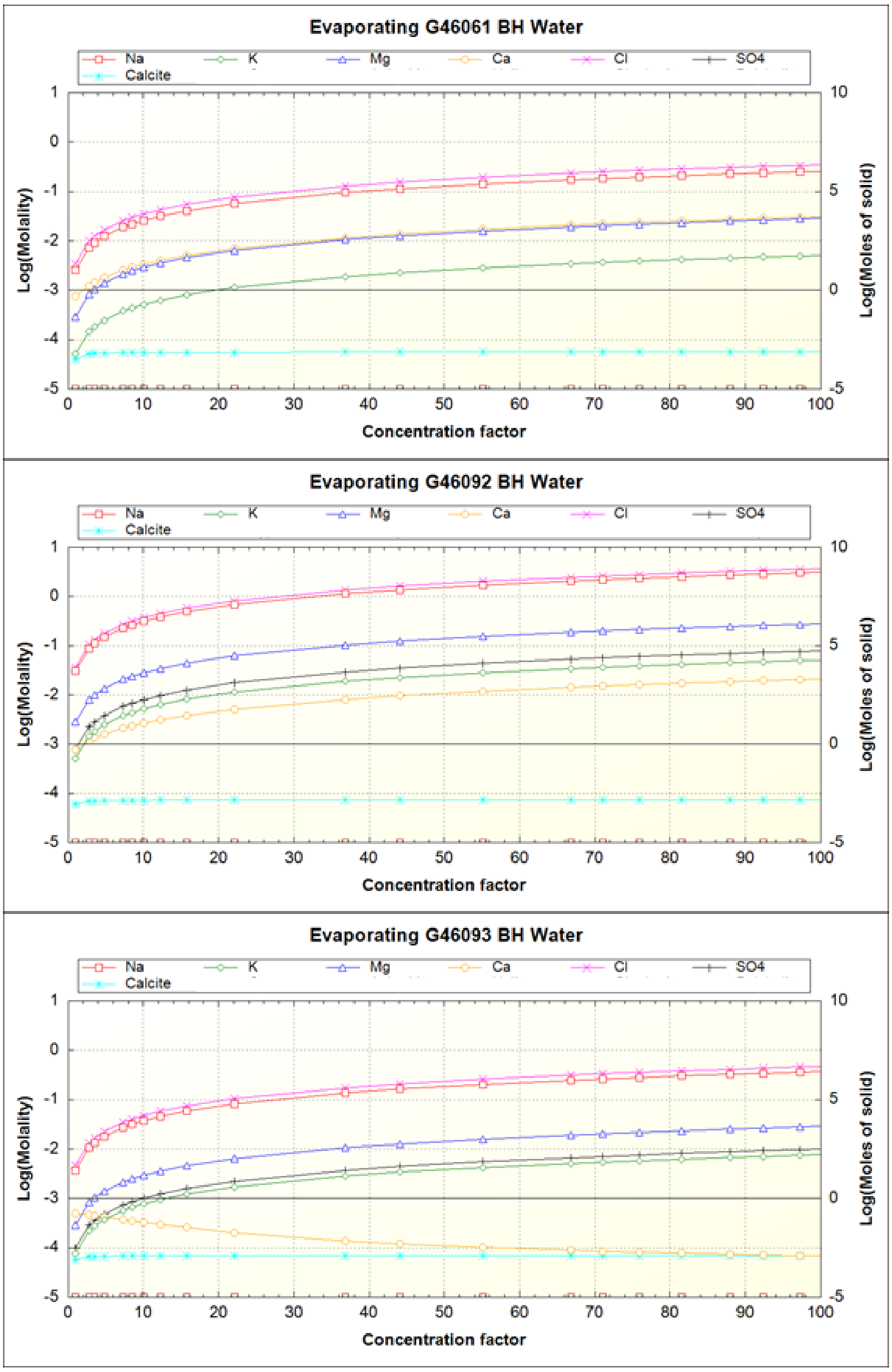


Figure 55: Geological logs for lower aquifer boreholes LRA-1A4 and G6093 in the Langebaan Road area



Evaporating G46061 BH Water

Evaporating G46092 BH Water

Evaporating G46093 BH Water

Figure 56: PhreeqC mineral precipitation results for lower aquifer boreholes in the Langebaan Road area

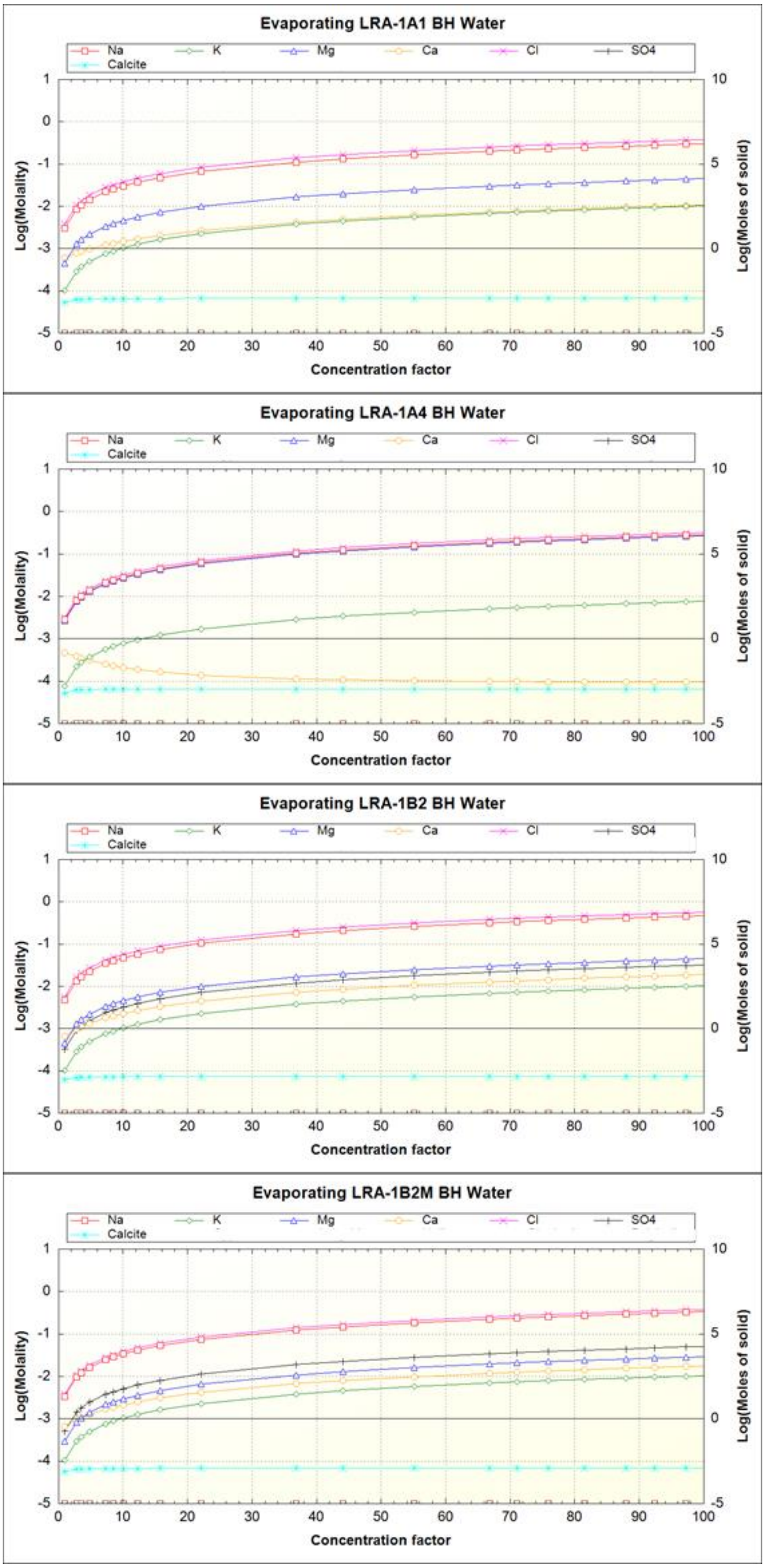
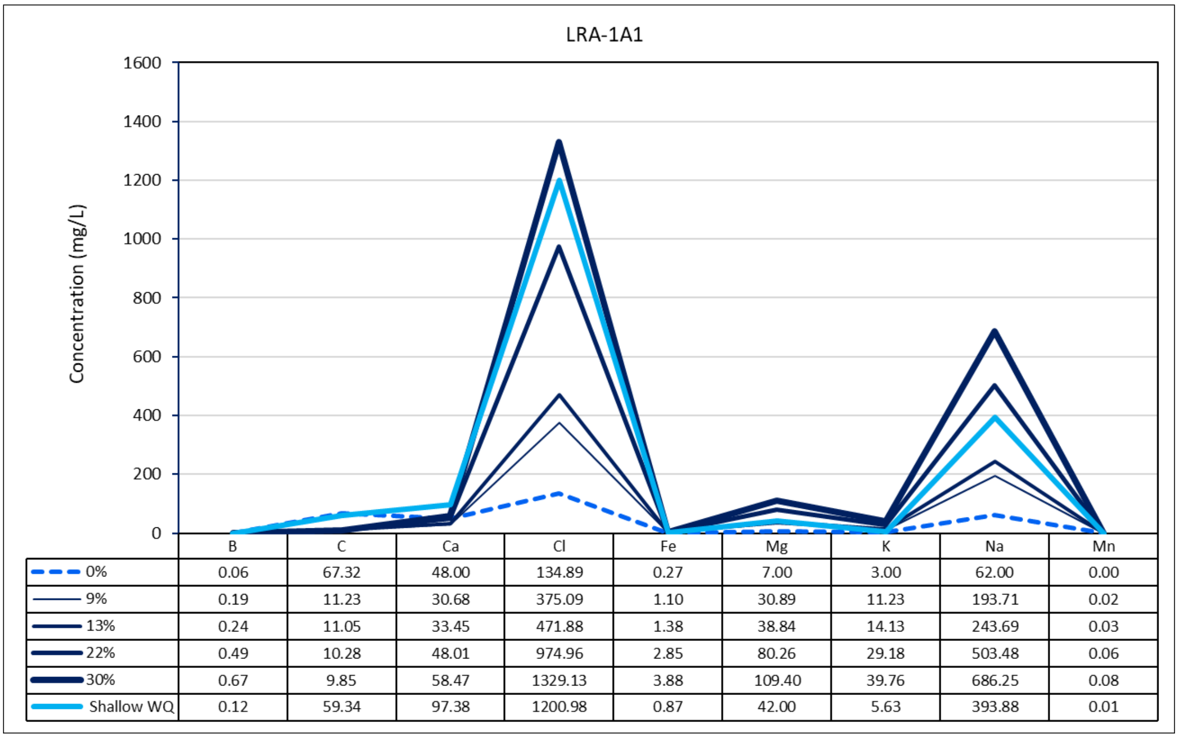


Figure 57: PhreeqC mineral precipitation results for lower aquifer boreholes within the Langebaan Road Wellfield

Changes in the concentration of dissolved salts (Na and Cl), as well as calcium (Ca) and magnesium (Mg) in the groundwater, were also observed to determine at which point the lower aquifer water quality began to resemble the upper aquifer quality. The results are displayed in Figure 58 to Figure 63 below. The light blue line on the figures are representative of the general upper aquifer water quality in the Langebaan Road area. The water quality of five upper aquifer boreholes (LRA-1B3M, G46108, G46106, G46094 and G33323) in the Langebaan Road area was averaged to generate this line.

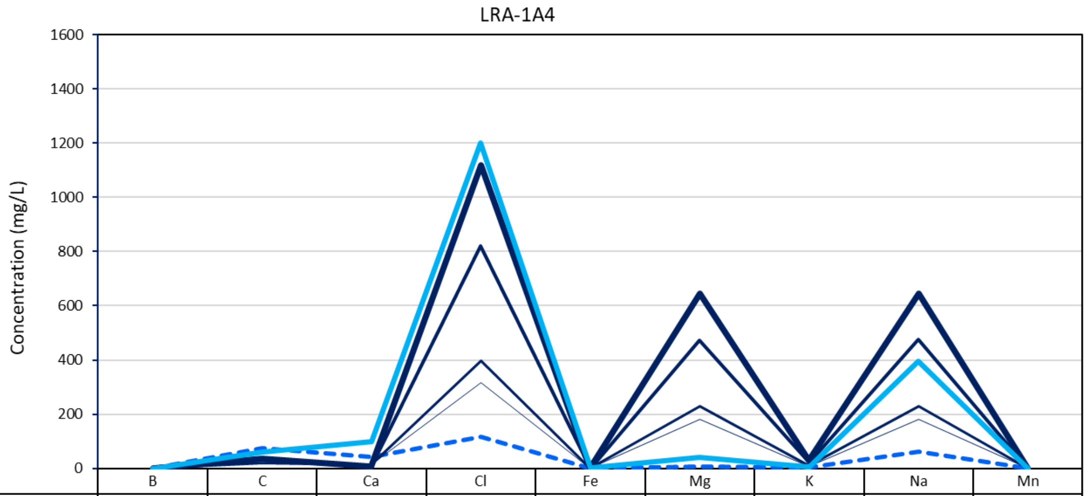
Modelling results indicated that the lower aquifer (Dotted Line) was most likely discharging into the upper aquifer in the Langebaan Road region and that the saline water quality (increased concentrations of ionic compounds) of the upper aquifer, together with the calcrete layers, is most likely due to evaporative processes. Therefore, rainfall is likely to play a minor role in the upper aquifer's available groundwater at Langebaan Road.

Water quality of the Langebaan Road Wellfield boreholes (LRA-1A1, LRA-1A4, LRA-1B2M) and borehole G46061 start to resemble the upper aquifer water quality at 30% evaporation. LRA-1B2 and G46093 begin to resemble the upper aquifer water at approximately 22% evaporation.



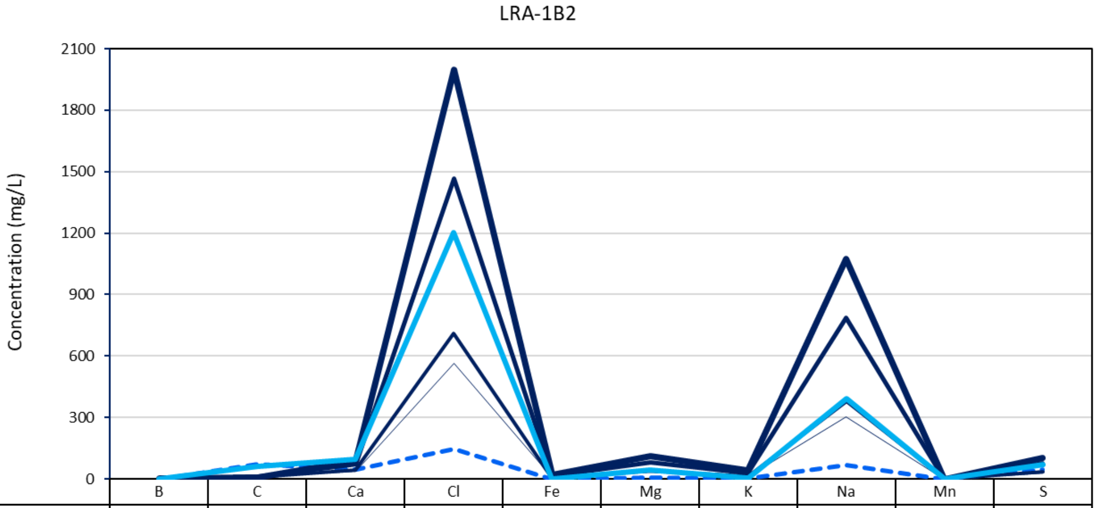
	B	C	Ca	Cl	Fe	Mg	K	Na	Mn
0%	0.06	67.32	48.00	134.89	0.27	7.00	3.00	62.00	0.00
9%	0.19	11.23	30.68	375.09	1.10	30.89	11.23	193.71	0.02
13%	0.24	11.05	33.45	471.88	1.38	38.84	14.13	243.69	0.03
22%	0.49	10.28	48.01	974.96	2.85	80.26	29.18	503.48	0.06
30%	0.67	9.85	58.47	1329.13	3.88	109.40	39.76	686.25	0.08
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01

Figure 58: PhreeqC results for LRA-1A1



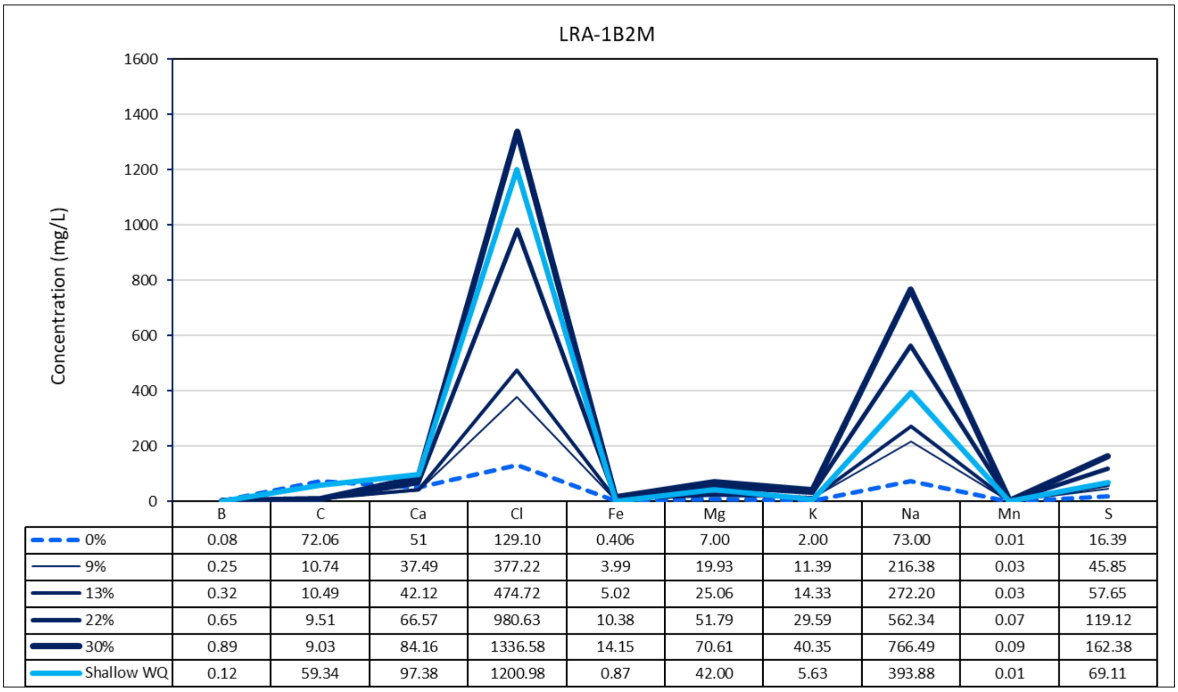
	B	C	Ca	Cl	Fe	Mg	K	Na	Mn
0%	0.07	75.06	42.00	115.78	0.032	6.00	3.00	61.00	0.00
9%	0.18	18.65	15.07	316.13	0.10	182.51	8.42	182.49	0.02
13%	0.23	20.38	13.96	397.78	0.12	229.56	10.60	229.58	0.02
22%	0.47	29.81	9.94	821.45	0.25	474.19	21.89	474.28	0.04
30%	0.64	36.62	8.33	1119.96	0.34	646.51	29.84	646.48	0.06
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01

Figure 59: PhreeqC results for LRA-1A4



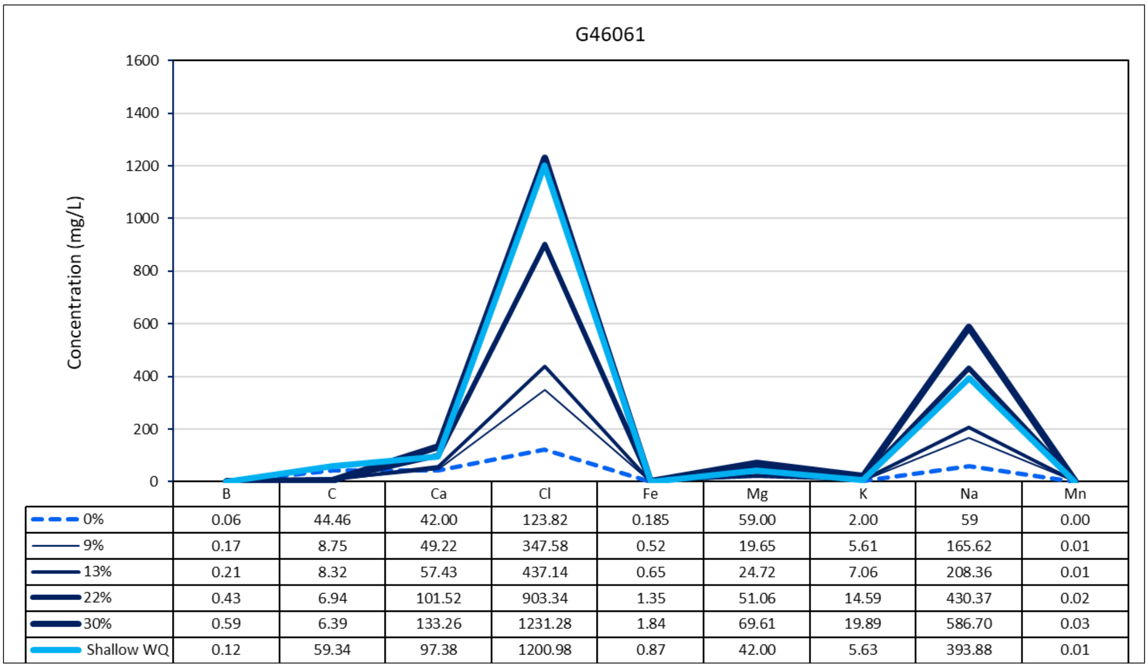
	B	C	Ca	Cl	Fe	Mg	K	Na	Mn	S
0%	0.08	70.86	47.00	145.12	0.353	7.00	3.00	66.00	0.004	44.010
9%	0.27	10.71	38.98	564.06	5.33	30.89	11.23	303.24	0.07	29.04
13%	0.34	10.45	43.97	709.77	6.71	38.86	14.13	381.40	0.08	36.52
22%	0.70	9.44	70.42	1465.98	13.86	80.26	29.19	788.10	0.18	75.45
30%	0.95	8.96	89.45	1998.49	18.89	109.42	39.80	1074.32	0.24	102.86
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01	69.11

Figure 60: PhreeqC results for LRA-1B2



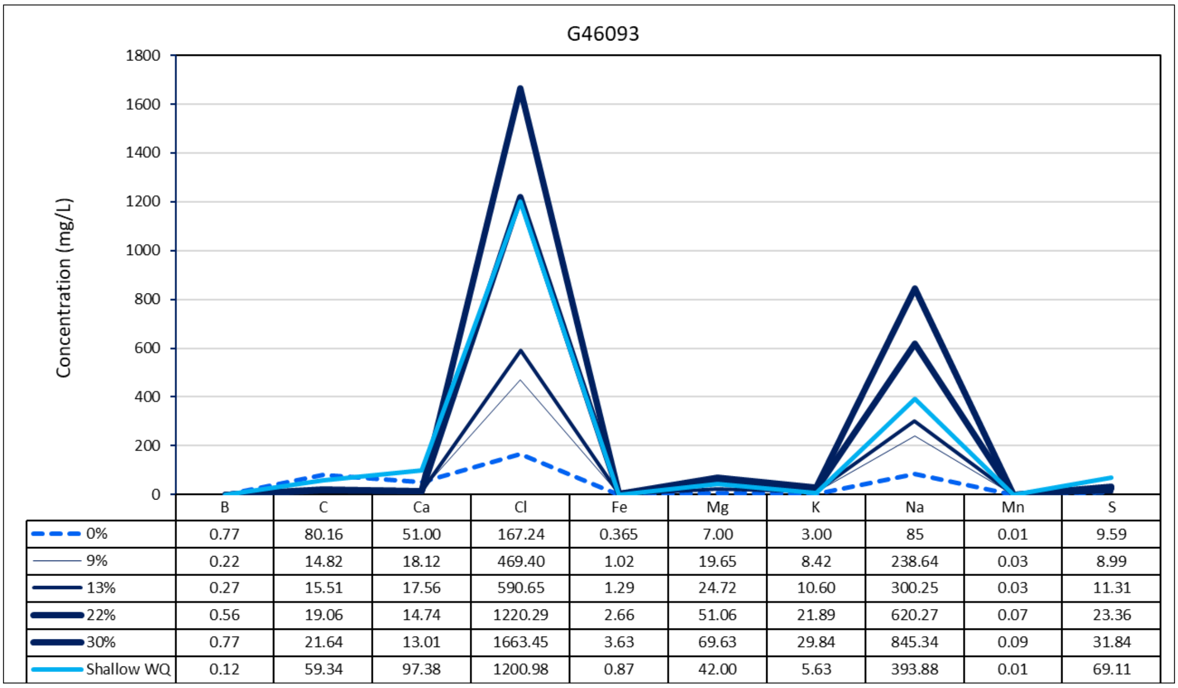
	B	C	Ca	Cl	Fe	Mg	K	Na	Mn	S
0%	0.08	72.06	51	129.10	0.406	7.00	2.00	73.00	0.01	16.39
9%	0.25	10.74	37.49	377.22	3.99	19.93	11.39	216.38	0.03	45.85
13%	0.32	10.49	42.12	474.72	5.02	25.06	14.33	272.20	0.03	57.65
22%	0.65	9.51	66.57	980.63	10.38	51.79	29.59	562.34	0.07	119.12
30%	0.89	9.03	84.16	1336.58	14.15	70.61	40.35	766.49	0.09	162.38
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01	69.11

Figure 61: PhreeqC results for LRA-1B2M



	B	C	Ca	Cl	Fe	Mg	K	Na	Mn
0%	0.06	44.46	42.00	123.82	0.185	59.00	2.00	59	0.00
9%	0.17	8.75	49.22	347.58	0.52	19.65	5.61	165.62	0.01
13%	0.21	8.32	57.43	437.14	0.65	24.72	7.06	208.36	0.01
22%	0.43	6.94	101.52	903.34	1.35	51.06	14.59	430.37	0.02
30%	0.59	6.39	133.26	1231.28	1.84	69.61	19.89	586.70	0.03
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01

Figure 62: PhreeqC results for G46061



	B	C	Ca	Cl	Fe	Mg	K	Na	Mn	S
0%	0.77	80.16	51.00	167.24	0.365	7.00	3.00	85	0.01	9.59
9%	0.22	14.82	18.12	469.40	1.02	19.65	8.42	238.64	0.03	8.99
13%	0.27	15.51	17.56	590.65	1.29	24.72	10.60	300.25	0.03	11.31
22%	0.56	19.06	14.74	1220.29	2.66	51.06	21.89	620.27	0.07	23.36
30%	0.77	21.64	13.01	1663.45	3.63	69.63	29.84	845.34	0.09	31.84
Shallow WQ	0.12	59.34	97.38	1200.98	0.87	42.00	5.63	393.88	0.01	69.11

Figure 63: PhreeqC results for G46093

CHAPTER 6 – NATURAL GROUNDWATER RECHARGE AND DISCHARGE OF THE AQUIFER SYSTEMS

Understanding groundwater flow paths is a prerequisite for the delineation of natural recharge and discharge areas, as groundwater flows from a recharge zone to a discharge zone. The interpretation of results from all recharge investigations carried out in the present study led to the finding that groundwater recharge in the area is a combination of regional and local recharge components. These recharge and discharge mechanisms are further described below:

- **Mountain-front recharge** (MFR) was found to take place at the foot of the Aurora-Piketberg Mountain Range in the north of the study area. MFR is described as the contribution of mountain regions to the recharge of aquifers in adjacent basins. Mountains, due to orographic effects, receive more precipitation than the basin floor. In addition, these areas have lower temperatures, and sometimes a larger surface albedo due to the snow cover, thus reducing the potential for evapotranspiration (ET). Mountains also have thin soils that can store less water, reducing the amount potentially lost by transpiration. Fast flow along bedrock fractures that underlie the thin soil cover may also limit water loss to ET (Wilson and Guan, 2013). The fractures in the TMG mountain can act as preferential pathways that channel water into the downgradient aquifer systems. There are also large weathered mass wasting zones at the foot of the mountain that will slow down fast-flowing storm water, improving infiltration and provide a zone of higher recharge of the underlying aquifer.

  Evidence of areas favourable for mountain front recharge (MFR) was seen in the TDEM airborne geophysical results displayed in cross-section 2 (Figure 40) where recharge takes place at the base of the Aurora-Piketberg Mountain Range after which the groundwater flows underneath the Berg River towards Saldanha Bay. Furthermore, infiltration tests carried out on the TMG sands indicate a high infiltration rate of 2.17 – 3.03 m/day, which shows that the high lying mountainous area north of Saldanha Bay is favourable for recharge. Groundwater levels of boreholes 37-1 and 37-2 situated at the top of the Aurora-Piketberg Mountain Range displayed an almost immediate response to rainfall in the area (Figure 30), further proving this to be a recharge zone. Stable isotopic signatures of rainfall on the mountain range were depleted and similar to groundwater in the study area, and tritium values of boreholes in this area have a signature of present-day rainfall which is an indication of recharge from modern day precipitation. The aforementioned results further indicate the likelihood of the high-lying mountain ranges being a regional source of groundwater to aquifer systems.

- **Granite Hill Recharge** was found to occur at the base of granite hills in the area between Geelbek and Langebaan, where intrusive granitic plutons are responsible for the raised highlands and koppies. Sands thin out where bedrock rises, which increase the recharge potential to bedrock fractures that carry water into the aquifer. Several ephemeral streams emanate from the granite hills after heavy rain. The runoff from rainfall tends to accumulate at the foot of hard rock granite hillslopes leading to oversaturation of the local zone at the base of the granite koppies. This is a focused recharge process where groundwater recharge occurs mainly in water-filled joints, fractures, and zones of weathering. Recharge to these features relates to the presence of higher porosity material such as weathered regolith and adjacent alluvium, which acts as a reservoir that slowly feeds water down towards the aquifer. The tritium signatures additionally show that boreholes in the vicinity of granite hills (G33313, BG00074 and G46108) in the area had signatures similar to that of the present-day tritium input of 1.6 TU. This is similar to the granite hill recharge identified by Smith (2020) who conducted a recharge study in the Elandsfontein Aquifer.

  The geophysical results provide evidence of potential groundwater flow paths, postulated from the granite hills towards the Langebaan Road wellfield and the Berg River in cross-section 1 (**Figure 39**) and cross-section 2 (Figure 40).

- **Moorreesburg Recharge:** This is a regional recharge process that is most likely occurring through rapid recharge from rainfall on the high lying Moorreesburg area. Rainfall in this region falls on dolomitic outcrops of the Bridgetown Formation. The dolomitic bedrock allows for preferential flow and a groundwater pathway towards the aquifer systems contained within the Saldanha Bay Local Municipality area.

  Evidence of this process was first seen in the geophysical results where groundwater of very good quality (12 – 30 mS/m) was observed in the vicinity of the Moorreesburg area. This region of good quality water was situated very close to the aquifer under investigation in the Elandsfontein region of the study area. A dolomitic borehole north of Moorreesburg was sampled and it was found that the tritium signatures of the groundwater in this area were approximately 0.9 TU, which was very close to the tritium input thus, suggesting that the region may contribute to the recharge of the aquifer systems.

- **The main discharge zones** for the area were found to be the Langebaan Lagoon, Berg River and the Atlantic Ocean. Aquifer zones with high salts (EC = >200 mS/m) are expected to be a result of evaporation and are considered groundwater discharge zones. PhreeqC modelling results suggested that discharge of the lower aquifer to the upper aquifer takes place in the Langebaan Road area where evaporation takes place resulting in the salinization of the water and precipitation of calcrete (Figure 54).

- **A combined conceptual model** of groundwater flow was generated for the Aquifer Systems (Figure 64) using all results from investigations that took place during this study. The findings of this study suggest that the main flow direction is from the recharge at Aurora-Piketberg Mountain Range and the Bridgetown Formation, flowing towards the Berg River and Hopefield. Some of the flow then moves from Hopefield to the Langebaan Road Wellfield. The groundwater flowing from Hopefield to Langebaan Road is seen to discharge into the Berg River with the rest of the water passing through Hopefield contributing to the primary aquifers, where some of it gets evaporated causing saline upper aquifers and, ultimately discharging into the Langebaan Lagoon.

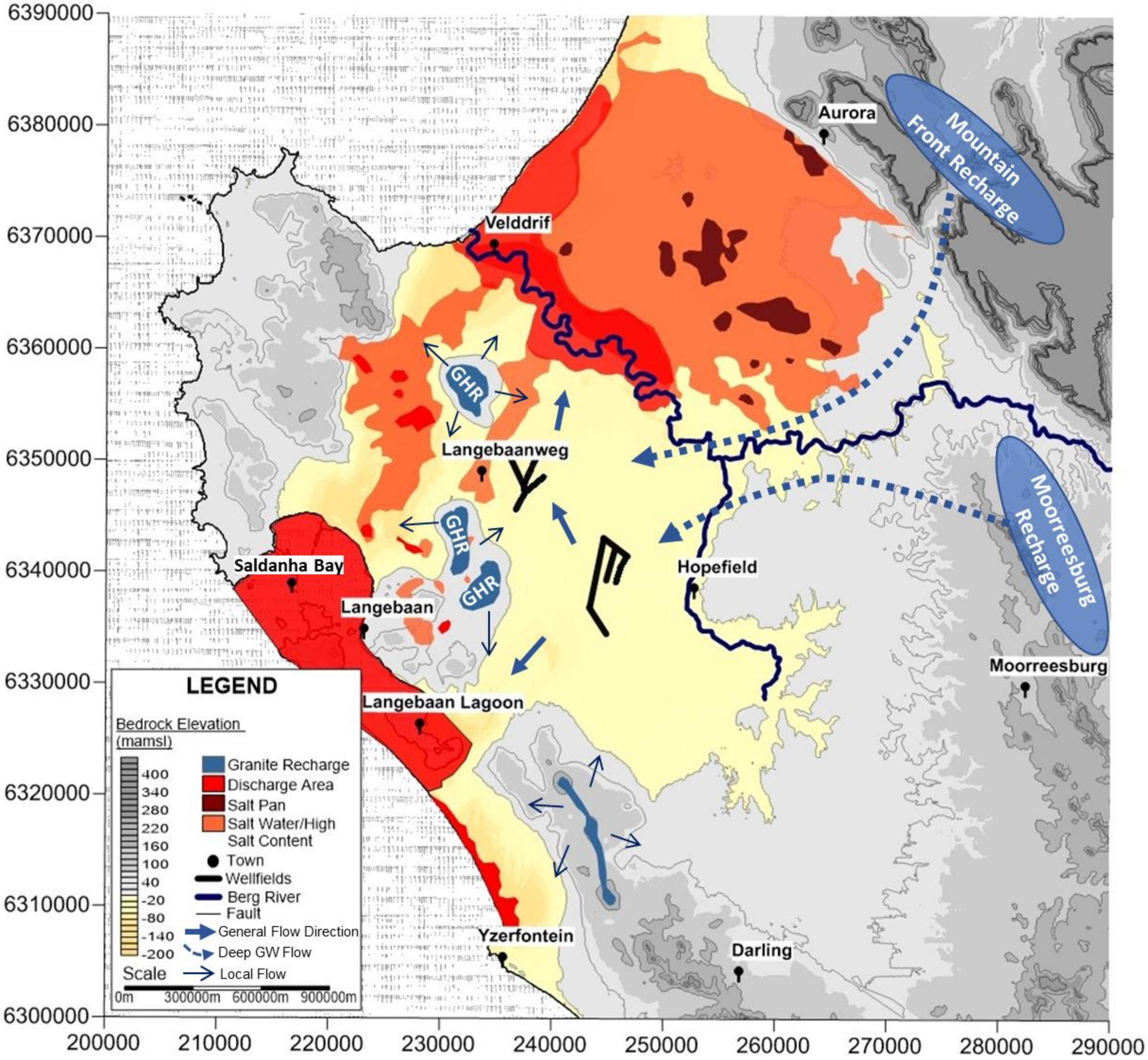


Figure 64: Groundwater flow paths, recharge and discharge zones of the Aquifer Systems contained within the Saldanha Bay Local Municipality area

CHAPTER 7 – CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The purpose of this chapter is to combine and conclude all the findings that were achieved through the objectives of this study, which aimed to identify recharge sources as well as recharge mechanisms and flow paths of the Aquifer Systems contained within the Saldanha Bay Local Municipality area. The objectives were achieved as follows:

1. The aquifer's geological layers and extent was identified using Time Domain Electromagnetic (TDEM) Airborne Geophysics. The geophysical survey results allowed for the mapping of the bedrock elevations, which indicated preferred groundwater pathways (low bedrock elevation). It also helped to delineate the thickness and extent of the saturated sands, indicating where there is usable groundwater in the study area. Due to the TDEM waves propagating differently in saline water, compared to freshwater, relative water quality could therefore be inferred, which assisted with the assessment of natural recharge processes. The Airborne Magnetic and Electrical methods provided information on the bedrock geology underlying the sand in the area, which was important to evaluate the regional groundwater flow paths and characteristics. It was found that the main aquifers in the area known as the Langebaan Road and Elandsfontein aquifer formed a continuum and had the same recharge source.

2. The groundwater flow paths of the aquifer systems in the study area were delineated using different water quality methods. These included hydrochemical (Boron, Carbon, Calcium, Chloride, Iron, Potassium, Magnesium, Manganese, Sodium and Sulphur), stable isotope (δ^2H and δ^{18}O) and tritium (^{3}H) analyses. Stable isotopes δ^2H and δ^{18}O signatures of the groundwater in the Saldanha Bay Local Municipality area were found to be similar to δ^2H and δ^{18}O signatures of the rainfall on the Aurora-Piketberg Mountain Range. Tritium values of groundwater in the Moorreesburg region showed that this area was most likely a recharge source as values of groundwater were very close to the present-day tritium input of 1.6 TU. High tritium values close to the input was also found in boreholes situated close to granite outcrops. When the hydrochemical and isotopic data were interpreted together, it was found that the main groundwater flow direction was from the Aurora-Piketberg Mountain Range and Moorreesburg area towards Hopefield via deep groundwater flow. Most of the groundwater then moves from Hopefield and discharges into the Lagoon. The groundwater that does not flow to the Lagoon discharge zone, flows towards, and passes Langebaan

Road after which it discharges into the Berg River. Groundwater was also found to flow from granite hills, towards the Langebaan Road wellfield and then discharging into the Berg River.

3. The different recharge mechanisms taking place in the study area was inferred using long-term groundwater level assessments, infiltration tests and PhreeqC evaporation modelling. Groundwater level assessments showed that there is no response in groundwater levels to local rainfall, suggesting an indirect recharge process. Infiltration test results supported this theory as findings showed that infiltration at Langebaan Road was very slow, due to very fine sands and solid calcrete layers, which inhibit infiltration from rainfall. Results also showed that local rainfall is unlikely to recharge groundwater in the Hopefield region due to thick, dry sands and deep groundwater levels. PhreeqC modelling results indicated that the lower aquifer in the Langebaan Road region discharges into the upper aquifer and that the salinity of the upper aquifer in this area is due largely to evaporative processes.

All investigations carried out in the present study allowed for the research question to be answered. The main recharge areas were found to be the high lying mountain ranges that surround the study area as well as the high lying Moorreesburg region, which brings groundwater to Saldanha Bay Local Municipality area through indirect, deep flow. On a smaller yet significant scale, it was found that direct recharge through local rainfall takes place at the foot of granite hills and that the main discharge zones were found to be the Langebaan Lagoon and the Berg River.

7.3 Limitations of study

- The ability to conduct fieldwork was limited by the national lockdown due to the Covid-19 Pandemic. Due to this, only two field trips took place, one for the wet season and one for the dry season.
- The postulated Moorreesburg recharge area could not be fully assessed due to very few boreholes in the area as well as limited information on the boreholes that were found.

7.2 Recommendations for future research

Due to limited borehole information in the Moorreesburg area and very few boreholes, it is recommended that further studies should include drilling of monitoring boreholes in the area to understand the Moorreesburg recharge zone more comprehensively. It is also recommended that an attempt to quantify recharge should take place within the area to get a more detailed picture of the regional groundwater recharge processes and flow.

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