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Assessing the hydrogeologic characteristics and sources of groundwater recharge and flow in the Elandsfontein aquifer, West Coast, Western Cape, South Africa

By

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Dissertation submitted to the University of the Western Cape in the fulfilment of the degree of Master of Science

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Abstract

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MSc Thesis

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Key Words: Coastal Aquifer, Recharge Processes, Groundwater Flow Mechanisms, Cumulative Recharge Departure, Stable Isotopes, Chemistry, Conceptual Model.

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Abstract:

This study is part of the current investigation of the Elandsfontein aquifer to assist with the management of the system and to ensure the protection of the associated Langebaan Lagoon RAMSAR listed site. The Elandsfontein aquifer unit is situated adjacent to the Langebaan Road aquifer in the Lower Berg River Region. The aquifer unit is bordered by the Langebaan Lagoon (west), possible boundary toward the Langebaan Road aquifer (north), the Groen River bedrock high (south-east) and the Darling batholith (south). The aim of the study is to characterise and conceptualise groundwater recharge sources and flow processes of the Elandsfontein Aquifer System (EAS). This study evaluated groundwater flow paths and recharge processes using the Cumulative Rainfall Departure (CRD), hydrochemical descriptors (major ion) and stable isotope $\delta^{2}H$ and $\delta^{18}O$ methods. Furthermore, the boundaries of the different aquifers and aquitards (Elandsfontein

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clay layer) in the EAS and their relationship with the Langebaan Lagoon were investigated.

The research study included 22 Department of Water and Sanitation (DWS) monitoring geosites whereby a field programme commenced from June 2015 to May 2016. Over a period of four seasons, 22 groundwater samples from boreholes and rain water samples were collected from 3 cumulative rainfall collectors. Three isotope samplers were also installed next to the DWS rainfall stations on the Elandsfontyn farm 349 (rainfall station BG00074-RF), Hopefield Private Nature Reserve (rainfall station G46024-RF) and Mountain Mist on the Piketberg mountain range (rainfall station G10K1-RF).

Scientific methods applied in the thesis included a modified version of the CRD that consisted of a short and long term memory of the EAS. Furthermore, using the CRD method provided a representative reconstruction of the long term groundwater level trends that was simulated using short term seasonal rainfall totals with reference to longer term average rainfall over the entire time series of 2007-2016. The CRD analysis proves that both short and long term memory responses to water level are present in the EAS. A direct recharge mechanism occurs for local rainfall processes within the area, whereas a delayed recharge mechanism could be seen as the predominant source of regional groundwater flow from the Paarl high lying area to the system.

The hydrochemical analyses are presented using qualitative methods such as time series Piper and Stiff diagrams. Macro elements analysis for the monitoring of boreholes and rainfall stations was analysed over a period of one hydrological year. These analyses show the water type characterisation for Elandsfontein to be of a mixed water type whereby the dominant anions and cations were Na-Cl, mixed Ca^2-Mg^2-Cl, Ca^2-Na-HCO_3-Cl, Na-HCO_3-Cl and Ca^2-Na-Cl. The Geelbek water type characterisation consisted also of Na-Cl and mixed Ca^2-Mg^2-Cl. The isotope composition of the groundwater and rainfall was used to establish whether recharge was immediate or delayed. The stable isotope δ^2H and $\delta^{18}O$ values

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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.

The development of a conceptual model for the EAS incorporated geological logs, CRD simulations, hydrochemistry (major ions) and stable isotopes $\delta^{2}H$ and $\delta^{18}O$. The model was constructed to assist with the management of the complex relationships between the recharge areas, flow paths through the different aquifer layers and aquitards towards the Langebaan Lagoon discharge area. The results are envisaged to contribute to knowledge on groundwater flow processes and quality to inform decisions regarding water resource protection, utilisation and associated ecosystems.

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Declaration

I, Kezia Smith declare that project title **Assessing the hydrogeologic characteristics and sources of groundwater recharge and flow in the Elandsfontein aquifer, West Coast, Western Cape, South Africa** is my own 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 acknowledge by complete references.

Full name: Kezia Smith

Date: July 2020

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Signed: _____

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I can do all things through Christ who strengthens me.

I would therefore like to give all thanks to my Saviour Jesus Christ for directing and providing me with the knowledge and perseverance to complete my Master's dissertation. He truly was my rock and fortress throughout this journey and I am sincerely grateful.

This thesis would not have been possible without the assistance and contribution of many individuals and organizations. I would like to acknowledge my debt of appreciation and sincerest thanks to the following:

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Abbreviations and Acronyms

CGS	Council for Geoscience
CSIR	Council for Scientific and Industrial Research
CRD	Cumulative Rainfall Departure
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EAS	Elandsfontein Aquifer System
GMWL	Global Meteoric Water Line
IAEA	International Atomic Energy Agency
LRAU	Langebaan Road Aquifer Unit
LRAS	Langebaan Road Aquifer System
LAU	Lower Aquifer Unit
NGA	National Groundwater Archive
OA-ICOS	Off-axis Integrated Cavity Output Spectroscopy
RAMSAR	Convention on Wetlands of International Importance Especially as Water Fowl Habitat
SANBI	South African National Biodiversity Institute
SANAS	South African National Accreditation System
SAWS	South African Weather Service
SGWCA	Subterranean Government Water Control Area
SLAP	Standard Light Antarctic Precipitation
UAU	Upper Aquifer Unit

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USA	United States of America
UWC	University of the Western Cape
VSMOW	Vienna Standard Mean Ocean Water
WCNP	West Coast National Park
WMA	Water Management Area
km	kilometres
m	metres
mm	millimetres
mbgl	metres below ground level
mamsl	metres above mean sea level
R^2	coefficient of determination

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CHAPTER 1
GENERAL INTRODUCTION

1.1 Introduction

The West Coast in the Western Cape of South Africa is a water-scarce area and is demarcated as a semi-arid region. Semi-arid regions represent 30% of global terrestrial surface area and are continuing to expand due to climate change. Groundwater is identified to be one of the alternative water sources in semi-arid areas as the dependence on surface water resources has become limited in these regions (Scanlon et al., 2006). The Elandsfontein aquifer is located in the southern part of the West Coast which is one of the protected groundwater resource areas situated in the Lower Berg River Valley/Saldanha Subterranean Government Water Control Area (SGWCA). The Saldanha SGWCA was declared on 10 September 1976 whereby the Lower Berg River Valley SGWCA was an expansion of the Saldanha SGWCA. Therefore, this proclamation was put in place for provision of future large scale groundwater development and urban supply in the West Coast (Timmerman, 1985). The groundwater control area was declared for future water supply to Saldanha and surrounding towns with limited surface water supply.

According to Jiao and Post (2019), human activities are increasingly influencing coastlines and their ecosystems. The increasing population growth in coastal areas results in great pressure on coastal aquifers to meet the water demand of these areas (Neumann et al., 2015). Little is known about the potential of coastal aquifers along the West Coast to provide water for human consumption and industrial development. Furthermore, there is less known published and gray literature on knowledge about the dependence of coastal ecosystems on fresh aquifer water along the southern west coastline of South Africa. The Langebaan Lagoon forms part of the West Coast National Park and is located in the southern region of the West Coast.

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A direct connection between the Elandsfontein aquifer and Langebaan Lagoon has always been assumed, however, more research is needed to understand the flow of groundwater from the Elandsfontein Aquifer System (EAS) into the lagoon. The research will contribute to assist with solving the uncertainty in groundwater discharge volumes and flow processes. This may lead to ineffective groundwater resource management if the EAS and its hydrogeologic characteristics are not fully understood. Without adequate understanding of groundwater recharge, flow and discharge processes in the EAS; protection of the groundwater resources and the lagoon with its surrounding ecological dependent ecosystems cannot be managed conservatively and sustainably. Therefore, it is important for stakeholders such as SANParks and Department of Water and Sanitation (DWS) to develop a better understanding of the system to prevent negative impacts on the aquifer and Langebaan Lagoon due to development.

The Langebaan Lagoon was declared a RAMSAR wetland in 1998 and is known to be of high ecological significance (IBA No 105, Barnes 1998). The vegetation seen in the lagoon is in fact typical of an estuary (Whitfield, 2005); therefore the lagoon may be considered an aquifer-fed estuary.

The Langebaan Lagoon is not predominantly fed by overland rivers, only few small, seasonal streams enter the lagoon but no other surface runoff is visible (Weaver and Wright 1994). This is supported by Allanson et al. (1999), who stated that 'the Langebaan marine embayment is not influenced by river inflow of any magnitude but rather by an exceptional resource of fresh groundwater inflow'.

1.2 Study aim and objectives

The main aim of the study was to characterise the groundwater recharge sources and flow processes of the Elandsfontein Aquifer System.

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Specific objectives of this study were to:

- Establish groundwater recharge mechanisms using the Cumulative Rainfall Departure (CRD) method.
- Identify groundwater flow paths and recharge mechanisms using chemical tracers such as hydrochemistry and stable isotopes ($\delta^{2}H$ and $\delta^{18}O$).
- Develop a conceptual model of the Elandsfontein Aquifer System.

1.3 Outline of the thesis

This research study consists of 8 chapters and is structured according to the logic progression that forms the basis of the study. 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 literature that identifies gaps in knowledge on a global and local scale and it addresses the two major objectives that briefly discussed the different application tools to estimate groundwater flow and sources of groundwater recharge mechanisms. Chapter 3 provides an overview of the study geographical location, catchment characteristics and hydrogeology. Chapter 4 provides the description of the study sites, the methods and materials along with the experimental setup used to achieve the study objectives. The results and discussion form Chapters 5 and 6, which provide the results attained from the use of the CRD method, chemical and isotopic methods. Chapter 7 provides a conceptual model of the overall groundwater recharge and flow in the Elandsfontein aquifer. Lastly, Chapter 8 concludes and outlines the recommendations for management and future studies.

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CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter aims to provide a theoretical overview of groundwater movement in coastal aquifers commencing from the groundwater recharge sources to discharge zones. It will introduce scientific concepts that will characterise groundwater recharge and flow processes in the Elandsfontein aquifer and its discharge to the Langebaan Lagoon. Furthermore, a description of various qualitative methodologies and applications of groundwater recharge, hydrochemistry and stable isotopes will be assessed to assist with the investigation of coastal aquifers in the southern West Coast area.

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'Groundwater is an integral part of the Earth's hydrologic cycle or movement of water between oceans, atmosphere, and land' (Kresic, 2006:7). In low lying coastal zones in the western part of South Africa lagoons and wetlands are formed where low rainfall is experienced. Coastlines are comprised of beaches, dunes, mangroves, salt marshes, hills or cliffs and are regarded as high biologically diverse areas as a result of interface between freshwater and marine saline ecosystems. Coastal aquifers are considered complex due to its multi-layered aquifer and aquitard system, a full groundwater regime is important to understand these aquifer and aquitard systems factoring in recharge and discharge areas. Large areas may be under tidal influence, causing seawater in estuaries to penetrate tens of kilometres up streams (Jiao and Post, 2019). According to Jiao and Post (2019), aquifers and aquitards discharge relatively fresh water to streams, rivers, lakes, marshes, estuaries and to oceans as represented in Figure 2.1.

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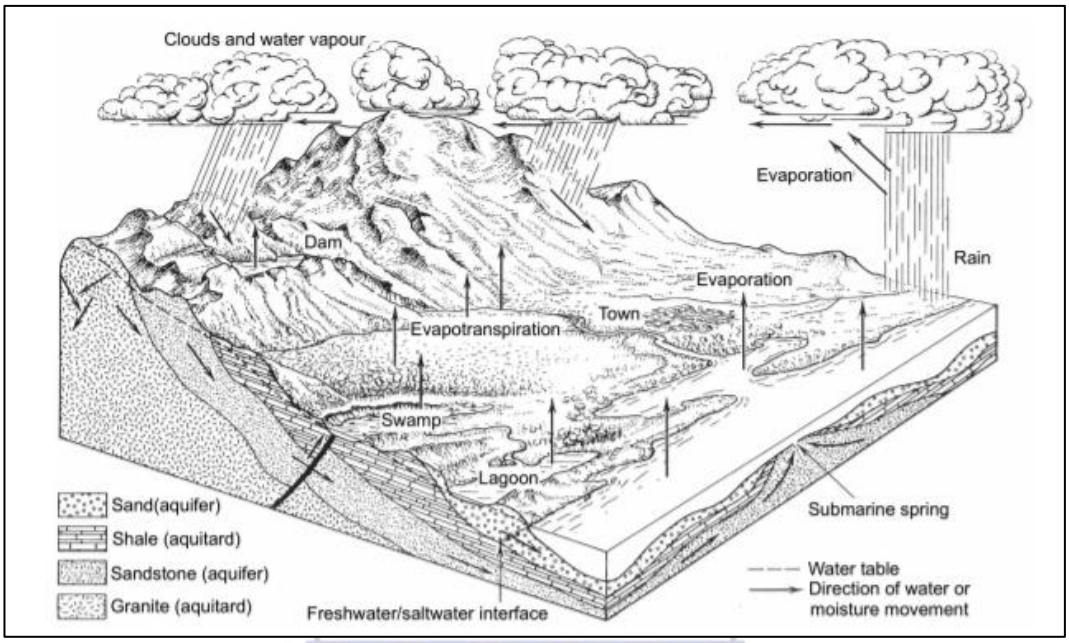

Figure 2.1: The hydrological cycle for a coastal area. In a natural coastal environment, groundwater flows into the sea by diffuse discharge or concentrated springs, located either along the coastline or in the seabed. The focal points for discharge are outcrops of a confined aquifer or fracture of fault zones (Jiao and Post, 2019).

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2.2 Groundwater recharge

Groundwater recharge is defined as 'the downward flow of water reaching the water table, adding to groundwater storage' (Healy, 2010:3). However, groundwater recharge does not include interaquifer flow also known as groundwater underflow and is recognized as water flow from an unconfined aquifer flowing across a confining bed to a semi-confined or confined aquifer. Groundwater recharge is a key component in any model of groundwater flow or contaminant transport. Accurate quantification of recharge rates is imperative for proper management and protection of valuable groundwater resources. In semi-arid and arid environments recharge studies are important where groundwater is known to be the primary water source and susceptible to depletion (De Vries and Simmers, 2002).

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2.2.1 Recharge mechanisms

'Semi-arid areas are characterised through the occurrence of direct and indirect recharge' (Lloyd 2009:286). Whereby, recharge occurs through direct/diffuse and localized/focused mechanisms (Figure 2.2). The three principal recharge mechansims defined by Lerner et al., (1990) are direct recharge, indirect recharge and localized recharge. Direct/diffuse recharge is distributed over large areas in response to precipitation infiltrating the soil surface and evapotranspiration by percolating vertically through the unsaturated zone to the water table (Healy, 2010). Indirect recharge results into percolation of water contributing to the water table through riverbeds and surface watercourses (Beekman and Xu, 2003), and localized/focused recharge is an indirect form of groundwater recharge resulting from the ponding of surface water in the absence of well-defined channels of flow (Healy, 2010). According to Healy (2010), variation of recharge mechanisms differs from region to region and localized sites within these areas and these regions could encounter direct/diffuse and localized/focused mechanisms, which are not restricted to one type of mechanism.

Lloyd (1986) argued that in arid areas where the basic recharge mechanisms are reasonably delineated, there are deficinecies in quantifying the elements especially in areas where data is scarce. Therefore, this is evident of the area between the Cederberg/Paarl inland and Geelbek, Langebaan Lagoon at the coast.

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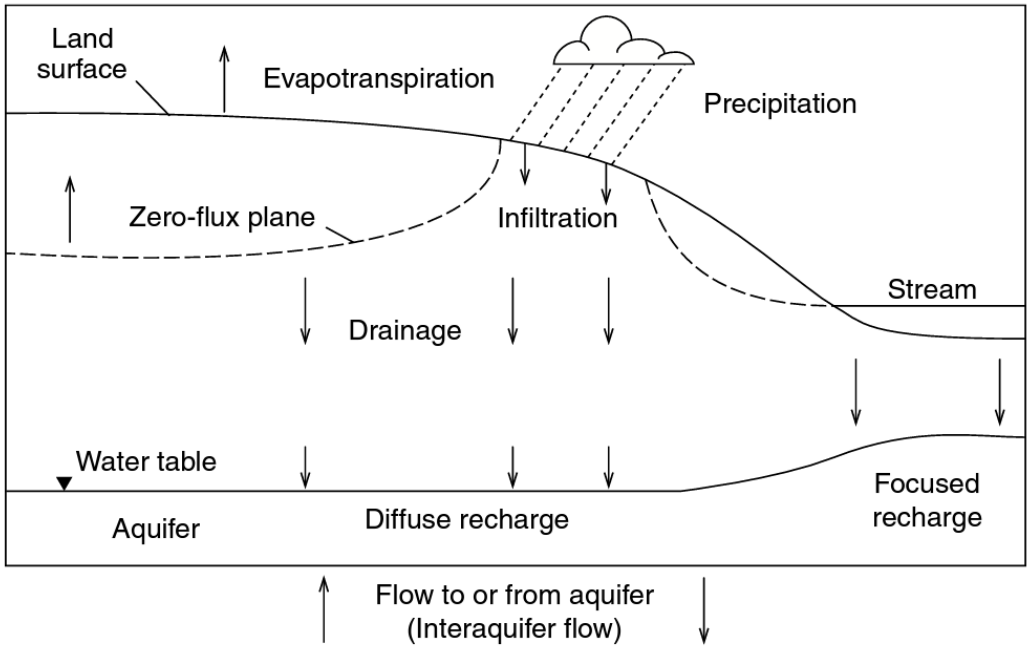

Figure 2.2: A vertical cross section displaying infiltration at land surface, drainage through the unsaturated zone, diffuse and focused recharge to an unconfined aquifer, flow between the unconfined aquifer and an underlying confined aquifer (interaquifer flow) and the zero-flux plane (Healy, 2010).

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2.2.2. Recharge estimation techniques

Various recharge estimation techniques are available for quantifying groundwater recharge in available recharge literature suggesting quantifying recharge in semi-arid environments is often difficult. According to Scanlon (2004), these difficulties are due to complex processes and factors including spatial variability in topography, geomorphology, geology and the temporal variability in climate. 'Techniques for evaluating recharge based on surface water, unsaturated zone, or groundwater data, including physical, chemical, isotopic, and numerical modelling approaches' (Scanlon, 2004:235), can be applied for estimating recharge and reduce uncertainties of each technique to better understand recharge sources and processes.

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2.2.2.1 Natural tracer method

The isotopic tracer method which provides information on recharge sources can be used to estimate recharge in semi-arid areas. However, it is generally difficult to quantify recharge rates due to isotopic signatures comprising of various mixing ratios of different aquifer systems could result in similar δ^2H and $\delta^{18}O$ values (Scanlon, 2004). It should be noted that stable isotopes are useful for processes and origins but not applicable to providing quantitative recharge estimates because they are non-conservative and are subject to fractionation by evaporation (De Vries and Simmers 2002).

Stable isotopes of δ^2H and $\delta^{18}O$ can be used to identify recharge from the source, evaporation rates and flow processes in unconfined and confined aquifer systems. According to Bredenkamp et al. (1995), groundwater in semi-arid regions is found to have more depleted δ^2H and $\delta^{18}O$ values than surface water. For this reason a higher depleted signature is characteristic of groundwater deriving from prolonged and intense rainfall events. 'The recharge could also have orginated from higher rainfall during a previous pluvial period' (Bredenkamp et al., 1995:231).

2.2.2.2 Water balance method

The Cumulative Rainfall Departure (CRD) method can be applied to the saturated and unsaturated zones in a semi-arid environment. The CRD is based on the principle that the water level response from recharge is proportional to the cumulative rainfall departure, indicating that groundwater level fluctuation is triggered by rainfall events (Beekman and Xu, 2003).

Bredenkamp et al. (1995) demonstrated that the CRD series corresponds remarkably well with the fluctuations of the groundwater level. Whereby the rationale behind the departure method is that in any area, despite large annual variations in precipitation, equilibrium is established between the average annual

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precipitation and the hydrological response (run-off, recharge and losses from the system).

The CRD series is represented by the following mathematical equation (Bredenkamp, et al., 1995):

$$\frac{m}{n}\ CRD_i = \left[\frac{1}{m}\sum_{j=i-(m-1)}^{i} Rfj\right] - \left[k \times \frac{1}{n}\sum_{j=i-(n-1)}^{i} Rfj\right] + (CRD_{i-1}) \quad \text{Equation 2.1}$$

Where: m represents the number of months denoting the short term memory carry-over e.g. 1, 6, 12, 18, 24 months' rainfall average values and n the number of months for which the long term reference rainfall is calculated (long term memory) e.g. 1, 3, 5, 7, 10 years' rainfall average preceding a specific month.

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The CRD reflects the outcome of the natural balance of groundwater due to the combined effects of both recharge and losses from the system. By which is commonly accepted that under natural conditions and in the absence of abstraction, a dynamic balance between recharge and drainage in an aquifer is established (Bredenkamp et al., 1995).

Bredenkamp et al. (1995) further demonstrated that an improved correlation is attained between the groundwater level fluctuations if the cumulative rainfall departures are calculated relatively to the moving average rainfall over the preceding years. In terms of the CRD approach this implies that as the average rainfall changes, the total water balance is adjusted. Therefore, the aquifer responds differently during prolonged wet and dry rainfall cycles and the system adapts to the prevailing conditions. Many aquifers indicate a delayed (time lag) in groundwater response to rainfall and can incorporate carry-over of recharge from year to year, resulting in long term memory representing the period over which the long term reference rainfall is calculated. Conversely, short term memory represents the period over a short term reference rainfall.

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2.3 Groundwater movement

Movement of water in coastal aquifers mostly flows towards the sea due to a positive hydraulic gradient set up by the balance between recharge inland and discharge to the estuary or ocean. The quantification of groundwater flow in aquifers can be derived from Darcy's law whereby hydraulic conductivity 'the permeability of a given rock with respect to fresh groundwater' is considered to be one of the most important physical properties used for groundwater flow quantification (Younger, 2007:50). Recharge areas are commonly found in topographical high areas, whereas, the discharge areas are situated in topographic lows where the water table is found to be near or at the land surface at discharge zones (Fetter, 2000). Freeze and Cherry (1979) came to the conclusion that flow lines transport groundwater from high altitude recharge areas to low altitude discharge areas.

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Toth (1963) derived three forms of groundwater flow systems which were divided into local, intermediate and regional flow systems (Figure 2.3). Local flow systems form where topographic areas receive high precipitation whereby 'the higher the relief, the deeper the local systems' (Toth, 1963). These systems are also known to be the shallowest and have the highest interchange with surface water bodies (Winter et al., 1998). Local systems flow to discharge zones of stagnant areas allowing the formation of intermediate and regional systems which are underlain by local flow systems (Toth 1963; Winter et al. 1998). Regional flow systems are regarded to be deeper and longer flow paths that discharge relatively freshwater to streams, rivers, lakes, marshes, estuaries and to oceans (Winter et al., 1998).

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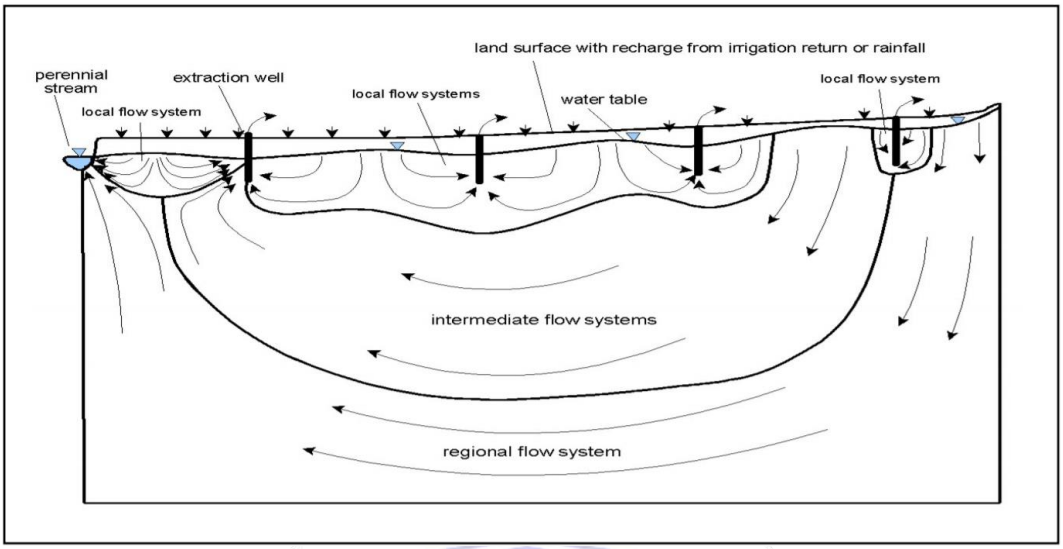

Figure 2.3: After Toth 1963 local, intermediate and regional systems of groundwater flow (Harter, 2001).

Previous studies of coastal terrain for local and regional systems located in the east-central and southern coasts of the USA are alike to those identified in the West coast study area. Figure 2.4 displays the conceptual model for these systems to be from high altitude areas identified as scarps and terraces that discharges into the ocean. The formation of these topographical features originated when the ocean bed was higher as to present oceanic bedrock. The model also identifies ocean tides affecting streams, estuaries and lagoons and ponding of freshwater associated by coastal sand dunes and barrier islands. Groundwater and surface water interaction of coastal terrains can be affected by aquifers discharging in freshwater surface bodies, through regional flow systems derived from inland and local systems associated with scarps and terraces (Winter et al., 1998).

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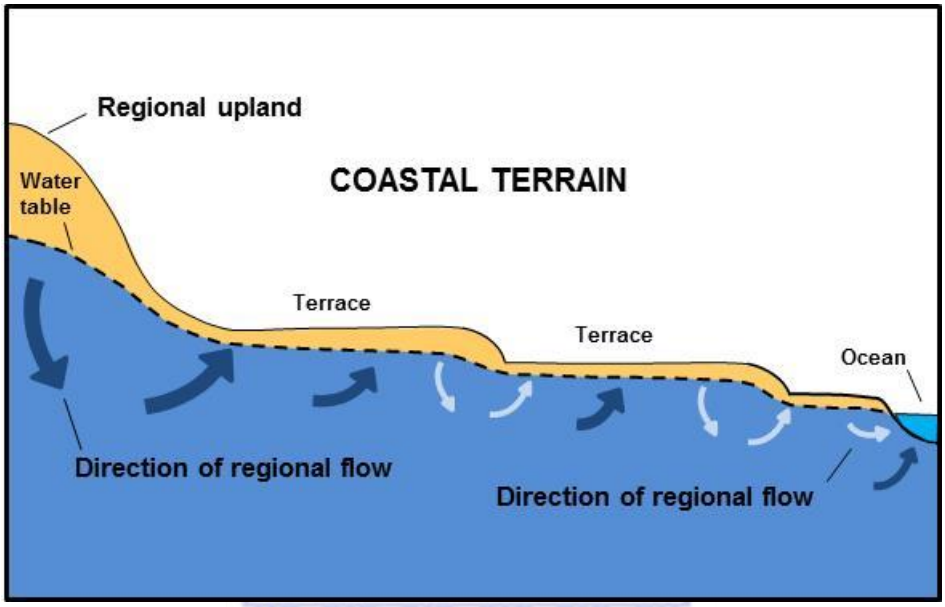

Figure 2.4: Illustrates the conceptual model in a coastal terrain, where small local groundwater flow cells are associated with terraces that overlie regional groundwater flow systems. In the tidal zone, saline and brackish surface water mixes with fresh groundwater from local and regional flow systems (Winter et al., 1998).

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2.4 Coastal hydrochemistry

Winter et al., (1998) provided an example of the origin for groundwater hydrochemistry from recharge and discharge areas in a regional flow system that can be derived from the changes in the chemical composition of groundwater in sediments of the Atlantic Coastal Plain (Figure 2.5). In the shallow aquifer systems percolated water from precipitation comes in contact with gases in the unsaturated zone, resulting in fast chemical reactions that dissolve minerals and cause degradation of organic material; which causes contact in the local flow system. In deeper aquifer systems, slower chemical reactions occur such as precipitation and dissolution of minerals and ion-exchange that adds or removes solutes.

Hydrochemical facies are produced by these natural reactions. Previous studies of the Atlantic Coastal Plain identified freshwater recharge to have ample concentrations of HCO_3^- ions and small concentrations of dissolved solids near

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high relief areas. Whereas, for discharge zones discharging groundwater into streams, estuaries and the Atlantic Ocean high concentrations of Cl^- ions and dissolved solids are present (Winter et al., 1998).

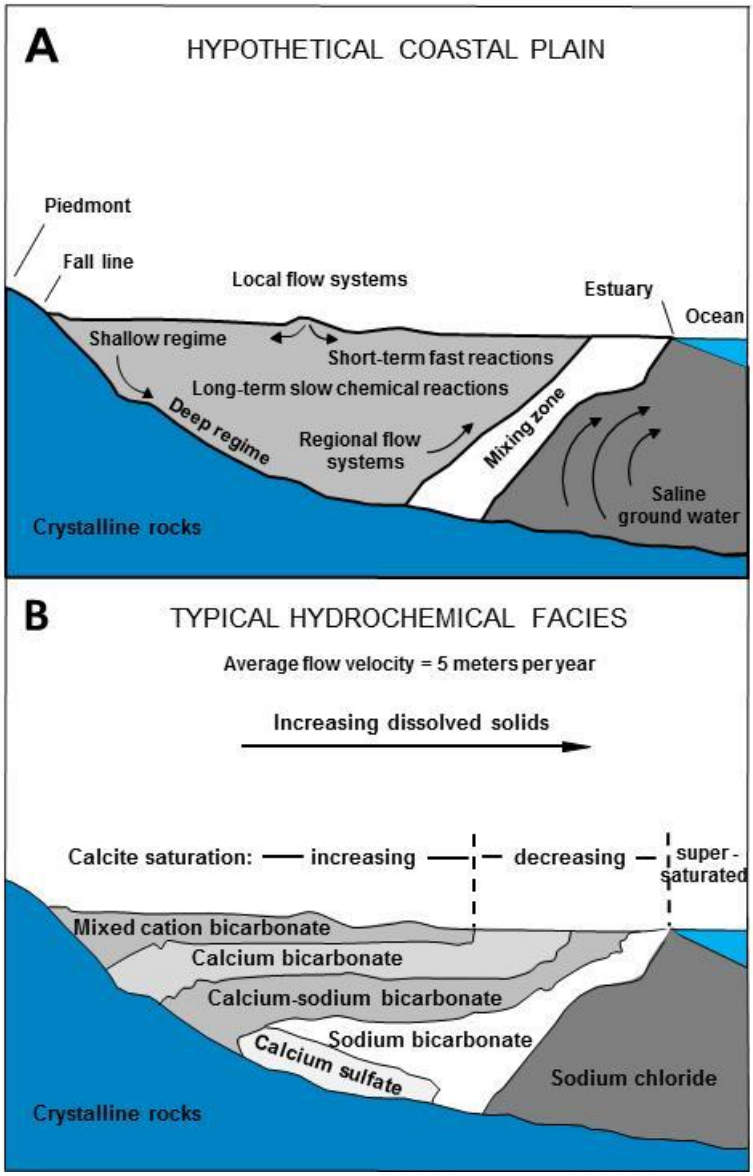

Figure 2.5: Illustration of a coastal plain, along the Atlantic Coast of the USA, displaying the interrelations of different rock types, shallow and deep groundwater flow systems (regimes), and mixing with saline water (A) results in the evolution of a number of different groundwater chemical types (B) (Winter et al., 1998).

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2.5 Stable isotopes δ^2H and $\delta^{18}O$

Stable Deuterium (δ^2H) and Oxygen ($\delta^{18}O$) are the two primary indicators we need to know about the origin and age of groundwater in the aquifer. According to Stewart (2006), the most common way of determining its origin and residence time below the surface is by using natural and manmade tracers. These tracers are substances which accompany the water molecule from the upper atmosphere through the deepest aquifers. Natural tracers such as stable isotopes are conservative in nature and once they enter groundwater they are not modified by natural processes such as reduction or oxidation (Stewart, 2006). This process makes them ideal tracers to identify and track the source of groundwater recharge or its flow path. Isotopes, also give a direct insight into the movement and distribution processes within aquifers. Isotope hydrology is a technique which calls for the use of isotopes for water resource management and provides complementary information on the type, origin and age of groundwater.

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Isotope ratios of compounds in nature deviate slightly from the average values and often do so in a predictable manner. Characteristic patterns in δ^2H and $\delta^{18}O$ isotopes are present in precipitation that are related to latitude, temperature, land mass, altitude and seasonality and, as a result, this data can provide information relating to recharge sources, flow paths and mixing of natural waters (Freeze and Cherry 1979; Clark and Fritz 1997). There are isotope ratio variations between different phases of the same compound and different compounds of the same element. For instance, the oxygen isotope composition of rain and snow is determined by isotopic fractionation during evaporation, condensation, and rainout (Mazor 1997).

The isotopic composition of δ^2H and $\delta^{18}O$ in water is expressed in permil (‰) deviations from SMOW (Standard Mean Ocean Water) and written as δ^2H and $\delta^{18}O$. Global and local meteoric water lines (GMWL and LMW), equations resulting from the linear regression of δ^2H and $\delta^{18}O$ data for water samples

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collected globally and locally, respectively, can be used to assist in the interpretation of isotopic data (see Equation 2.2).

The global meteoric water line was first defined by Craig (1961) and is based on around 400 water samples of rivers, lakes and precipitation from various countries with the equation

$$\delta\ \delta^{2}H = 8\ \delta^{18}O + 10 \qquad \text{Equation 2.2}$$

When plotted this equation is known as the Global Meteoric Water Line (GMWL) and provides the approximate compositions of rain/snow on earth (Johnson 2007).

Fractionation of naturally occurring $\delta^{2}H$ and $\delta^{18}O$ isotopes in water occur in the hydrologic cycle during evaporation and condensation processes, indicating that light isotopic water molecules evaporate before heavy ones. As a result, surface water exposed to evaporation tends to be enriched in heavy isotopes relative to meteoric water and will have a less negative or more positive $^{18}O/^{16}O$ ratio (Craig 1961; Gat and Gonfiantini 1981).

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CHAPTER 3
DESCRIPTION OF STUDY AREA

3.1 Introduction

This chapter describes the location, topography, vegetation, climate, geology and aquifer characteristics for the study area, which are important for the understanding of recharge processes. The study area is situated along the southern Western Coast of the Western Cape of South Africa as displayed in Figure 3.1. The main areas of interest for the research study are the Elandsfontein aquifer and its discharge at Geelbek situated at the southern part of Langebaan Lagoon within the West Coast National Park (WCNP). The Elandsfontein aquifer includes all portions of the cadastral farm Elandsfontyn 349 and part of WCNP that extends to Geelbek.

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3.2 Geographical location

The study site is located near the town of Langebaan, which is situated on the eastern shore of the Langebaan Lagoon and are bordered by the Sout and Groen Rivers. The areas of interest are the geosites that occur in Geelbek in the south and EAS that occupies the Elandsfontyn farm 349 and the WCNP areas within the quaternary catchment G10M, (Figure 3.1). A palaeochannel was delineated for the research area which represents the Elandsfontein palaeochannel that flows towards the southern part of the Langebaan Lagoon. A fault also extends through the study area known as the Colenso Fault.

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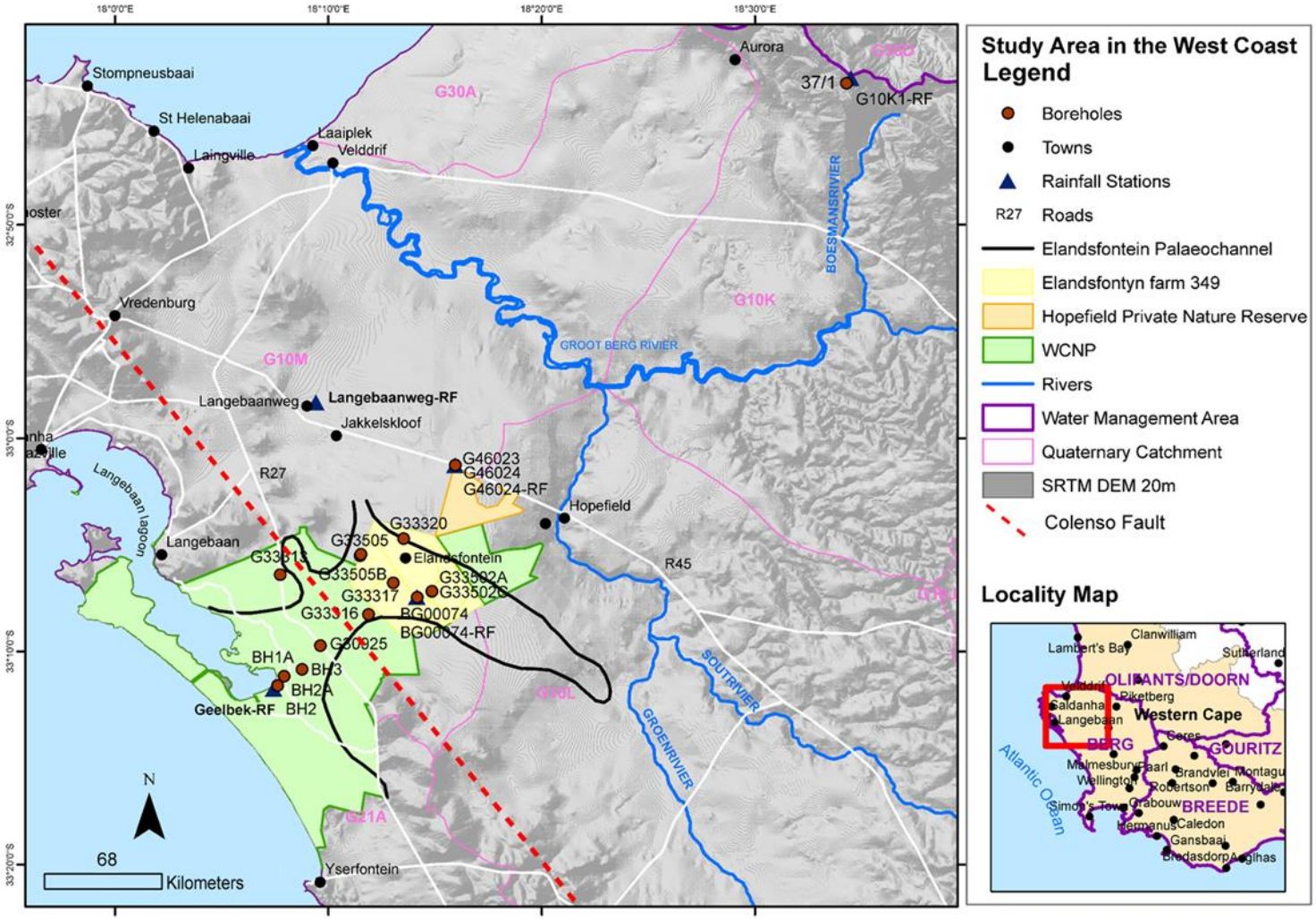

Figure 3.1: Location map of the study area in the West Coast, Western Cape.

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3.3 Topography and vegetation

The topography of the Elandsfontein aquifer consists of plains which are covered by unconsolidated and consolidated sand and dunes, located on the Elandsfontyn farm 349 reaching an average elevation of 96 mamsl (metres above mean sea level). The granite outcrop between the southern portion of the Elandsfontyn farm and the southern part of the lagoon reach heights of up to 117 mamsl. Calcareous sandy soils and surface limestone ridges are evident on the surface landscape (Visser and Schoch, 1973).

The vegetation (Figure 3.2) in the upper part of Elandsfontein palaeochannel consists of the Hopefield Sand Fynbos and the middle portion of the palaeochannel is made up of the Saldanha Flats Strandveld. In Figure 3.2 a potential source of depression-focused recharge could be found in the Saldanha Flats Strandveld area as a result of low precipitation and the area being nearly flat. The lower part of the palaeochannel consists of the Langebaan Dune Strandveld whereby Geelbek at the southern part of the estuary comprises of the Cape Estuarine Flats Marshes (SANBI vegetation, 2006). Surrounding the rounded granite hills is the sparse vegetation of the Saldanha Granite Strandveld.

According to Whitfield (2005), the vegetation found at the Langebaan Lagoon shows characteristics of an estuary. Halophytic vegetation and the zooplankton which has an estuarine character (Grindley, 1981) are also found along the southern edge of the lagoon. According to the WCNP (2013), the salt and freshwater marshes are dominated by Sarcocornia, Salicornia, Spartina, Limonium, Phragmites, Typha, Juncus and Scirpus species (Boucher and Jarman, 1977). A part of the Cape Salt Estuarine Marshes indicates freshwater signatures especially in the Geelbek vicinity, which could be indicative of the EAS discharging into the southern part of the lagoon.

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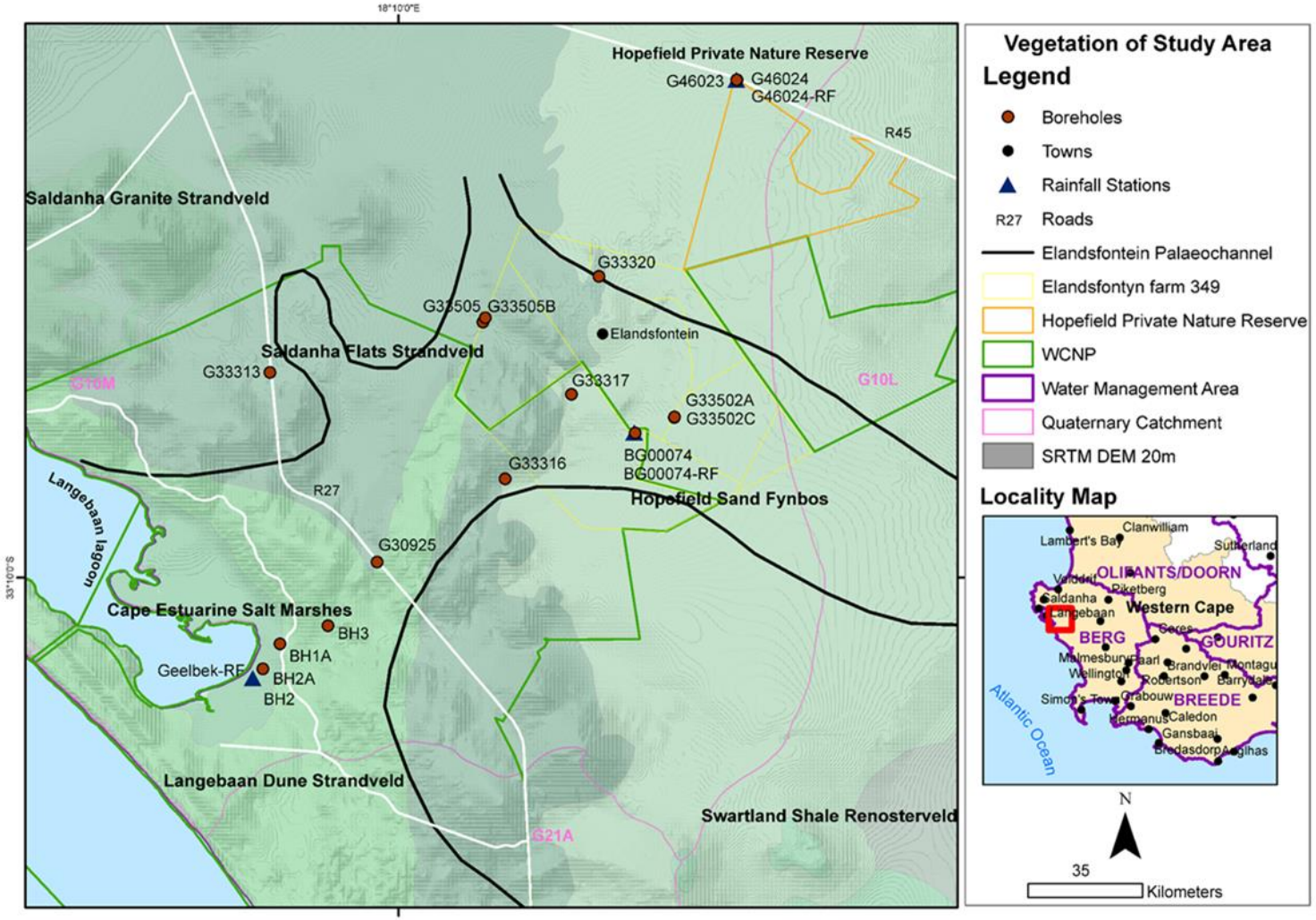

Figure 3.2: Vegetation map of the study area in the West Coast, Western Cape, (SANBI vegetation, 2006).

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3.4 Climate

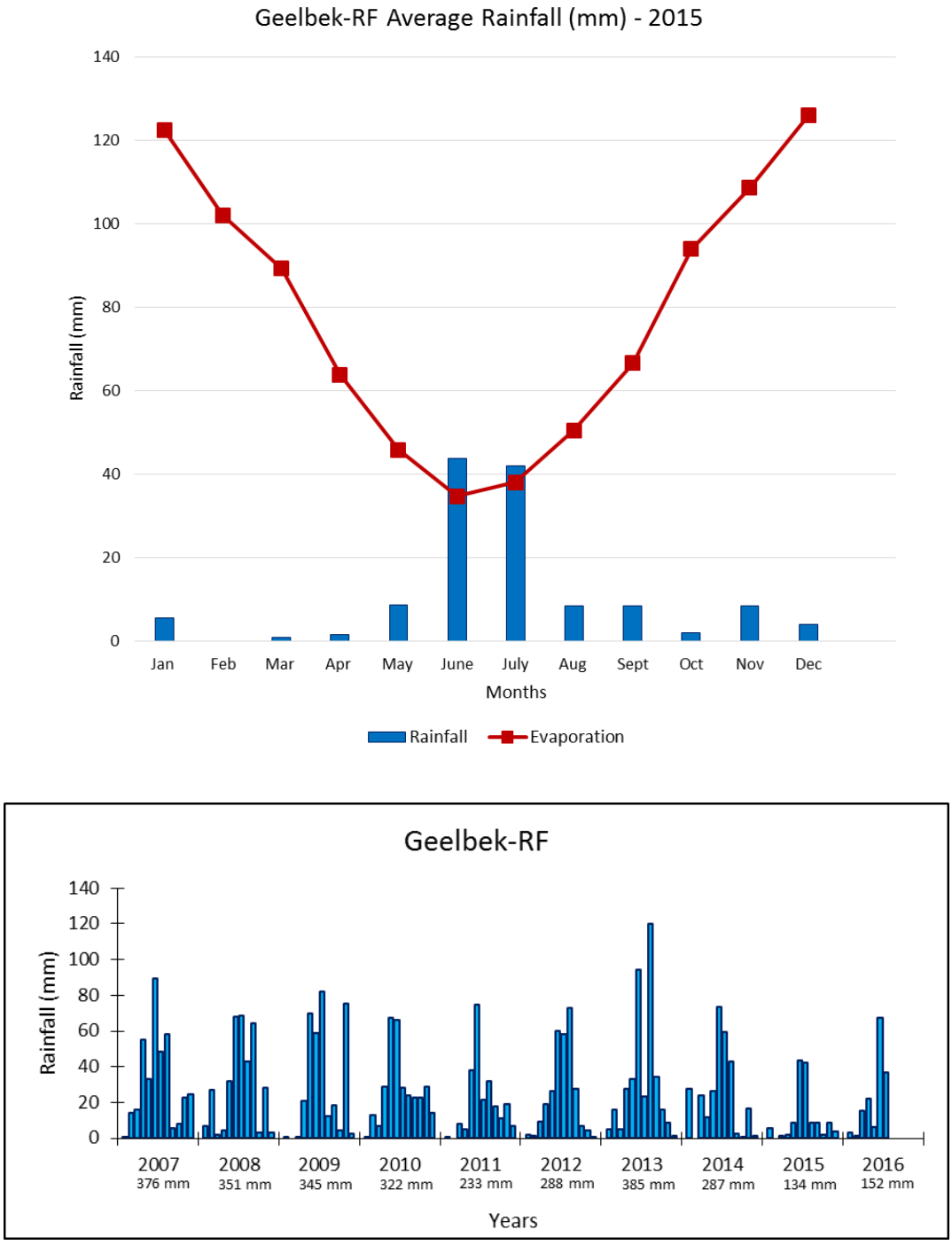

Figure 3.3: Monthly rainfall variation in 2015 and 10 year rainfall period for SAWS Geelbek rainfall station with average monthly evaporation mean (Western Cape Government Department of Agriculture).

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The climate for the study area is semi-arid Mediterranean with a winter rainfall and the rainfall period for the study year 2015, indicates lower rainfall compared to previous rainfall patterns. High evaporation rates were experienced throughout the year 2015, especially for the Geelbek vicinity according to data obtained from the Western Cape Government Department of Agriculture. Rainfall data from 2007 to 2016 for the Geelbek rainfall station was obtained from the South African Weather Service (SAWS), which indicated a below annual average rainfall of approximately 134 mm in 2015. Rainfall at the Geelbek site usually occurs during the months of May to July, with the highest rainfall in June and July (Figure 3.3). Figure 3.3 also indicates that February is the driest month with no rainfall for the year 2015.

Rainfall data for BG00074-RF rainfall station located in Elandsfontein in the WCNP indicates a below annual average rainfall of approximately 190 mm as opposed to previous years (Figure 3.4). Higher evaporation rates are experienced in 2015 for the Elandsfontein area than that of Geelbek, which leads to rain at BG00074-RF usually occurring during the months of May to July. Presenting the highest rainfall during June and July whereby June displays a peak of 70 mm as shown in Figure 3.4. The Elandsfontein area experienced the driest month during February with no precipitation. March, April and October did not receive any rainfall as well for the year 2015, given that it was quite a dry hydrological year.

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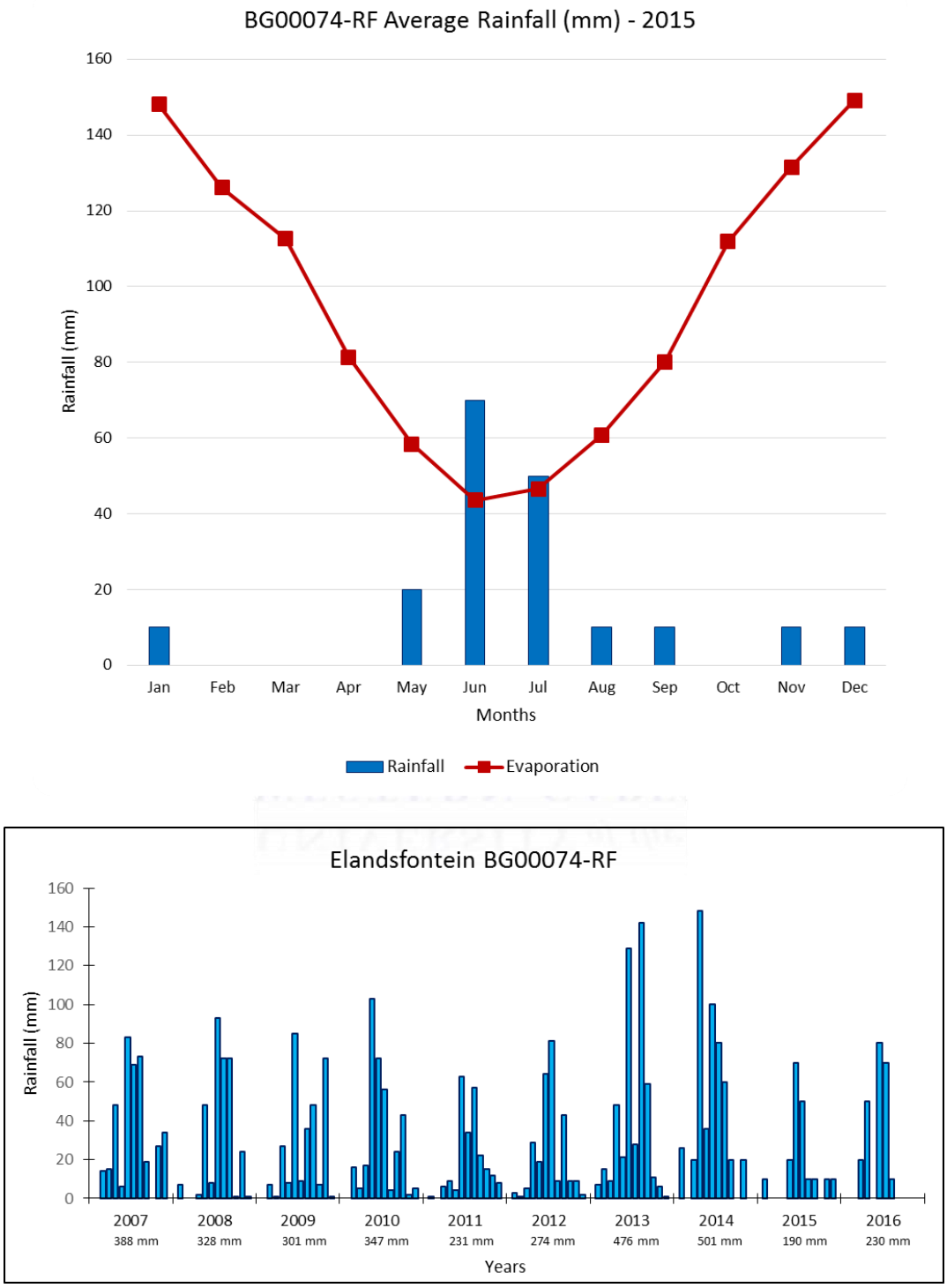

Figure 3.4: Monthly rainfall variation in 2015 and 10 year rainfall period for DWS Elandsfontein rainfall station with average monthly evaporation mean (Western Cape Government Department of Agriculture).

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3.5 Geology

The geology of the study area consists of the Malmesbury Group basement rock, which was intruded by granite and related intrusives of the Cape Granite Suite covered mainly by unconsolidated and semi-consolidated sediments forming part of the Sandveld Group (Rogers, 1982).

The Sandveld Group overlies a variety of pre-Mesozoic basement rocks and is thickest in structurally and lithologically controlled basement depressions (Roberts et al., 2006).

3.5.1 Elandsfontein Aquifer Stratigraphy

The Elandfontein aquifer stratigraphy (Figure 3.5) consists of the following formations from top (youngest) to bottom (oldest): Witzand Formation, Springfontyn Formation, Langebaan Formation, Velddrif Formation, Varswater Formation and Elandsfontyn Formation (Roberts et al., 2006).

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3.5.1.1 Witzand Formation

Rogers et al. (1990) is of the opinion that the Witzand Formation is the uppermost and youngest unit of aeolian activity in the Sandveld Group that consists of unconsolidated biocalcareous to siliciclastic dune sand and beach deposits. According to Rogers (1980, 1982), the sands in this formation are up to 28 m thick. The dominant dune systems are onshore transgressive plumes consisting mainly of barchanoid dunes, penetrating up to 14 km inland (Rogers, 1980).

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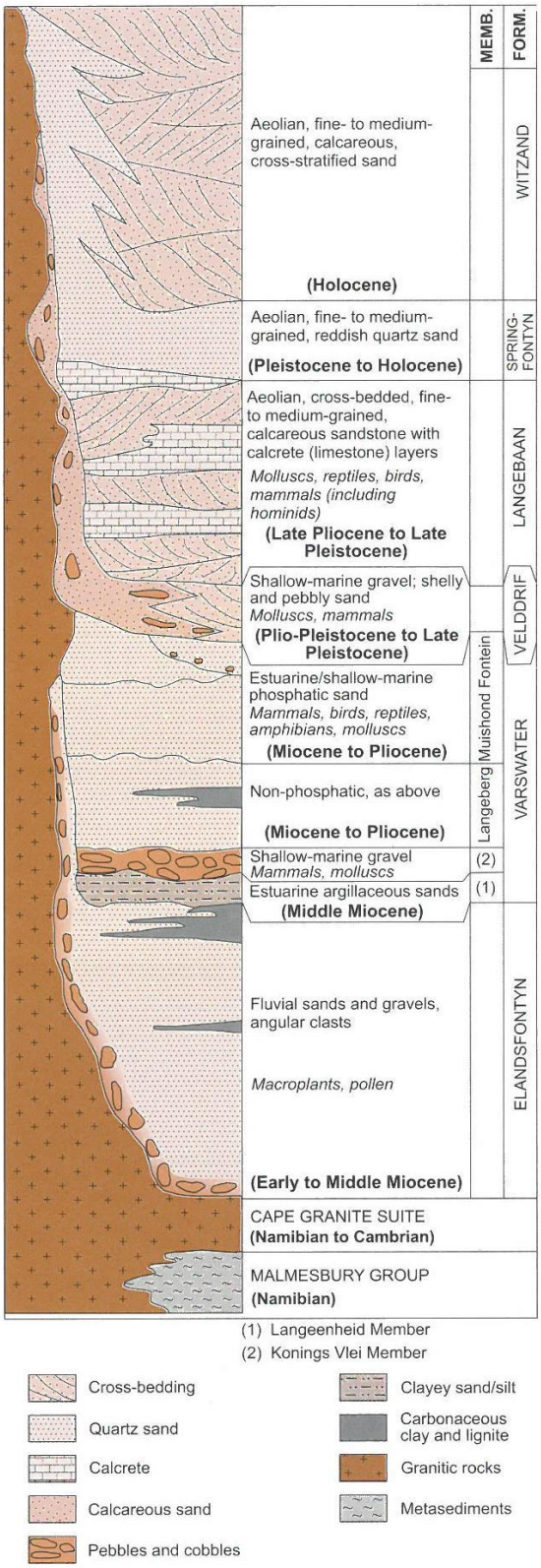

Figure 3.5: Composite stratigraphy of the Sandveld Group (Roberts et al., 2006) that represents the Elandsfontein aquifer lithology for the study area.

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3.5.1.2 Springfontyn Formation

According to Rogers (1980), the Springfontyn formation consists of reddish to grey, unconsolidated quartzose aeolian sands, which are muddy and peaty in places. The sands of this formation are considered to be thin and related to ancient buried leached dunes (Timmerman, 1985).

3.5.1.3 Langebaan Formation

The Langebaan Formation consists of an aeolian origin. The aeolianites are fine grained calcareous, with biolistic carbonate content (Roberts and Berger 1997). This could be an indication of major rivers in most of the area that contain more siliciclastic detritus with aeolianites thickness of 80 m occurs on the farm Elandsfontyn 349 (Roberts and Siegfried, 2014).

3.5.1.4 Velddrif Formation

The Velddrif Formation comprises of shallow-marine gravel, shelly sand, calcified sand and coquina (Roberts et al., 2006). The formation occurs on the western coastline of the Langebaan Lagoon, which is overlain by the Langebaan Formation (Tankard 1976; Rogers 1983; Roberts and Berger 1997).

3.1.5.5 Varswater Formation

The Varswater Formation is made up of the basal Langeenheid Clayey Sand Member, followed upwards by the Konings Vlei Gravel Member, the Langeberg Quartzose Sand Member and lastly the Muishond Fontein Phosphorite Member (Roberts, 2006b). The Varswater Formation rests on the Elandsfontyn Formation or Precambrian bedrock and is unconformably overlain by the Langebaan, Velddrif and Springfontyn Formations (Rogers, 1980). Roberts and Siegfried (2014) mentioned that the Varswater Formation consists of quartzose and muddy sand, which includes phosphatic shell fragments and pellets in places and also contains isolated lenticular lignite horizons. A thickness of up to 60 m is attained for the Varswater Formation (Timmerman, 1988) and is distinguished in cores by the presence of phosphate and rounded quartz grains, as well as a fine to medium-

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grained sand texture. Lastly, the formation is envisaged as an estuarine/shallow-marine environment and phosphate (Tankard and Rogers, 1978; Dingle et al., 1983).

3.5.1.6 Elandsfontyn Formation

Roberts and Siegfried (2014) share the sentiment that the Elandsfontyn Formation is the lower most formation of the Sandveld Group and rests unconformably on Precambrian bedrock. The formation consists of angular, fine to coarse-grained, quartzose gravely sand with less abundant sandy clay, carbonaceous clay and lignite, depositional environment predominantly fluvial, but a lacustrine environment has also been recognised. South-east of Saldanha on the eastern part of the Langebaan Lagoon, saturated sand thicknesses of up to 70 m have been recorded for the Elandsfontyn Formation (Roberts et al., 2006).

3.5.1.7 Cape Granite Suite – Saldania Belt

The Saldania Belt is made up of the Cape Granite Suite and according to Scholtz (1946), the granites intrudes into the Malmesbury Group on a regional scale as clusters. The study area falls in the South-western Pluton where the granites form part of the Saldanha Batholiths that occurs in the Tygerberg Terrane. The granites in the study area weather positively relative to the Malmesbury Group, forming rounded hills that dominate the landscape topographically (Roberts and Siegfried, 2014).

3.5.2 Elandsfontein palaeo-valley

The Council for Geoscience (CGS) inferred the basement topography of the palaeo-valley extending from Velddrif in the north to Langebaan Lagoon in the south. The research study mainly focused on the southern part of the palaeo-valley as demarcated by the red diminished line in Figure 3.6, which comprises of the Elandsfontyn farm 349 (Elandsfontein) and WCNP extending southwards to Geelbek. The Elandsfontein palaeo-valley basement comprises of the Malmesbury

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Group and intrusive rocks of the Cape Granite Suite (Roberts and Siegfried, 2014).

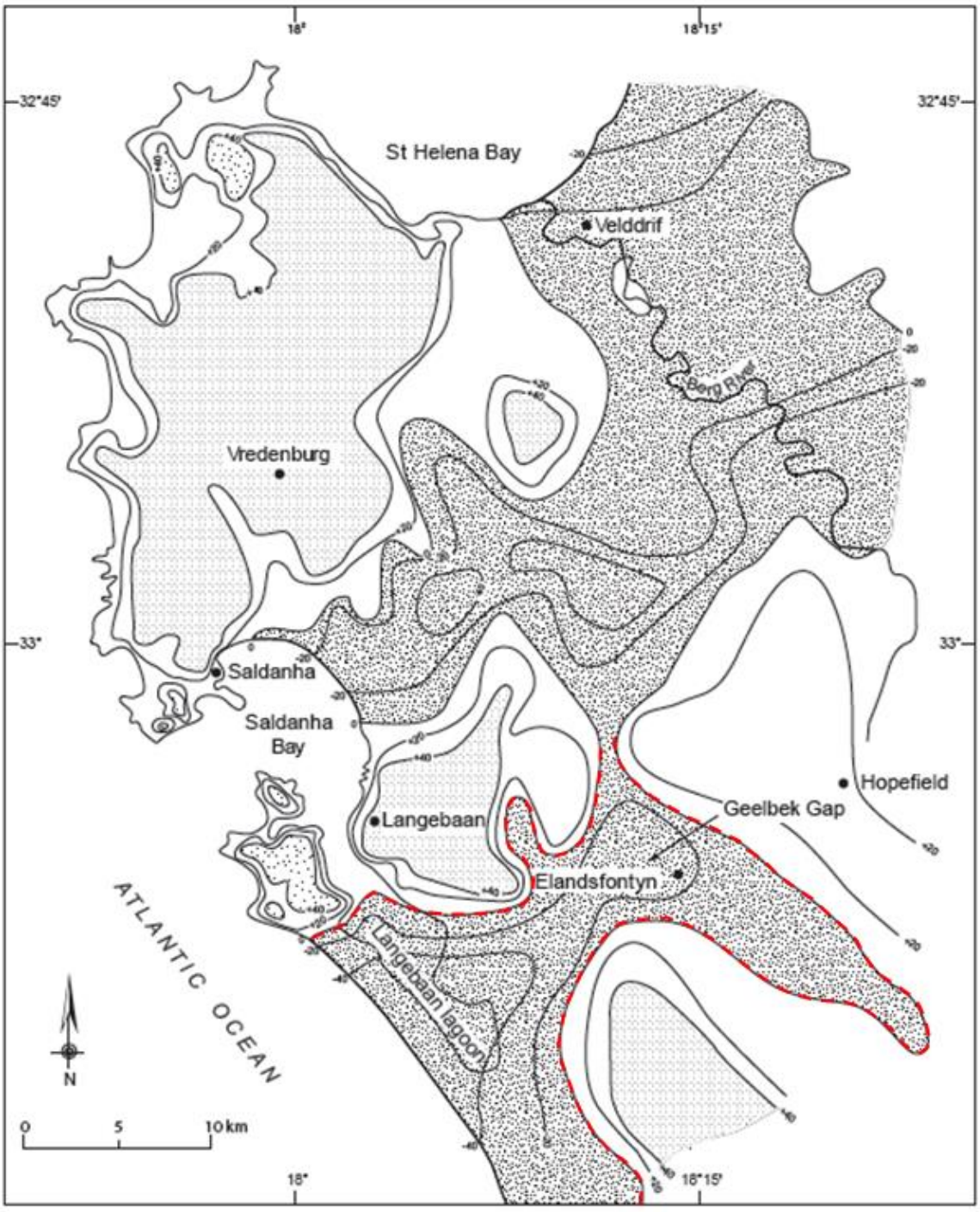

Figure 3.6: Map displaying the Pre-Cenozoic basement topography of the Saldanha, Vredenburg and Velddrif sheets. Heavy stipple indicates the elevations below present sea level (Roberts and Siegfried, 2014).

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In 1982 Smith conducted an electrical resistivity survey using the geo-electric method, where the resistivity work has confirmed the existence of two coarse-grained deposits presumed to be the Pre-Cenozoic and palaeo-valleys. The contours from the geo-electrical basement map (Figure 3.7) for the southern valley propose the existence of two palaeochannels, which extend from the Groen River on the east and south-east to join on the farm Elandsfontyn before changing direction to the west and exiting into the southern end of the Langebaan Lagoon. The maximum depth to bedrock for this valley is expected to be from -50 m to -60 m below sea level (Smith, 1982).

According to Smith (1982), the east of the granite and Malmesbury contact show that the material below -60 m contour is exclusively weathered Malmesbury and not recent material. This could possibly be caused from high erosion activity that occurred and deposited the Cenozoic on top of the basement. Whereas, on the edge of the Langebaan Lagoon the material below -60 m contour is assumed to be weathered granite only.

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Furthermore, Smith (1982) mentioned that the thickness of the unconsolidated material and the depth of weathering of the Malmesbury bedrock need to be determined at Elandsfontein. With this determination in mind it will confirm if the proposed palaeochannels exists from the survey conducted. The survey also identified the presence of faults within the bedrock on line 10 whereby three boreholes G30925, G30952 and G30953 are situated along this line (refer to Figure 3.7 and 3.8), which is approximately 4.74 km east of Geelbek from line 10.

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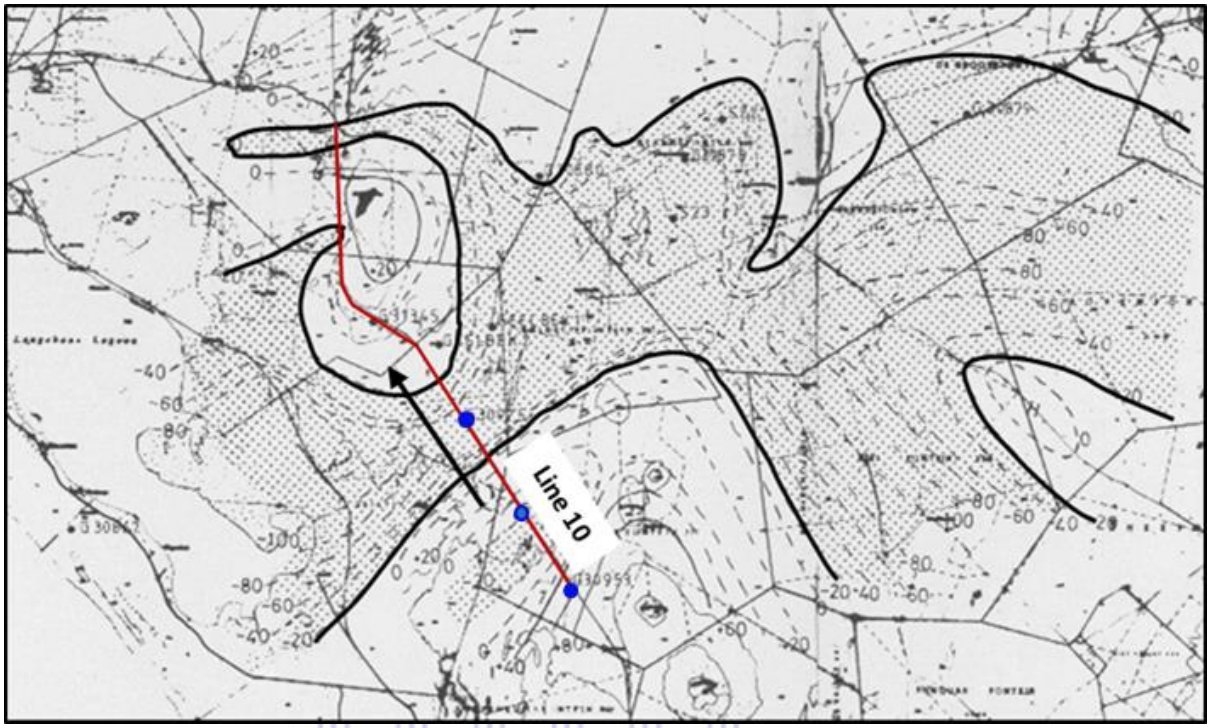

Figure 3.7: Simplified contour map of depth to the geo-electric basement displaying area below -20 m (msl) and direction of survey line 10 intersecting boreholes G30953, G30952 and G30925 by Smith 1982 (GH3224 report).

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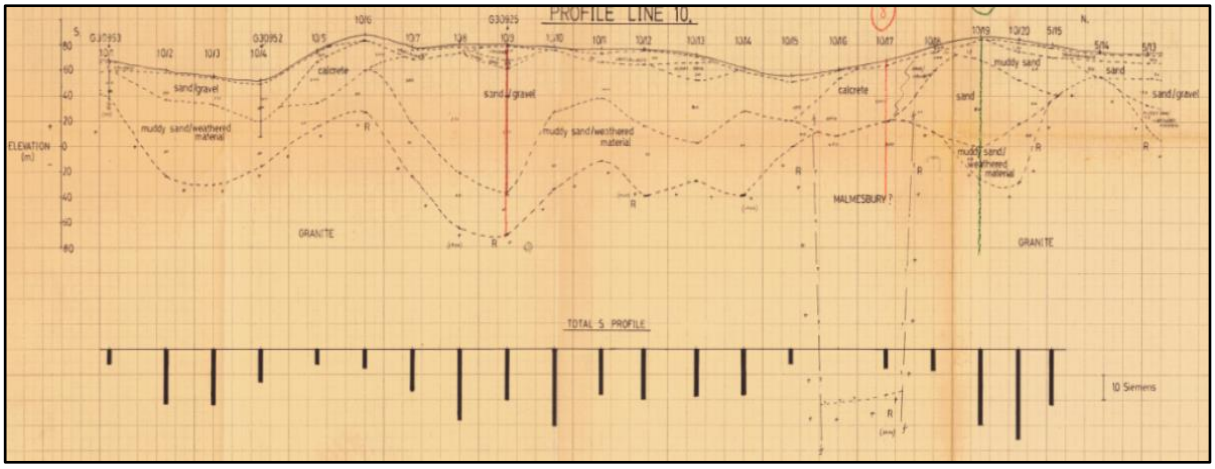

Figure 3.8: Total S Profiles featuring profile line 10 by Smith 1982 (GH3224 report).

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3.5.3 Colenso fault

The western Saldania belt in Figure 3.9, clearly displays the Colenso Fault Zone that stretches all the way from the granite hills (koppies) between Paarl and Stellenbosch to the West Coast whereby strike slip faults are evident. The most prominent structural feature of the Saldania belt is the north westerly trending sub-vertical of the Colenso (Kisters and Belcher, 2018); with the Colenso Fault Zone an important geological structure for the research study as it could serve as the dominant regional preferential flow path to the EAS.

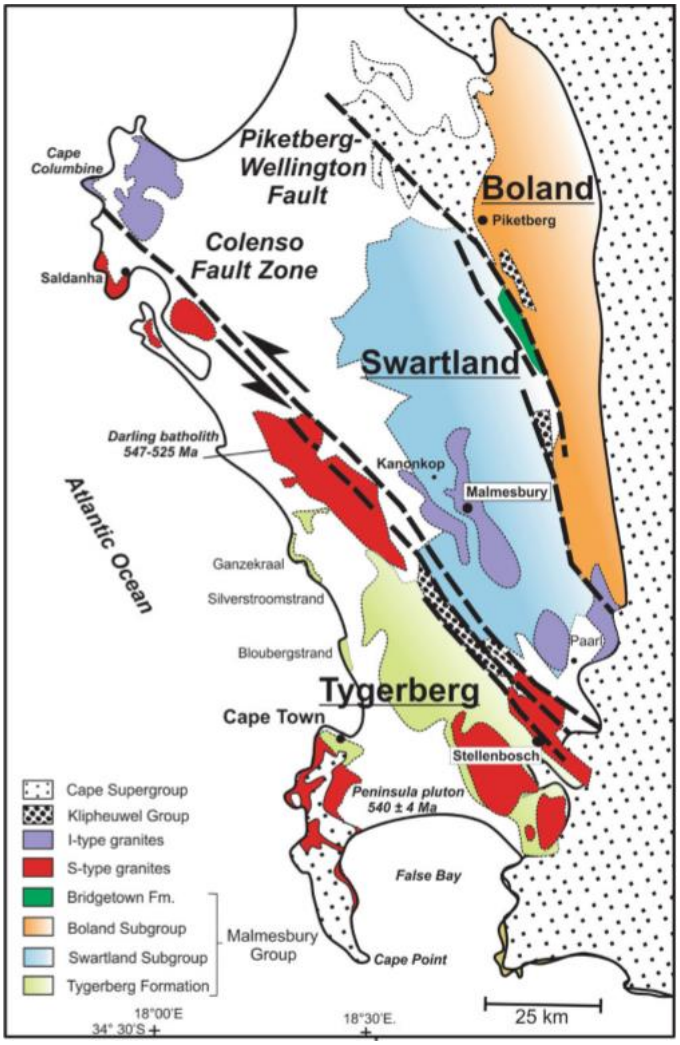

Figure 3.9: Schematic geological map of the western Saldania belt showing the currently accepted subdivision of the belt into three tectonostratigraphic domains or terranes (Tygerberg, Swartland and Boland), separated by strike-slip faults and intruded by plutons of the Cape Granite Suite (Rozendaal et al. 1999; Gresse et al, 2006) & (Kisters and Belcher, 2018).

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3.5.4 Borehole logs

Boreholes in the Elandsfontein aquifer were drilled by Timmerman in 1985, two of these boreholes are G33316 VL1 and G33317 (Figure 3.10), which are situated in close proximity to each other and both boreholes are found to be in the Elandsfontein palaeochannel (Roberts and Siegfried, 2014). G33316 VL1 at a depth of 83 mbgl (metres below ground level) comprises of aeolian sand, a calcrete layer underlain by shelly and quartzose sand with a thickess of 40 m that is below a clay layer and ends 3 m in the granite formation. Borehole G33316 VL1 is situated right on the southern edge of the palaeochannel, whereas borehole G33317 comprised of a 28 m thickness of aeolian sand imbedded with calcrete layered lenses. The dominant formations are comprised of quartzose sand with a thickness of 28 m and a thin peat lense of 1 m along with silty quartzose sand, medium to course quartzose sand and gravel with a thickness of 56 m underlain with clay that ends at a depth of 138 mbgl. Thus, indicating that the EAS might consists of one aquifer unit and not separate units as shown in borehole G33317 in Figure 3.10.

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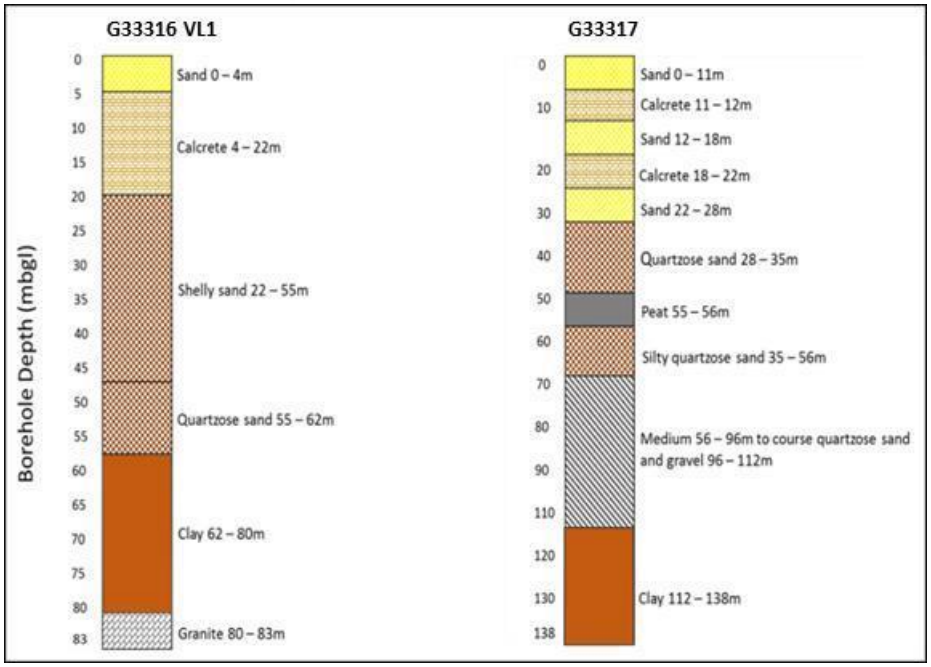

Figure 3.10: Graphical geological logs representing the lithology of G33316 VL1 and G33317 (Timmerman, 1985a).

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On Figure 3.11 we see that the borehole log for G33320 VL1 drilled by Timmerman in 1985 is located on the northern east boundary of the Elandsfontein area, which is assumed to be situated on the northern top edge of the Elandsfontein palaeochannel with a depth of 80 mbgl. The mentioned borehole comprises of a 25 m thickness of aeolian sand and clean quartzose sand followed by quartzose sand that is imbedded with peat layered lenses. The next layer consists of clayey quartzose sand with a thickness of 13 m underlain with clay that ends at 80 m in depth below ground level. According to the geological log of borehole G33320 VL1 below, represents a one unit aquifer indicating no confirmation of an unconfined and confined aquifer unit derived from the geological log.

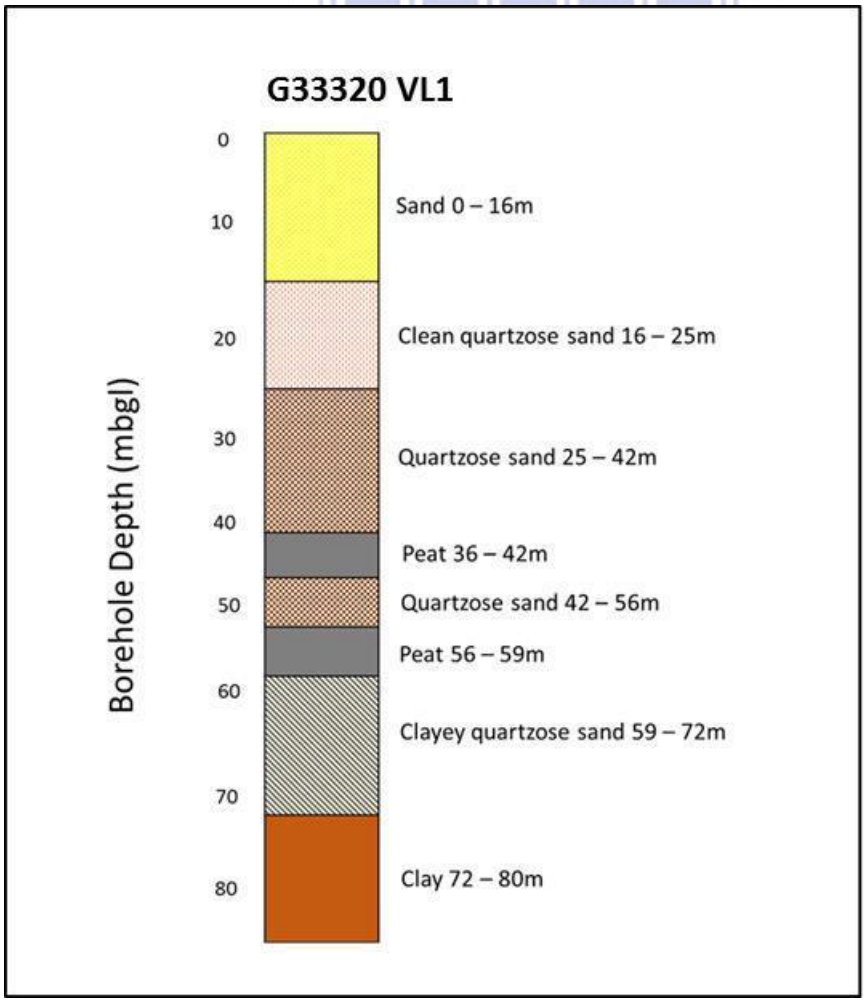

Figure 3.11: Graphical geological log representing the lithology of G33320 VL1 (Timmerman, 1985a).

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Four other boreholes are used in the study which has borehole logs sourced from the National Groundwater Archive (NGA), but these borehole logs do not provide useful information and due to the uncertainty of the logs it was not included in the cross section below. The boreholes are as follows: G333505B with a depth of 161 mbgl consists of sand, clay and siltstone, borehole BG00074 at a depth of 102 mbgl comprised of sand, clay and gravel, G33502A has a depth of 159 mbgl and is made up of soil and shale; and borehole G33502C consists of soil only at a depth of 66 mbgl.

Borehole G30925 is located in between the southern edge of the Elandsfontein and Geelbek areas. Figure 3.12 indicates the lithology of the borehole which comprises of aeolian sand with a thickness of 44 m imbedded with thin calcrete lenses. The succeeding layer consists of 29 m calcrete layer separating the aeolian sand and clay layer, following the last two layers consisting of medium to course sand and gravel with a 17 m thickness ending at a depth of 117 mbgl.

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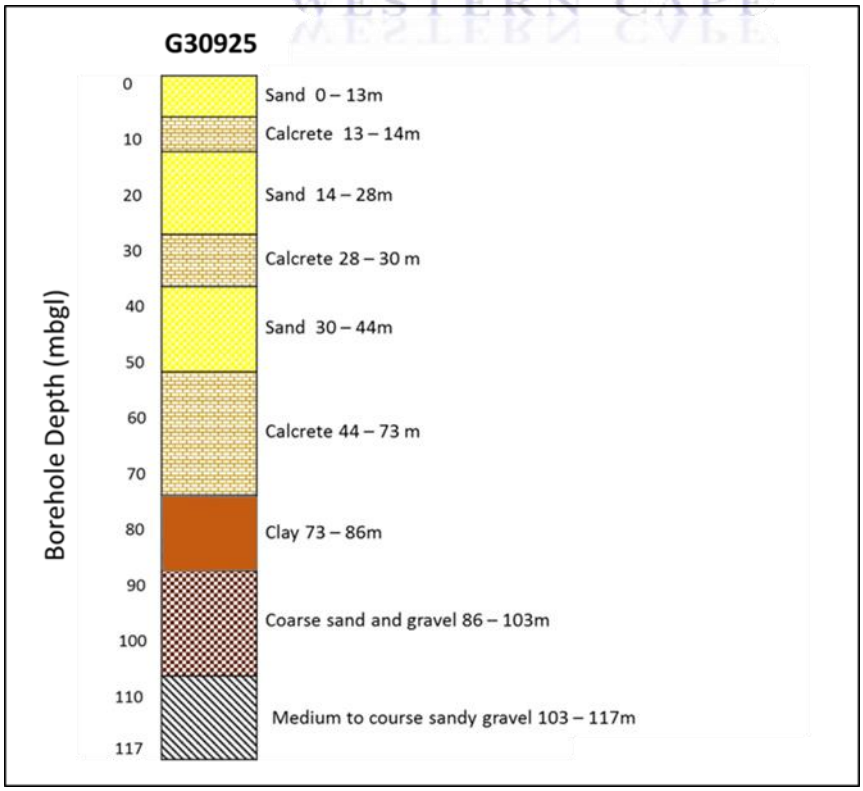

Figure 3.12: Graphical geological log representing the lithology of G30925 (Timmerman, 1988).

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CSIR drilled boreholes in the West Coast National Park near the lagoon (Colvin et al., 2007), where the following four boreholes BH1A, BH2, BH2A and BH3 are situated in the southern part of the lagoon Geelbek area. BH3 is located slightly further from the lagoon east of the Geelbek boreholes near Duinepos. According to the electrical resistivity survey conducted by Smith (1982), there is a possibility that all four boreholes are situated in the deeper bedrock of the Elandsfontein palaeochannel. Borehole BH1A is 13 mbgl deep located on the eastern edge of the lagoon comprised of 9 m sand layer and ends in 4 m calcrete. Boreholes BH2 and BH2A are situated on the southern edge of the lagoon in close proximity of each other. Borehole BH2 is situated much deeper and comprises of 8 m sand layer, followed by 29 m calcrete layer and protruding the clay layer with a depth of 45 mbgl. BH2A is a shallow borehole with a depth of 13 mbgl consisting of 4 m sand, followed by a thin calcrete lense and then 3 m sand layer ending in a 5 m thick calcrete layer. Borehole BH3 has a depth of 66 mbgl and comprises of 2 m sand made up of the Witzand Formation, which is then followed by 62 m calcrete layer and ending into the granite (Figure 3.13). It can be anticipated that the Witzand Formation is thinning out towards the lagoon approaching Geelbek, which then continues into the Langebaan Formation and calcrete layers of the Elandsfontein aquifer near the discharge area.

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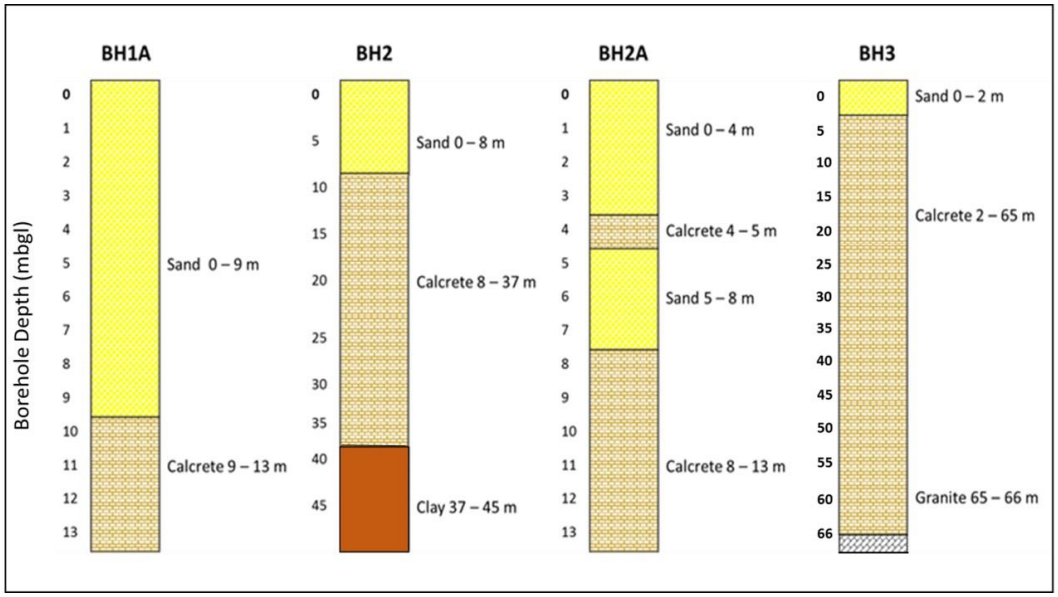

Figure 3.13: Graphical Geelbek geological logs representing the lithology of BH1A, BH2, BH2A and BH3 (Colvin et al., 2007).

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3.5.5 Cross section

Figure 3.14 displays the cross section for the study area that begins on the farm Elandsfontyn 349 with boreholes G33320 VL1, G33317 and G33316 VL1; through the middle area of the study where borehole G30925 is located next to the R27 Road and then continues towards the southern part of the lagoon where boreholes BH1A, BH2, BH2A and BH3 are situated south-west. The gap area located in between Elandsfontein and Geelbek is unknown and requires additional groundwater exploration work for better understanding and representation of the area.

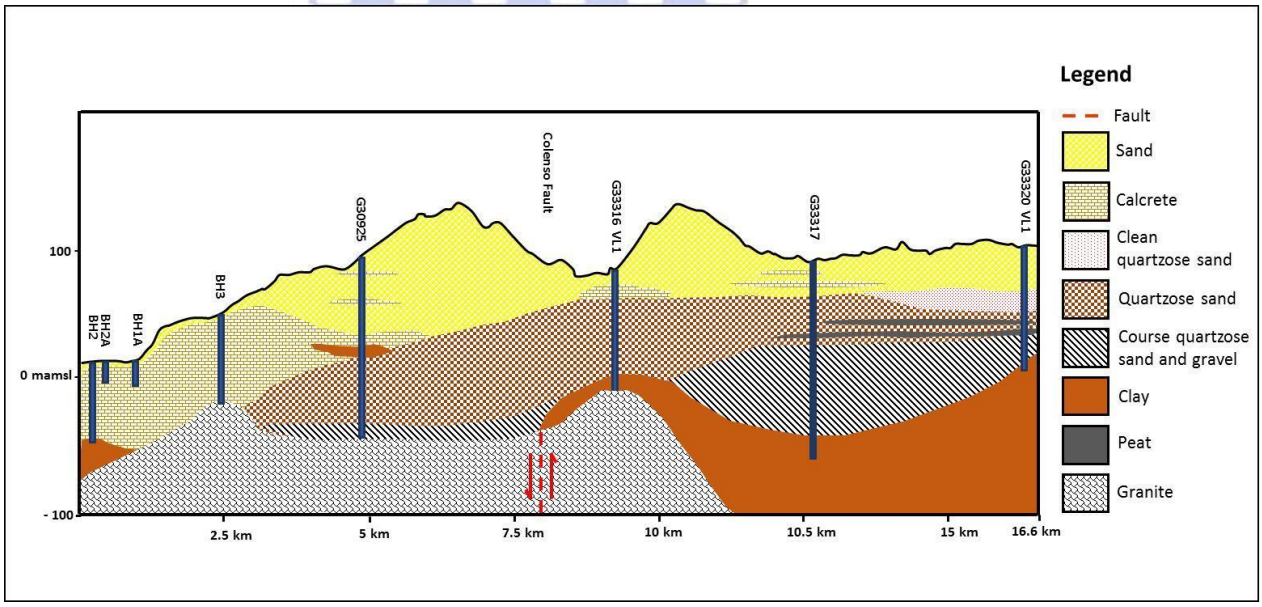

Figure 3.14: Cross section displaying the interpreted geology of the monitoring boreholes of the study area from Elandsfontein to Geelbek, Langebaan Lagoon as shown in Figure 3.15.

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3.5.6 Geology summary

Figure 3.15 provides the surface geology of the study area based on the 1:250 000 map by Council of Geoscience. The Colenso fault that runs through the study area from a south-east to a north-west direction is displayed on the map and represents the regional fault extending from Paarl. The southern palaeochannel from Roberts and Siegfried (2014) is also presented and indicates that most of the boreholes from the Elandsfontein and Geelbek areas are located within the palaeochannel except for borehole G33313. Boreholes G46023 and G46024 are also excluded, which are located in the LRAS on the north-east part of palaeochannel.

The study area is covered mainly by the surface geology comprised of Quaternary sediments made up of Witzand Formation and Langebaan Formation according to the 1:250 000 map by Council of Geoscience (Figure 3.15). The EAS also consists of quartzose sand for the Varswater Formation and medium to course quartzose sand and gravel for the Elandsfontyn Formation. Calcrete lenses are also present in the upper formations of the system. Lastly, the basement granites that penetrated from the Precambrian Malmesbury shale also occupy the study area.

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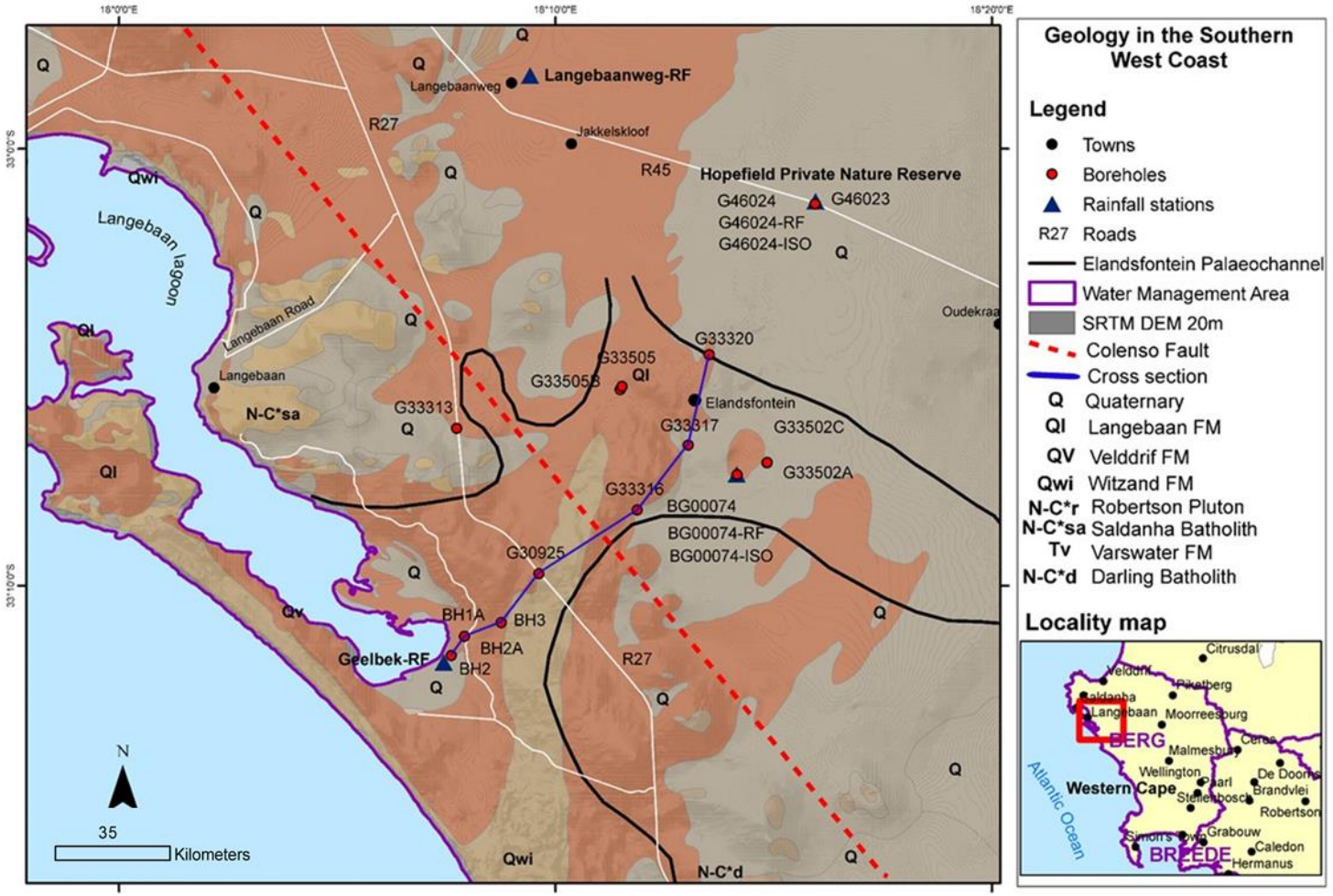

Figure 3.15: Geology map of the study area in the West Coast, Western Cape (Council of Geoscience 1:250 000).

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3.6 Aquifer characteristics

The Elandsfontein aquifer has been investigated since 1982 by various studies that attempted to understand how the aquifer system functions. Previous studies that investigated the aquifer are as follows:

- Smith (1982) conducted an electric resistivity study over the Elandsfontein aquifer to estimate sand thickness of approximately 70 m.

- Timmerman, 1985a carried out a comprehensive geohydrological assessment of the study area reporting on the Langebaan Road aquifer and Elandsfontein aquifer. Exploration work was undertaken that included exploratory drilling; pumping tests (multi-rate test, constant discharge pumping test and recovery test); geophysical survey near the Berg River; water level and quality monitoring. The transmissivity, hydraulic conductivity and storativity for the Elandsfontein aquifer were assigned values for transmissivity of 5-250 m^2/day, hydraulic conductivity of 2-69 m/day and storativity of 15.5×10^6 m^3 and 750×10^6 m^3 as proposed by Timmerman (1985a). Only direct recharge for the area is proposed by Timmerman (1985a) and is estimated to be near 27×10^6/year. Timmerman argued that the groundwater flows in a northerly direction from Sonquas Fontein towards Elandsfontein where the flow turns west towards Langebaan Lagoon within the Elandsfontein catchment area (Figure 3.16). Timmerman (1985a) concluded that the EAS boundaries are defined by a palaeochannel that could be the preferential groundwater flow path to Langebaan Lagoon.

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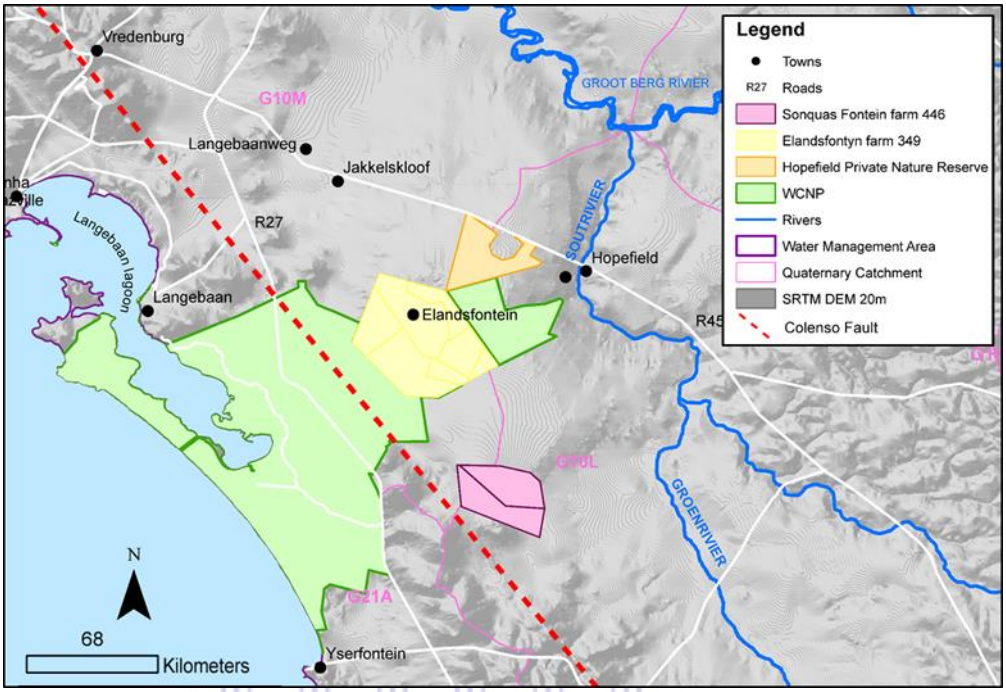

Figure 3.16: Sonquas Fontein and Elandsfontein (Elandsfontyn farm 349 and WCNP) areas.

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- Timmerman (1988) undertook his Doctoral study and reported that two discharged zones were identified in the West Coast. A second discharged zone was located on the western part of the farm Elandsfontyn 349 and that there was no connection between the other discharged zones east of the Langebaan Lagoon. For the shallow aquifer of the Elandsfontein aquifer a 168 hour constant discharge pumping test was conducted on borehole G32939 near Koningsvlei the following values were obtained for the borehole a transmissivity of 2500 m^2/day, hydraulic conductivity of 100 m/day and specific yield of 0.13. Timmerman mentioned that recharge to the groundwater was from the foot of the granite hills situated south and west of the farm, and that the western slopes of the Darling hills recharges the Geelbek area located south of the lagoon.

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- Woodford and Fortuin, 2003b defined the EAS and LRAS to be comparable consisting of an upper aquifer and lower aquifer. The Elandsfontyn Formation comprised of a basal confined aquifer formed by sand and gravel of the Elandsfontyn Formation, found below a thick sequence of clay and peat (Woodford and Fortuin, 2003b). The Langebaan and Varswater Formations constitute the Upper Aquifer Unit (UAU) composed of consolidated sands and calcrete while the confined Lower Aquifer Unit (LAU) composed of the basal gravels of the Elandsfontyn Formation. An aquitard (clay and peat) separates the Upper Aquifer Unit and Lower Aquifer Unit (Woodford and Fortuin, 2003b). It is also found that the EAS was formed by a thick average 90 m sequence of sediments deposited in a palaeochannel of the Sout or Groen Rivers reaching a maximum thickness of 140 m between Geelbek, lagoon and the farm Elandsfontyn 349.

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- Saayman et al., 2004 undertook a CSIR study that assessed the Langebaan Lagoon as a study which applied various methodologies (geophysical survey, remote sensing and hydrochemical methods) to characterise coastal ecosystems and the interactions between groundwater and surface water systems. Subsequently, the study contributed to the: An introduction to Aquifer Dependent Ecosystem in South Africa study (Colvin et al., 2007). Colvin et al., 2004 proposed ‘that the discharge zone from the Elandsfontein aquifer is greatest where the aquifer is thickest in an infilled palaeochannel’ and that the only potential source of freshwater to the wetland vegetation at the Geelbek is aquifer dependent.

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According to previous literature, the EAS is comprised of an upper aquifer unit and a lower aquifer unit whereby the clay layer is understood to be a semi-confined layer throughout the various hydrogeological units for the EAS (Figure 3.17). Most of the Departmental monitoring boreholes located in the Elandsfontein area were drilled into the clay layer of the EAS.

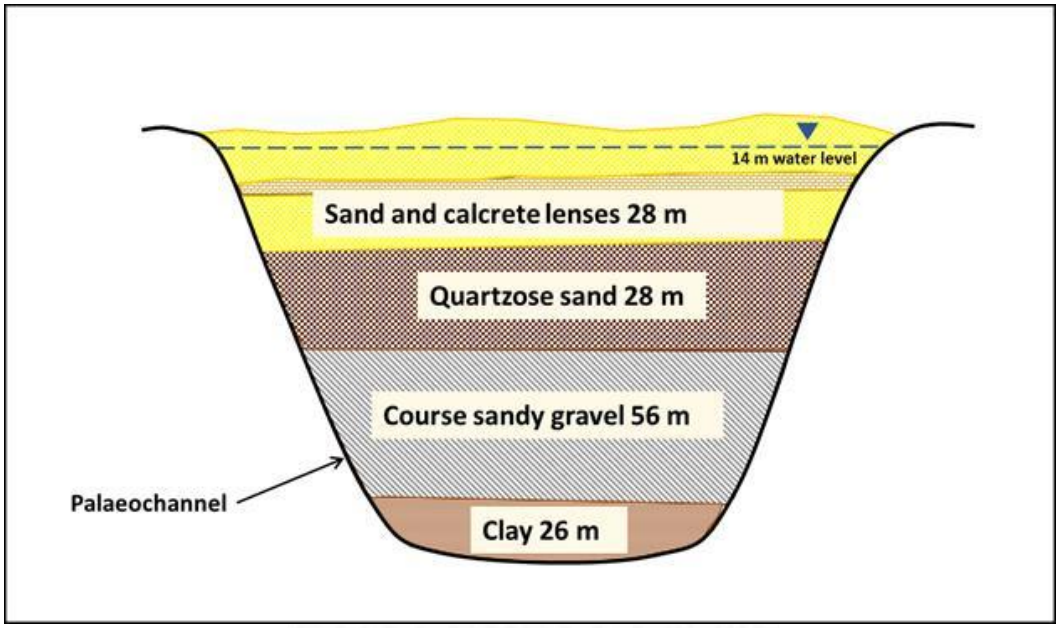

Figure 3.17: Cross section displaying the upper part and lithological thicknesses of the Elandsfontein Aquifer System.

Borehole G30925 situated between the Elandsfontein farm and Geelbek is the only borehole that intercepted the course gravel below clay according to the geological logs of Timmerman (1988), as seen in Figure 3.18. The borehole is also located in the middle of the EAS palaeochannel.

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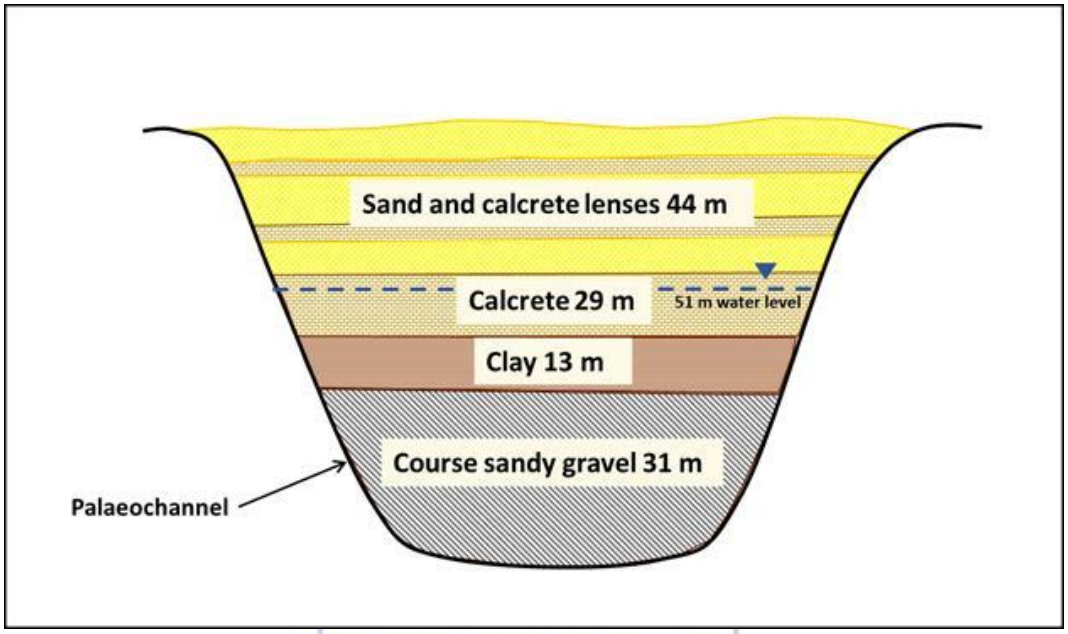

Figure 3.18: Cross section displaying the lower part and lithological thicknesses of the Elandsfontein Aquifer System.

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Whitfield (2005) defined the Langebaan Lagoon as an aquifer fed estuary due to its vegetation which is distinctive of an estuary. Figure 3.19 displays a conceptual cross section of the Elandsfontein aquifer consisting of a shallow and deep aquifer discharging into the southern part of the lagoon. The Phragmites australis roots cannot stand high amounts of salts to the reed beds. This vegetation located at the southern end of the lagoon suggests that the only source of freshwater entering the lagoon is from groundwater inflow. Therefore, the discharge zone is thought to be greatest where the aquifer is thickest in an infilled palaeochannel (Colvin et al., 2007).

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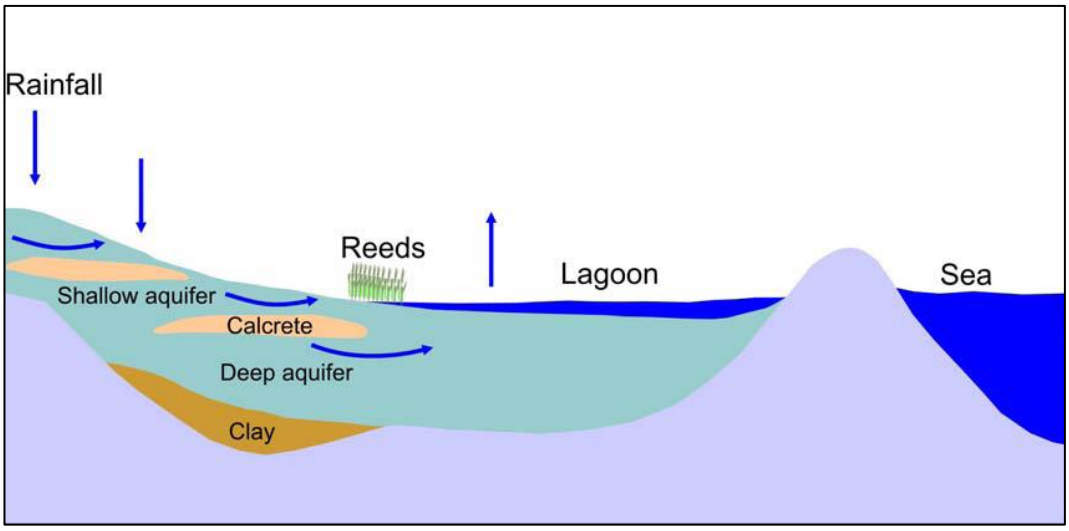

Figure 3.19: A conceptual cross section of the Langebaan Lagoon presenting groundwater flow paths from the sand and calcrete aquifer discharging to Phragmites reed beds in the intertidal zone and towards the lagoon, (Colvin et al., 2007).

Langebaan Lagoon estuarine characteristics are dependent on groundwater inflow at the southern end of the lagoon at Geelbek and this discharge zone is considered to be the only source of freshwater contributing to the system. The boreholes displayed in Figure 3.13 indicate that the discharge zone of the EAS consists of a coastal sand and calcrete aquifer (Colvin et al., 2007).

3.6.1 Surface water and groundwater interaction

There are two ephemeral rivers that could intercept the Elandsfontein palaeochannel, namely the Sout River to the east and Groen River to the south-east. Groundwater flow from the EAS is likely to flow towards the Groen and Sout Rivers as the rivers are situated at lower elevations than the EAS groundwater level. Therefore, the dominant recharge processes cannot be derived from these ephemeral rivers.

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CHAPTER 4
RESEARCH METHODOLOGY AND MATERIALS

4.1 Introduction

This chapter investigate and presents methods and materials used for the research study. A field programme was piloted in June 2015 to May 2016 for a period of 12 months. Monthly sampling was conducted to obtain site-specific information in Geelbek, WCNP (EAS); Elandsfontyn farm 349 (EAS); Hopefield Private Nature Reserve (LRAS) and Mountain Mist, Aurora (Piketberg Mountain range). The field programme included data collection of various existing Departmental monitoring geosites that consisted of boreholes, rainfall stations and the installation of three isotope samplers next to the DWS rainfall stations. These geosites provided necessary data for water level monitoring, hydrochemistry and stable isotope sampling. Data analysis and interpretation of the following main methods were used to achieve the study objectives:

- Cumulative Rainfall Departure (CRD) method;
- Hydrochemistry and stable isotope $\delta^{2}H$ and $\delta^{18}O$ methods and
- Conceptual groundwater flow model.

4.2 Data review

A desktop study was completed to review the hydrogeology of the study catchment. The data review process involved acquiring and reviewing available geological and hydrological information, which include lithological logs and geological maps (1:250 000 map by Council of Geoscience). The precipitation information was obtained from SAWS providing climate data and DWS provided time series rainfall and water level data from the Berg Water Management Area

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(WMA) database. All information was sourced from various reports including Departmental GH reports, theses and publications on the research study.

4.3 Monitoring network

For this specific study monthly monitoring of the geosites were conducted as part of the monitoring programme, which included 22 monitoring geosites and all 22 Departmental geosites consisted of 19 boreholes and 3 rainfall stations including isotope samplers. These geosites also formed part of the monitoring routes that are monitored on a quarterly basis by DWS (Figure 4.1).

Table 4.1 shows the two geosites (borehole, rain gauge and isotope sampler) that were monitored in the quaternary catchment G10K on Mountain Mist, which is located above the town of Aurora on the Piketberg Mountain range for recharge and isotopic signatures.

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Table 4.1: The location, altitude of the Departmental borehole and rainfall station in Aurora located in the quaternary catchment G10K.

	Geosite_ID (NGA_ID)	Latitude S (°)	Longitude E (°)	Elevation (mamsl)	Geosite type
Piketberg Mountain range route	37/1	-32.72276	18.57145	845	Borehole
	G10K1-RF & isotope rainfall sampler	-32.71861	18.57510	966	Rainfall gauge

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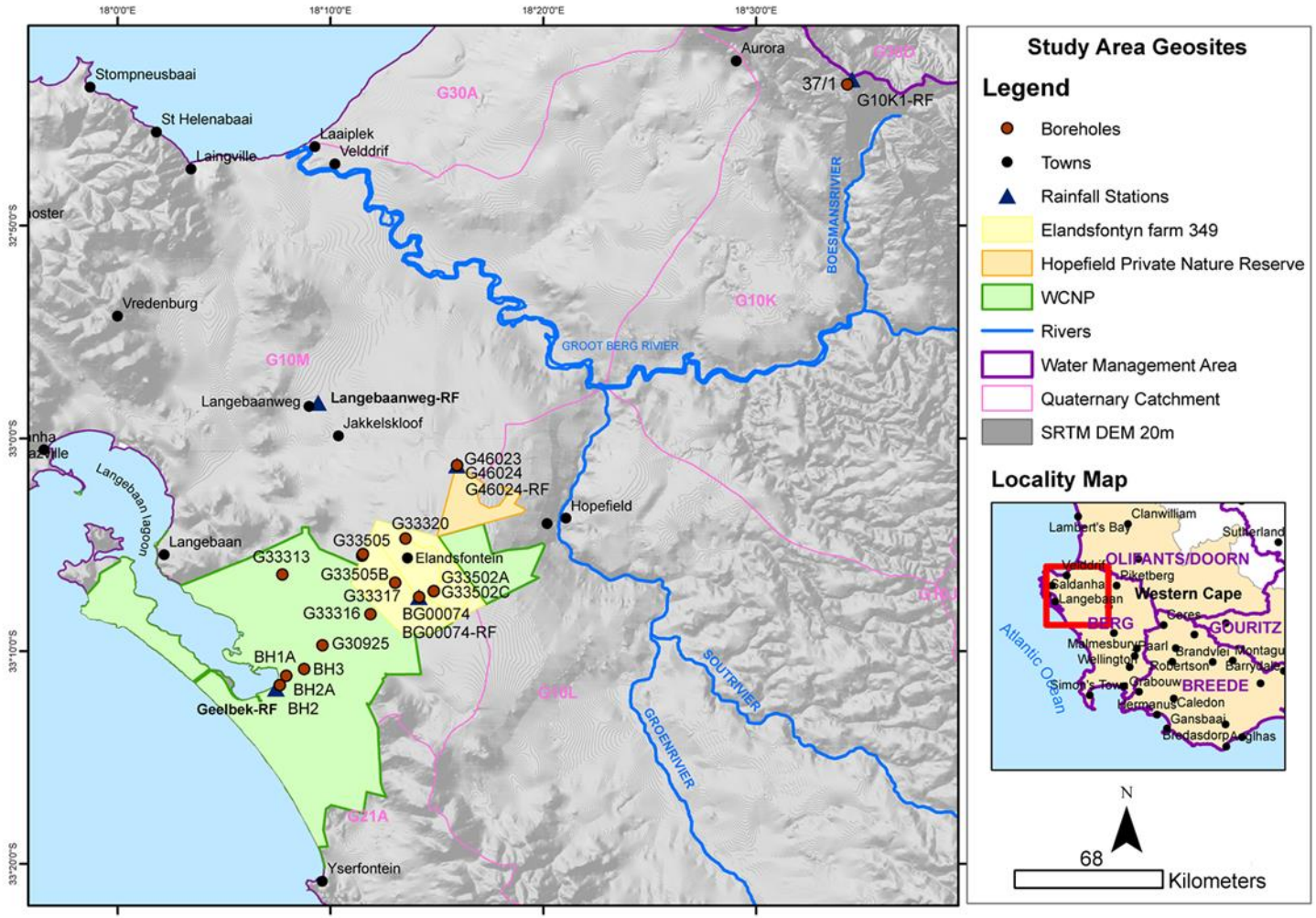

Figure 4.1: Map displaying all the monitoring geosites of the study area in the West Coast.

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Another monitoring area was selected in quaternary catchment G10M that forms part of the Langebaan Road aquifer located in Hopefield Private Nature Reserve. Three geosites consisting of 2 boreholes, 1 rain gauge and isotope sampler were identified for this area to determine the local recharge for the EAS (see Table 4.2).

Table 4.2: The location, altitude, depth of the Departmental boreholes and rainfall station in the Hopefield Private Nature Reserve area.

LRAS	Geosite_ID (NGA_ID)	Latitude S (°)	Longitude E (°)	Elevation (mamsl)	Borehole depth (m) and geosite type
Hopefield Private Nature Reserve route	G46023	-33.02111	18.26570	89	77
	G46024	-33.02123	18.26626	91	18
	G46024-RF & isotope rainfall sampler	-33.02101	18.26586	92	Rainfall gauge

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The monitoring network for the study mostly focused on the coastal plain located in the Elandsfontein area in quaternary catchment G10M. The EAS is situated on the Elandsfontyn farm 349 and Geelbek, WCNP (see Table 4.3) in order to investigate the discharge zone and flow path of the EAS.

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Table 4.3: The location, altitude, depth of the Departmental boreholes and rainfall station in Elandsfontein; and Geelbek, WCNP representing the discharge area.

EAS	Geosite_ID (NGA_ID)	Latitude S (°)	Longitude E (°)	Elevation (mamsl)	Borehole depth (m) and geosite type
Elandsfontein route	G33320 VL1	-33.07849	-33.07849	87	80
	G33320 VL2	-33.07849	-33.07849	87	42
	G33502A	-33.11956	18.24752	102	159
	G33502C	-33.11978	18.24746	99	66
	BG00074	-33.12440	18.23593	93	102
	BG00074-RF & isotope rainfall sampler	-33.12440	18.23593	94	Rainfall gauge
	G33505	-33.09064	18.19211	82	126
	G33505B	-33.09192	18.19130	82	161
	G33317	-33.11320	18.21729	81	138
	G33316 VL1	-33.13773	18.19792	64	83
	G33316 VL2	-33.13773	18.19792	64	35
	G33313	-33.10663	18.12896	63	57
	G30925	-33.16211	18.16035	78	117
Geelbek WCNP route	BH3	-33.18071	18.14599	39	66
	BH1A	-33.18601	18.13195	4	13
	BH2	-33.19332	18.12690	5	45
	BH2A	-33.19331	18.12692	5	13

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4.4 Data collected during the research study

4.4.1 Site inspection of specific boreholes and rain gauges

The field programme included:

- Monitoring of groundwater levels in existing DWS monitoring boreholes to determine time series water level fluctuations;
- Sampling and laboratory analyses of groundwater and rainfall from selected DWS monitoring stations, including three isotope samplers used to acquire water chemistry and stable isotope information.

The data gathered aim to assist with understanding groundwater quality, groundwater recharge sources and preferential flow pathways within the system and to support the development of the conceptual model.

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4.4.2 Groundwater level monitoring

A series of measurements were taken using a Solinst™ water level meter (a probe attached to a permanently marked polyethylene tape, fitted on a reel), at an error of ± 0.02 m for static water levels readings from 19 boreholes (Figure 4.2). These water levels were recorded on a monthly basis for the period from June 2015 to May 2016 for time series observations in water level response to daily rainfall. Most of the boreholes consisted out of automated water level loggers installed in them except for the following boreholes that had no installation of level loggers: 37/1, G33320 VL2, G33502A, G33502C, G33317 and G33316 VL2. Elevation readings were obtained from a Garmin GPS having an error of ± 3 m on the x, y co-ordinate and were used to calculate static water levels in metres above mean sea level (mamsl).

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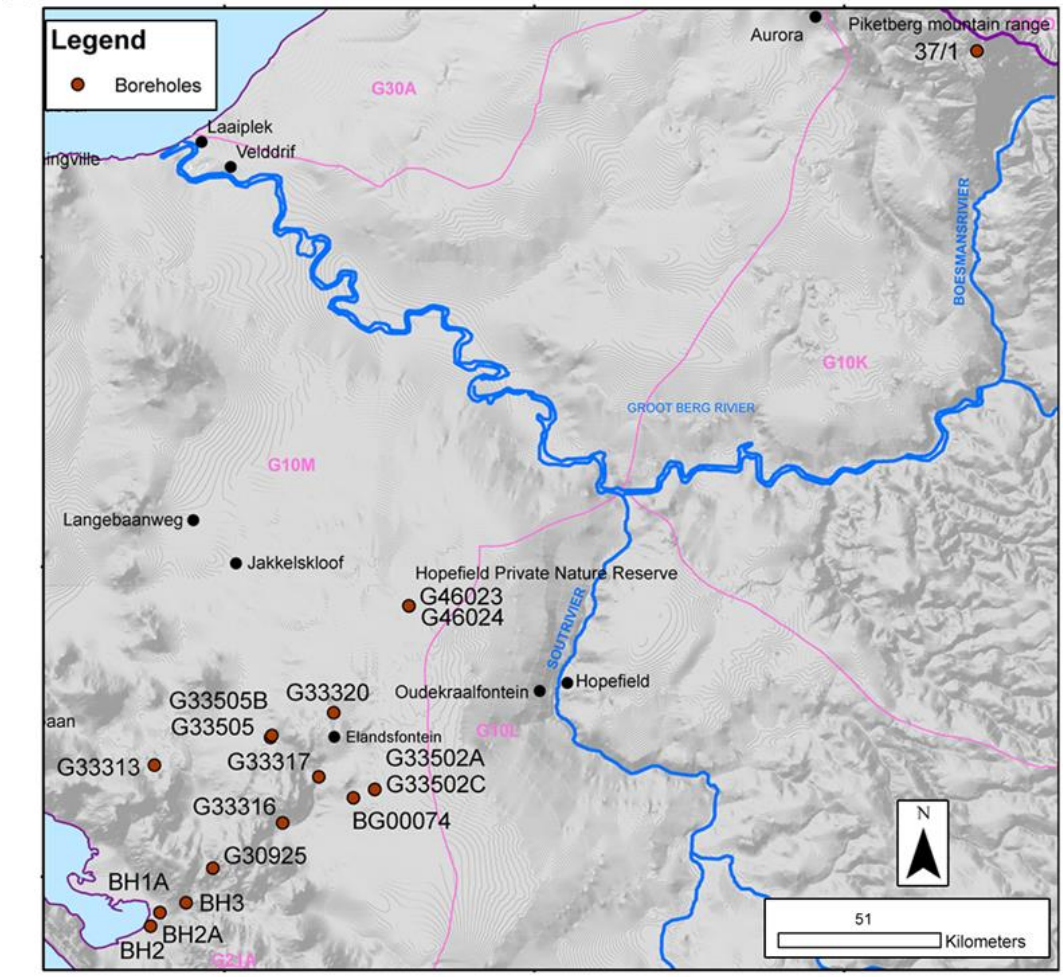

Figure 4.2: Boreholes of the study area in the West Coast.

4.4.3 Rainfall monitoring

The rainfall monitoring programme consisted of 3 cumulative rainfall collectors (Figure 4.3). Three isotope samplers were erected in May 2015 next to existing DWS rainfall stations (Figure 4.4). The installation of the volumetric rainfall collectors/samplers were constructed in the WCNP area located next to the Elandsfontyn farm 249 (rainfall station BG00074-RF), Hopefield Private Nature Reserve (rainfall station G46024-RF) and Mountain Mist on the Piketberg Mountain range (rainfall station G10K1-RF).

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The Departmental rainfall stations BG00074-RF, G46024-RF and G10K1-RF were designed and installed by Eddie Van Wyk in his Doctoral study that formed part of DWS monitoring geosites. The rainfall station is an OTT Hydrometrie Thalimedes stage height logger (Figure 4.4), the rainfall instrument is a 1 m * 100/90 mm OD/ID acrylic tube equipped with a float and counter-weight water level type data logger that measures cumulative time series data to record rainfall events. The accuracy recorded of the OTT Hydrometrie Thalimedes stage height logger is 0.005 m (Van Wyk, 2010), and monthly samples from the 3 cumulative rainfall collectors and isotope samplers were collected over a period of one year from June 2015 to May 2016.

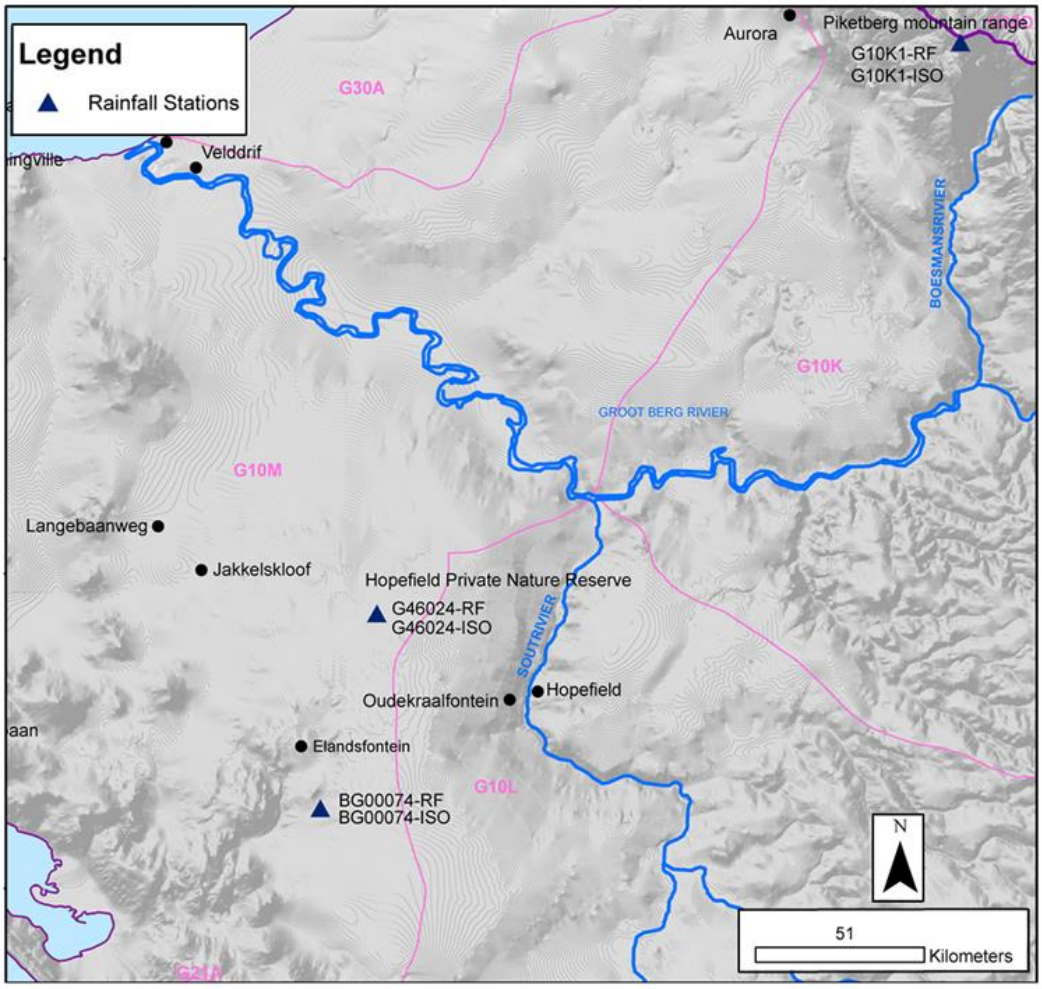

Figure 4.3: Rainfall stations of the study area in the West Coast.

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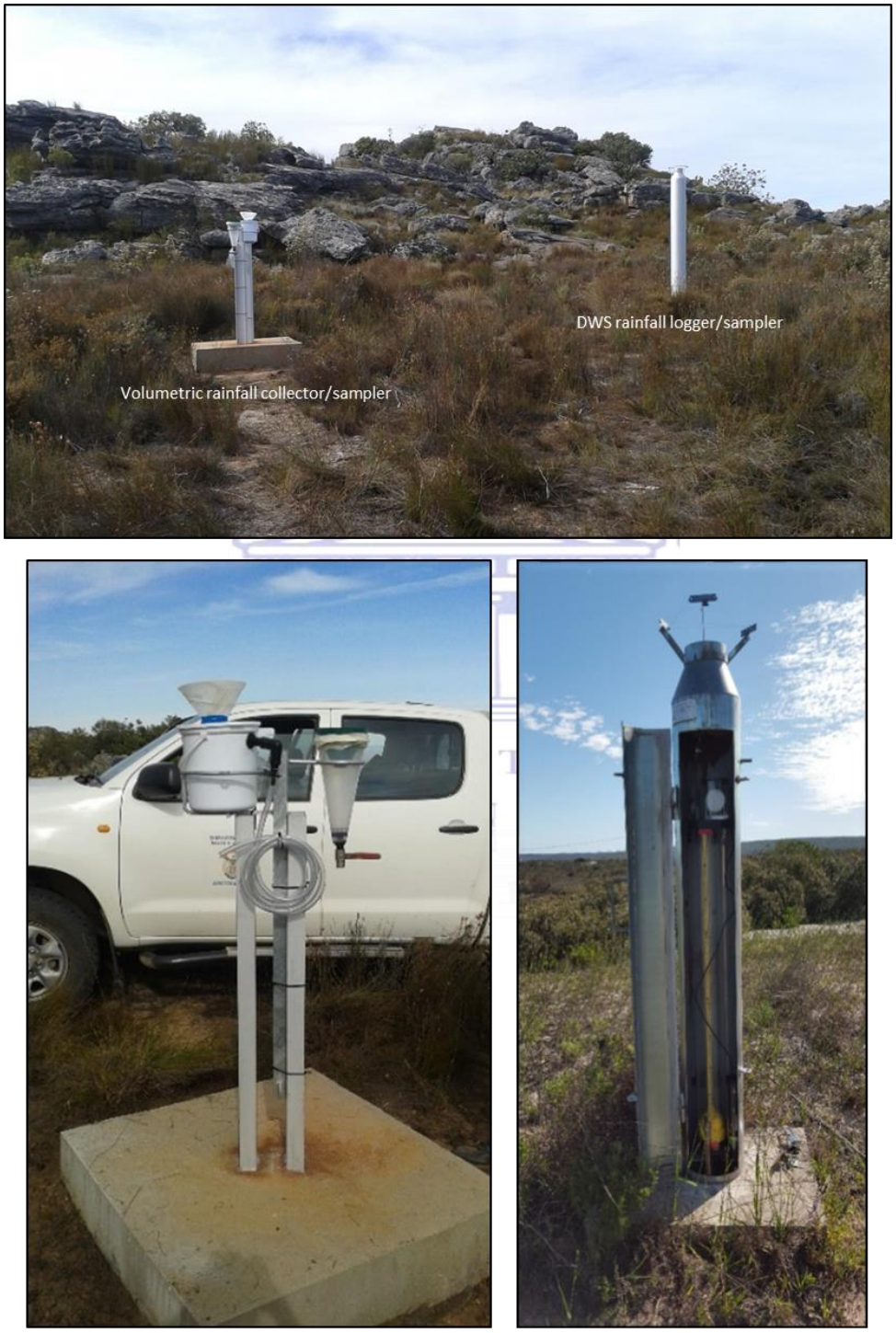

Figure 4.4: Displaying volumetric rainfall collector and isotope sampler (left) and DWS cumulative rainfall collector (right).

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Local rainfall stations from SAWS were assessed to determine if there was a correlation between the EAS boreholes but only one local rainfall station named Langebaanweg had a reasonable correlation with the EAS boreholes. Three SAWS rainfall stations located in Malmesbury, Porterville and Paarl were selected for regional scale representation of the study area, (Figure 4.5). Whereby, Porterville and Paarl presented a better correlation for the water level responses of the EAS boreholes and study area. The location of the three rainfall stations are as follows:

- Malmesbury, located ± 40 km from the coast along the West Coast situated ± 63 km from Geelbek, WCNP;
- Langebaanweg, located ± 18 km north west from Elandsfontyn farm 349 and ± 13 km north west from Hopefield Private Nature Reserve;
- Porterville situated at the base of the Cederberg mountain range and
- Paarl consists of a granite mountainous region which is situated furthest from the coast and is the highest area in elevation in relation to the study.

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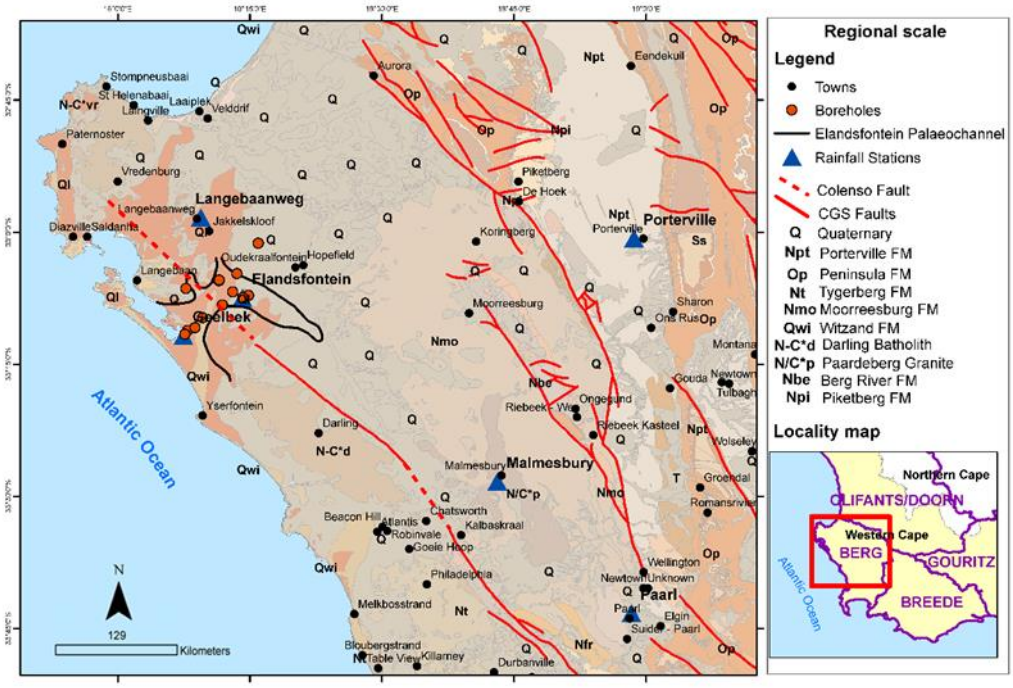

Figure 4.5: Regional scale map of study boreholes and rainfall stations relative to regional fault system, (geology from Council of Geoscience geology 1:250 000).

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4.5 Cumulative rainfall departure method

The Cumulative Rainfall Departure method is a water balance approach and is based on the principle that groundwater level fluctuations are caused by rainfall events. Bredenkamp applied the method successfully in South Africa on dolomitic aquifers (Stephens and Bredenkamp, 2002; Xu and Beekman, 2003). The following two equations of the CRD method that was first proposed by Bredenkamp et al. (1995) were applied to the study area. The CRD method was derived from the following mathematical equation:

$$av^1CRD_i = Rf_i - kRf_{av} + av^1CRD_{i-1} \quad \text{Equation 4.1}$$

Where: CRD_i is the accumulative rainfall departures from the mean at time i, RF_i is the rainfall at time i, k equates to 1 that indicate natural conditions and k > 1 indicate that the aquifer is being exploited; and RF_{av} is the average rainfall.

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Whereas, to calculate the short and long term memory responses for the effective recharge to the natural water balance were represented by the following equation:

$$\text{RE} = a(Rf - k.Rf_{av}) \quad \text{Equation 4.2}$$

Where: k equates to 1 that indicates the natural situation and k > 1 indicate that the aquifer is being exploited. The equation shows that when rainfall is more that the average for the selected time interval (short and long term) recharge occurs. The opposite applies for no recharge when rainfall is less than the average. The effect of pumpage (Δk) is incorporated inside the brackets whereby its influence is reduced depending on the value of **(**a) which is normally less than 1.

The method required monthly rainfall and groundwater level data for simulations to determine the water level fluctuations, which was obtained from the DWS boreholes and long term monthly rainfall data from SAWS. The groundwater level data for all 19 boreholes were sourced from historic time series data on the

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DWS database Hydras 3 software (January 2007 till August 2016) including the monthly monitoring data from June 2015 to May 2016 during the research study.

The SAWS rainfall stations used for the study were automated instruments that recorded daily rainfall over a period of almost 10 years (January 2007 to August 2016) for the CRD simulations. The rainfall stations were located at Geelbek (station 0040192 4), Langebaanweg (station 0061298 8), Piketberg (station 0062444 7), Porterville (station 0041871 1), Malmesbury (station 0041418 8) and Paarl (station 0021823 0), which measured the rainfall depth at daily time steps. The automated instrument has a high precision and measures rainfall in 0.254 mm and accuracy is 50 mm/h.

Monthly average rainfall values for the CRD simulation of 1,2,3,6 and 12 month average rainfall values were used for the short term memory and obtained from the SAWS and DWS rainfall stations. As for the long term reference value, rainfall values from all the rainfall stations were used to determine the average rainfall for 3 years (36 months), 5 years (60 months) and 10 years (120 months) preceding a specific month. A correlation coefficient for both short and long term between the measured water level and all the simulated CRD values was calculated. For the local and regional scales the highest correlation coefficient to the measured water level response were then used for the CRD simulation (Peterson, 2012).

4.6 Hydrochemistry and stable isotope sampling procedure

The monthly sampling procedure to sample for hydrochemical and stable isotope ($\delta^{2}H$ and $\delta^{18}O$) analysis from the boreholes and rain gauges was as follows: Initially, an elevation and co-ordinate from a Garmin GPS for all geosites were recorded for the first month. Before every sampling event the total depth and depth to the water level were measured within the borehole before sampling.

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In order to retrieve a groundwater sample, a Low-Flow Purging (Figure 4.6) and discrete depth sampling methods were applied. The method is based upon the use of a submerged pump that can be lowered down a borehole at specific depths to abstract groundwater to the surface at rates of 100 ml per minute to a maximum of 1 litre per minute (Durham Geo Slope Indicator, 2003). The purpose of this technique is to collect a representative sample of water in the formation in which the borehole screen is penetrating. The discrete depth sampler collected water at specific depths, where the borehole screens were situated in a borehole column to avoid minimal disturbance of water as opposed to purging with a bailer method.

The EXTECH Model D0700 was calibrated before the monitoring trip and was calibrated against the following standards for pH (4, 7 and 10 at 25°C) and EC (1413 µS/cm at 25°C). A submerged pump was then used to extract the water from the borehole and pumping continued until the EC and temperature readings were stabilised using the conductivity/temperature probes of a portable EXTECH Model DO700 multi-parameter meter. Before the sample was taken a grab sample was collected in a plastic beaker whereby the beaker was rinsed thrice with the geosite water. Thereafter, field parameters were measured and tested for in-situ parameters which included pH, electrical conductivity (EC) and temperature. The hydrochemical samples were collected in clear 250 ml polyethylene sample bottles (LHTT220-jar-cap). The stable isotope samples were collected in sterile 100 ml bottles (LLPS294221 W/M grad with inner seal and screw cap) and then filtered through a 0.45 µm membrane filter at the UWC laboratory before being analysed with the LGR Laser Isotope Instrument. All samples were kept in an automated cooler box during the day and refrigerated at night during the sampling trip. The hydrochemical samples were taken to Bemlab (Pty) Ltd laboratory in Strand, Western Cape after every sampling trip and the stable isotope samples stored in the UWC Earth Science laboratory.

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Figure 4.6: Displaying the Low-Flow Purging method.

4.6.1 Hydrochemistry analysis

Laboratory analysis of groundwater and rainfall from selected DWS monitoring stations was done to acquire water chemistry information. The 22 DWS geosites samples were analysed for major ion composition, pH, electrical conductivity (EC) and alkalinity at Bemlab (Pty) Ltd laboratory. The concentrations of major ions were analysed using ICP-OES, Titrimetric method and Auto analyser according to ISO 17025 and ISO 15189 standards and SANAS accredited.

4.6.2 Stable isotope $\delta^{2}H$ and $\delta^{18}O$ analysis

The 22 DWS geosite water samples were analysed at the Earth Sciences Department at the University of the Western Cape (UWC) Water Quality analysis laboratory, Bellville, South Africa. These samples were analysed using the LGR Laser Isotope Instrument (Figure 4.7). The water samples for this study were analysed using the off-axis integrated cavity output spectroscopy (OA-ICOS) method. The LGR laser isotope instrument uses off-axis integrated cavity output spectroscopy to measure absolute abundances of ^{2}HHO, HH^{18}O and HHO through laser absorption. Various natural and synthetic water standards and samples with a large range of isotope values were tested. The results demonstrated an adequate

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analytical precision and accuracy, these precisions are estimated to be 1‰ for $\delta^{2}H$ and 0.2‰ for $\delta^{18}O$ (IAEA, 2009b)

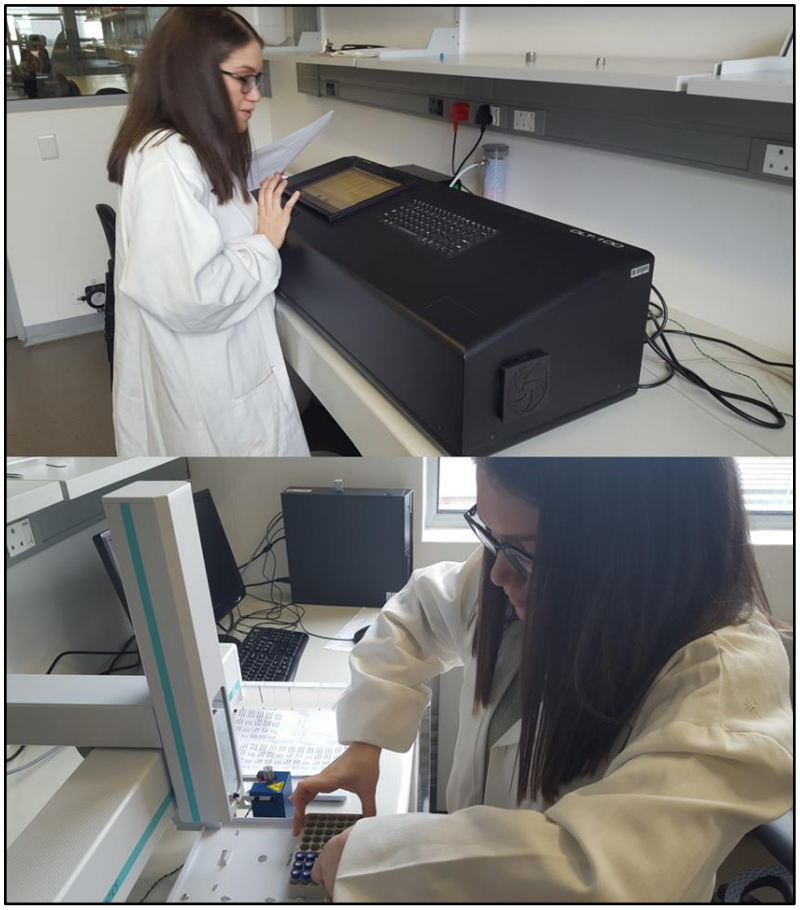

Figure 4.7: Displaying the LGR Laser Isotope Instrument.

4.6.2.1 Analytical procedure

The procedure adopted two calibration standards and a control standard with an intermediate isotopic composition. Measurements and known δ values for calibration standards were interpolated by means of a linear regression to convert measured absolute $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios (permil deviation of the isotope ratio from a standard) to delta values. The control standard was not included in the calibration and therefore it could be used as an indicator of the analysis accuracy by comparing the known value to the value measured by the laser spectroscope during the analysis. From the above equation one can conclude that R is the

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isotope ratio of the heavy to the light isotope (e.g. $^{18}O/^{16}O$) of the sample and the standard. For data normalization, the three standards UWC, EWC, EVIAN (Figure 4.8) were calibrated directly against VSMOW2 and SLAP2 international standard waters and the data were normalized to the VSMOW/SLAP scale. Standards used, were #1A, #4A and #5A. The values for standards #1A, #4A and #5A are -9.92 $\delta^{18}O$, -74.11 δD; -6.63 $\delta^{18}O$, -40.72 δD and -2.77 $\delta^{18}O$, -8.39 δD respectively.

Figure 4.8: Collecting snow for local standard to calibrate directly against VSMOW2 and SLAP2 international standard waters (Matroosberg Mountain).

All water samples were first filtered and 53 vials filled with 1-1.15 ml of water sample leaving approximately 0.5 ml headspace. The vials were sealed with a silicon septum cap to prevent evaporation during the analysis and placed into a 54 position tray on the auto-injector tray holder. Each vial was injected six times, and the first two measurements were discarded to reduce the memory effect being the influence of the previously injected sample on the isotopic content, with the reportable value based on the average of the last four injections. Every run commenced with a dummy sample to prime the flow with deionized water to clean the syringe (IAEA, 2009b). Standards were grouped in triplets, and samples formed sets of five unknowns.

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All values are expressed in the standard delta notation in the permil (‰) relative to VSMOW as:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \qquad \text{Equation 4.3}$$

From the above equation one can conclude that R is the isotope ratio of the heavy to the light isotope (e.g. $^{18}O/^{16}O$) of the sample and the standard. Isotopic measurement results were copied from the LGR Laser Isotope Instrument with a flash drive and data was processed in Microsoft Excel.

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4.6.2.2 Post analysis data correction procedure

For quality control check measures all raw data was imported into LGR's LWIA Spectral Contamination Identifier™ (version 1.0.0.69) and used to identify any samples that may have organic contaminants (alcohol, plant and soil water extracts, etc.) that can cause severe spectral interference, leading to poor isotopic measurement results. All the samples for the study underwent strict quality check measure processes and shown successful isotopic measurement results.

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CHAPTER 5
RESULTS AND DISCUSSION: CUMULATIVE RAINFALL DEPARTURE (CRD)

5.1 Introduction

The rainfall and water table response were analysed to evaluate the delay in peak times between rainfall and recharge using the CRD method (Bredenkamp et al. 1995). All monitoring boreholes and rainfall stations were analysed for the CRD correlation simulations. Analysis included historic water level and rainfall data from DWS monitoring records together with the monthly data collected for this study over a period of one hydrological year that commenced in 2015. Rainfall data from SAWS and DWS rainfall stations were collected and analysed as referred to in Chapter 4. Table 5.1 displays the results of the monitoring boreholes and their correlations with the various rainfall stations for the CRD simulations. Boreholes G46023 and G46024 are not situated in the Elandsfontein aquifer but in the Langebaan Road aquifer and were used to identify possible recharge processes to the EAS.

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Table 5.1: CRD correlations used for all the study geosites.

Elandsfontein aquifer	Boreholes	Rainfall station	CRD memory	Correlation coefficient (R^2)
Shallow	G33316 VL2	Paarl	12/120	0.90
		BG00074-RF	6/36	0.41
		Malmesbury	12/36	0.19
	BG00074	Langebaanweg	6/60	0.83
	G33313	Geelbek	6/36	0.41
	G33502C	Paarl	6/60	0.79
		BG00074-RF	6/36	0.14
			6/60	0.05
Deep	G33316 VL1	Paarl	6/120	0.77

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Langebaan Road aquifer	Boreholes	Rainfall station	CRD memory	Correlation coefficient (R^2)
Shallow	G46024	Porterville	12/60	0.89
		Langebaanweg	6/60	0.79
Deep	G46023	Porterville	6/120	0.78

Potential recharge processes were inferred from short term (6/36) and long term (6/60; 12/60; 6/120 and 12/120) memory of the system. The results are discussed based on the best fit CRD correlation to infer the recharge processes at regional and local scales.

5.2 Results

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The local spatial distribution of boreholes in the study area is displayed in Figure 5.1. The water level in the area is known to be relatively stable and no large temporal variations are observed. Possible factors contributing to this may be as a result of limited recharge in the area and high storage in the aquifer as well as the proximity of discharge area for the boreholes situated near Geelbek. The local groundwater flow direction is predominantly from an east to south-westerly direction but may be locally influenced by the topography, palaeochannel and surrounding granite hills (Figure 5.1).

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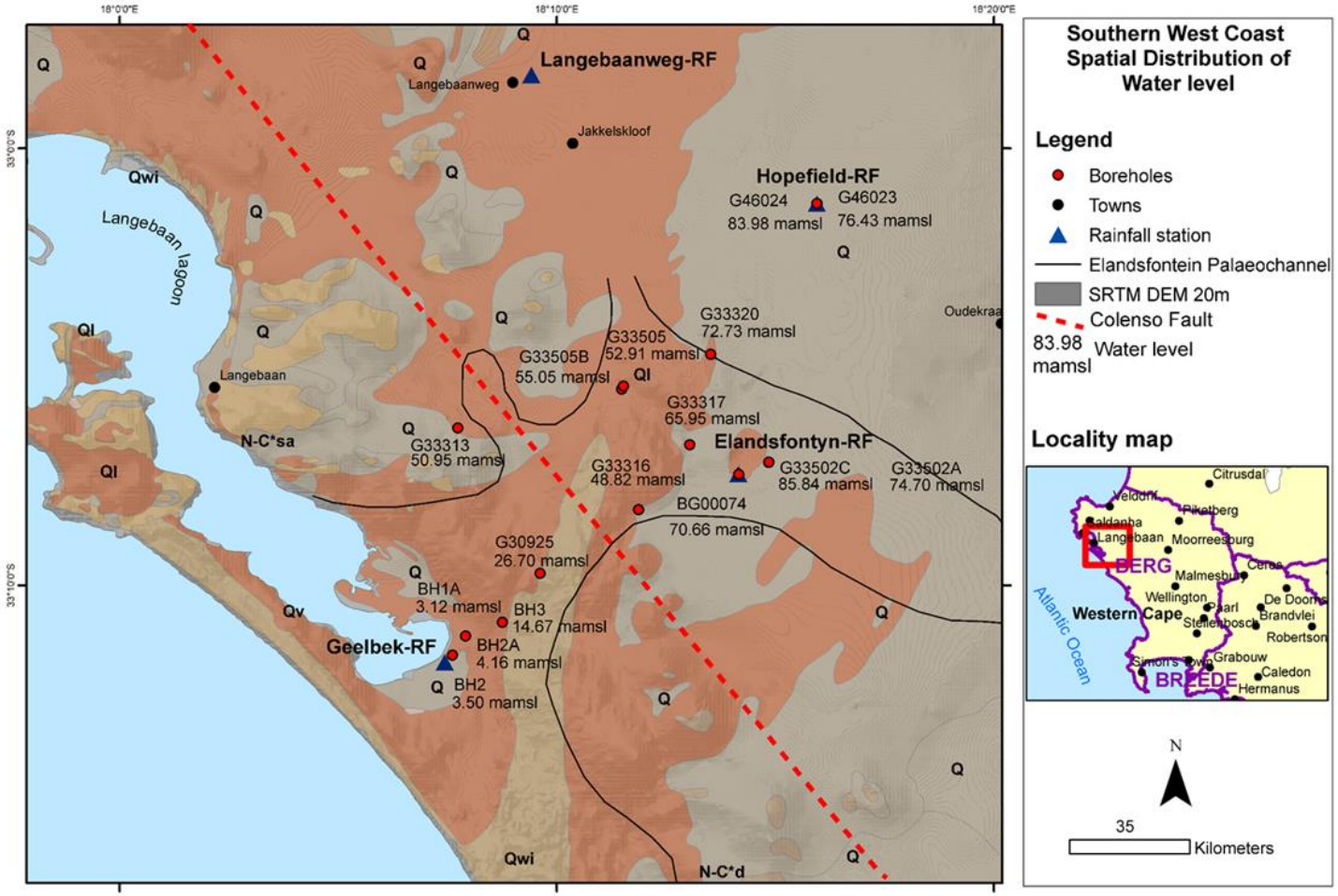

Figure 5.1: Spatial distribution of the local water level (mamsl) for the study area (geology from Council of Geoscience 1:250 000).

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5.2.1 Cumulative Rainfall Departure simulations

Borehole G33316 VL2 best fit with Paarl rainfall station

G33316 VL2 is situated in the shallow aquifer at a depth of 35 mbgl on the Elandsfontyn farm 349, with a best fit correlation using a CRD 12/120 and Paarl rainfall (Figure 5.2).

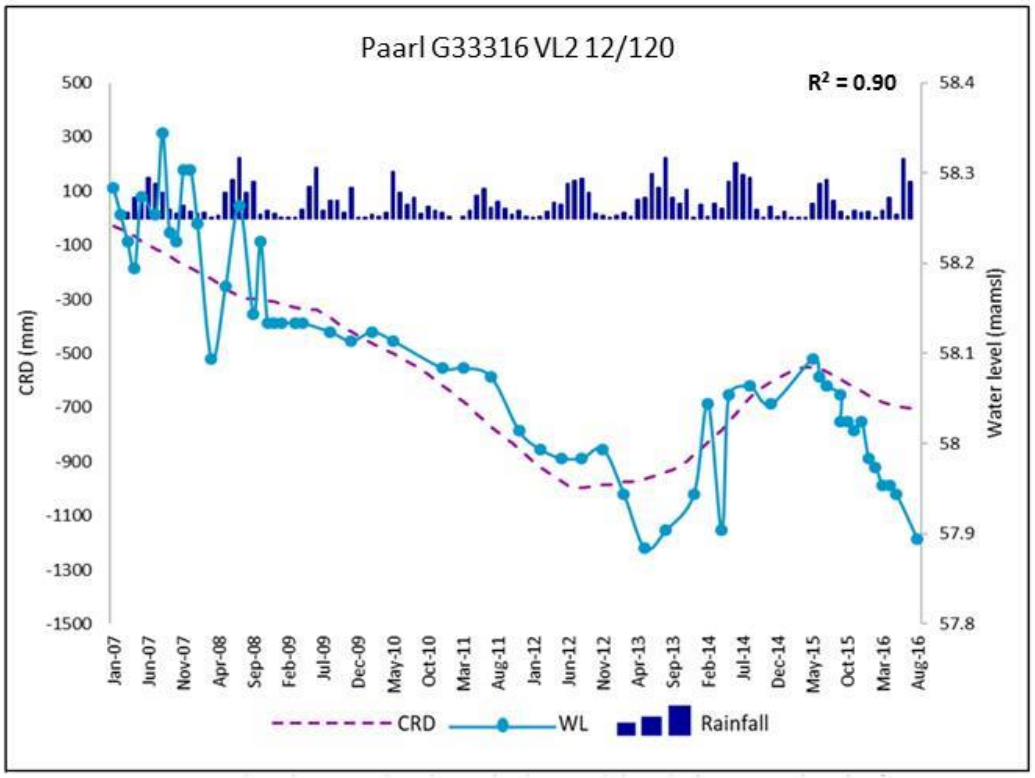

Figure 5.2: CRD simulated water levels and observed borehole water levels for G33316 VL2 located in Elandsfontein derived from monthly rainfall of the Paarl rainfall station.

A CRD 12/120 is the average rainfall over 12 months relative to a 120-month (10 years) average rainfall (Peterson, 2012); with the 120 month CRD memory indicative of a long memory response to the water levels. The comparison between the CRD and measured water level is illustrated in Figure 5.2, indicating that the CRD mimics the observed groundwater levels well. The observed groundwater level trend demonstrates a steady gradual decline of 0.52 m from

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January 2007 to April 2013 and thereafter increase by 0.11 m until May 2015. For the period from May 2015 to August 2016 a decline of 0.09 m was observed with the CRD simulated response that indicated an increase of 0.43 m over 31 months during the period September 2012 to April 2015.

Boreholes G46024 and G46023 best fit with Porterville

Borehole G46024 is located in Hopefield Private Nature Reserve with a borehole depth of 18 mbgl and is situated towards the Langebaan Road aquifer north of the Elandsfontein aquifer. The best fit correlation for G46024 water level was achieved using a CRD 12/60 using Porterville rainfall as seen in Figure 5.3.

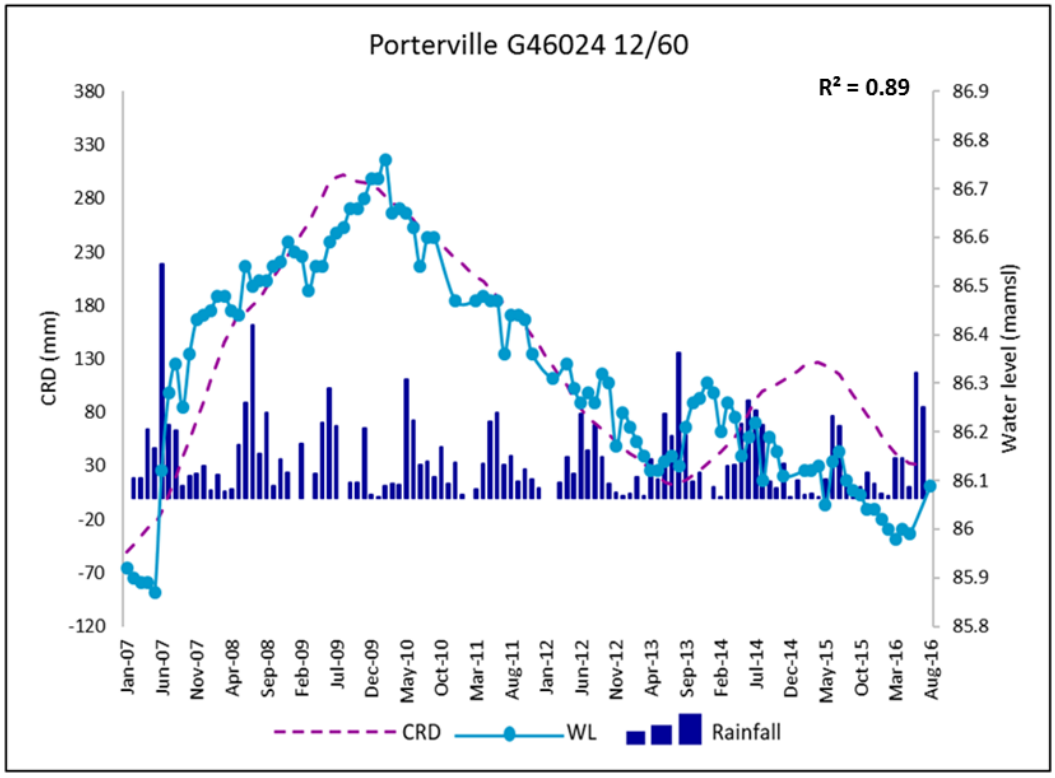

Figure 5.3: CRD simulated water levels and observed borehole water levels for G46024 derived from monthly rainfall of the Porterville rainfall station.

A CRD 12/60 is the average rainfall over 12 months relative to a 60 month (5 years) average rainfall (Peterson, 2012). This 5-year long term memory is indicative of a regional scale groundwater flow system whereby a gradual decline

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of the groundwater level from 86.8 – 86 mamsl observed over a period from January 2010 to May 2016; displays gradual fluctuations in the system and demonstrates that a distant regional scale groundwater recharge system is indicated.

Borehole G46023 is directly next to G46024 with a depth of 77 mbgl into the deeper part of the aquifer. The best fit correlation for G46023 was achieved using a CRD 6/120 with Porterville rainfall as referred to in Figure 5.4.

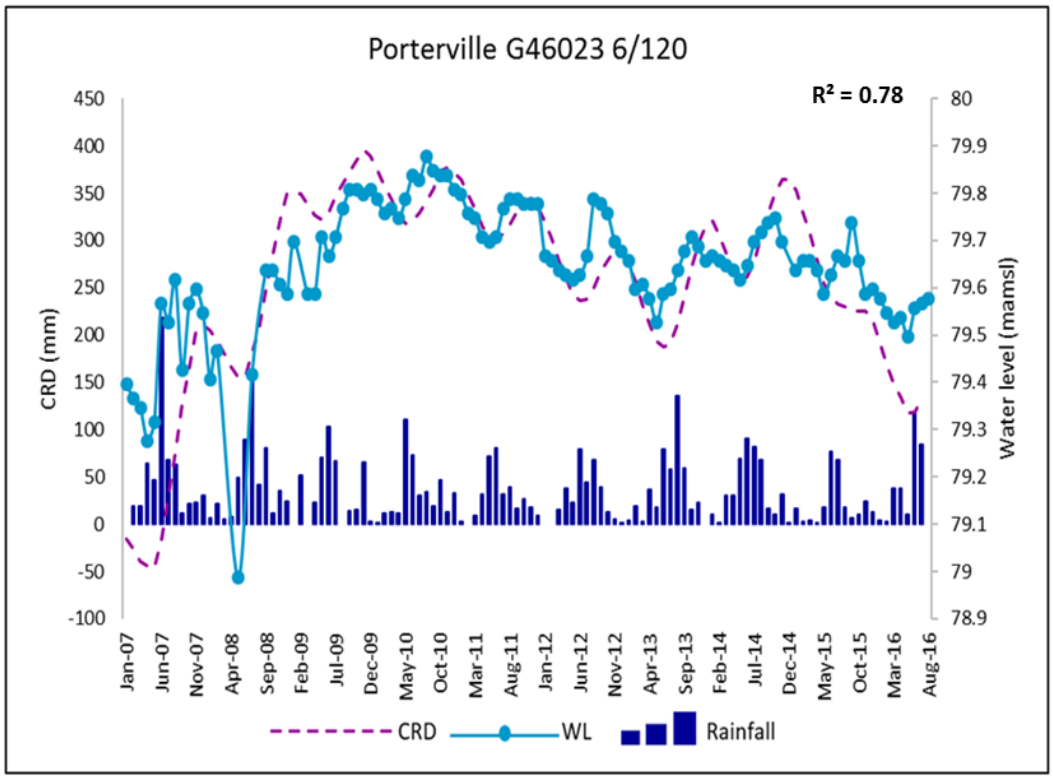

Figure 5.4: CRD simulated water levels and observed borehole water levels for G46023 derived from monthly rainfall of the Porterville rainfall station.

A CRD 6/120 is the average rainfall over 6 months relative to a 120 month (10 years) average rainfall. The short term memory of 6 months indicates seasonal effects superimposed onto a 10-year long term regional response of the system.

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Borehole BG00074 best fit with Langebaanweg rainfall station

Borehole BG00074 is located in SANParks next to the Elandsfontyn farm with an initial depth of 102 mbgl but collapsed at a depth of 92 mbgl and is situated on a high elevated dune of 102 mamsl. Due to its high altitude borehole BG00074 is possibly sited in the shallow aquifer of the Elandsfontein system. The best fit correlation for borehole BG00074 was achieved using a CRD 6/60 with Langebaanweg rainfall (Figure 5.5).

A CRD of 6/60 is the average 6 months' rainfall relative to a 60 month (5 years) average rainfall (Peterson, 2012). The groundwater level trend illustrates a gradual decline of 1.01 m throughout the data series period of ~ 10 years. The CRD simulated response for borehole BG00074 indicates that the observed water level responds to 6 month preceding cumulative rainfall events, which amounts between 0.4 m to 0.14 m superimposed onto the long term trend. Although, the CRD illustrates small amounts of water level response, the aquifer shows a long term response to rainfall events over the entire area and is an indication of long term average rainfall contributing to the area rather than direct recharge. The water level fluctuation after 2013 for borehole BG00074 varies between a range of 0 to 0.10 m and therefore the water level did not respond to seasonal fluctuations, resulting in the aquifer system responding to a long term of 5 – 6 year wet and dry cycles.

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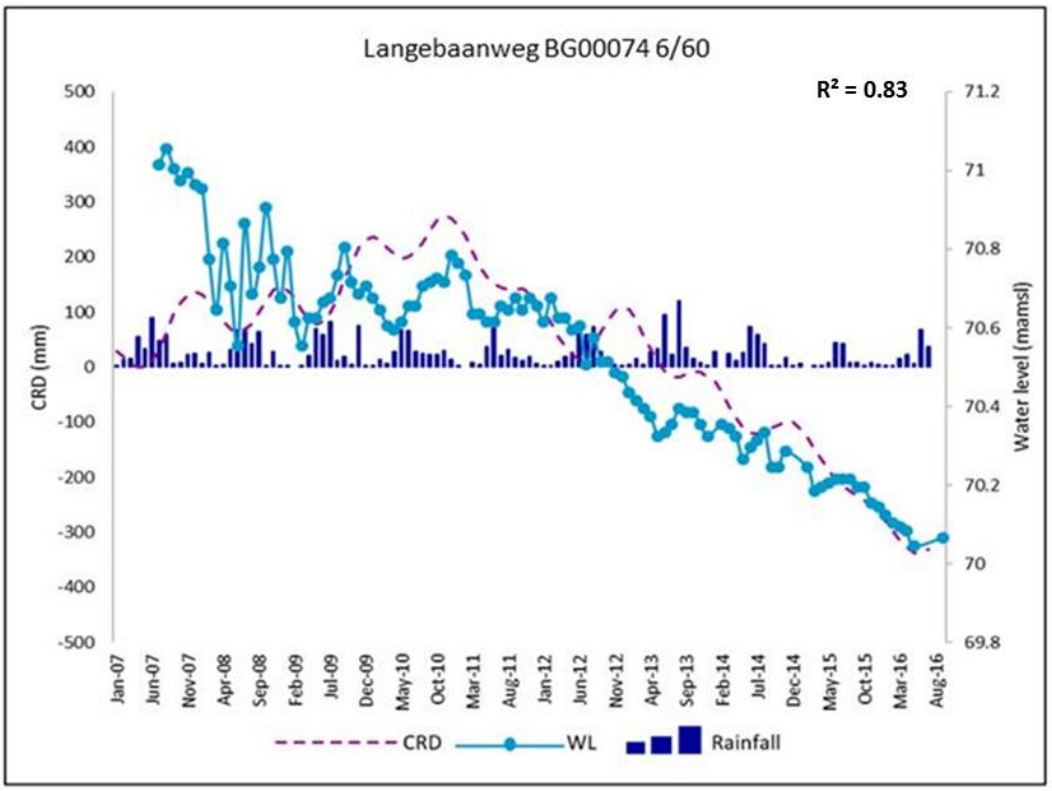

Figure 5.5: CRD simulated water levels and observed borehole water levels for BG00074 located in Elandsfontein derived from monthly rainfall of the Langebaanweg rainfall station.

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Borehole G33313 best fit with Geelbek rainfall station

Borehole G33313 is situated in the shallow aquifer at a depth of 57 mbgl that is at a distance of 8.8 km from Geelbek at the Langebaan Lagoon and located below the foot of a granite outcrop. A CRD 6/36 with Geelbek rainfall showed the best correlation coefficient for borehole G33313. This correlation illustrates a short term (6 month) seasonal response to rainfall events, superimposed on a 3 year long term trend derived from the Geelbek rainfall and proposes local recharge in the area.

During the wet season it is apparent that groundwater levels rise after rainfall events and then decline in the dry summer months. In Figure 5.6 it is evident that the water level responds quickly to high rainfall events. In August 2013 one of the

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highest rainfall events took place of 120 mm and the water level responded by 0.08 m a month later in September; with the water level response possibly indicating preferential recharge.

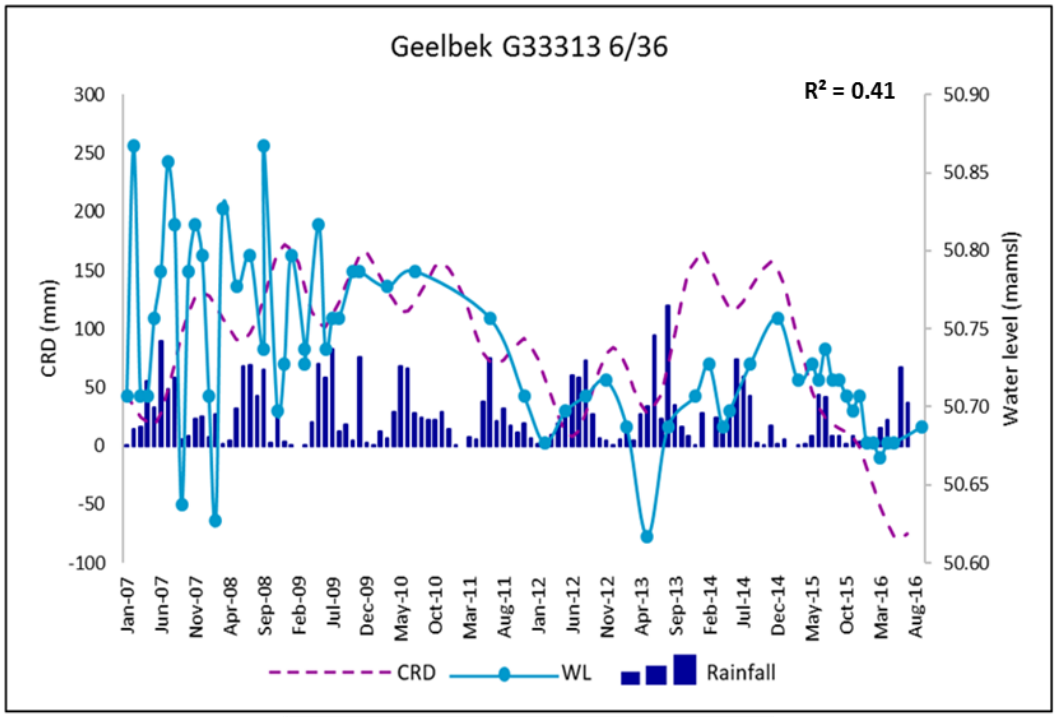

Figure 5.6: CRD simulated water levels and observed borehole water levels for G33313 derived from monthly rainfall of the Geelbek rainfall station.

5.3 Discussion

The CRD simulation results for borehole G33316 VL2 using a 120 month long term memory, could be indicative of the slow processes in the system or the distance from the recharge area. Therefore, the results for boreholes G33316 VL1, G33316 VL2 and G33502C; correlating with the Paarl rainfall station from the CRD simulation and measured water level response mimics that of regional recharge processes. This could explain the recharge process as a longer response time for the EAS. The CRD simulations provided evidence of regional rainfall contributing to the EAS; furthermore, regional faults also indicate potential

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preferential pathways to the system (Figure 5.7). Additionally, Smith (1982) survey indicated the presence of faults within the bedrock of the Elandsfontein Aquifer System.

Borehole BG00074 CRD simulation results displayed long term average rainfall contributing to the area using the Langebaanweg rainfall. The results obtained from the water level responses are slow ranging between 0.4 m to 0.14 m after a 6 month period. The water level responses are minimal and slow in water movement of which could suggest local recharge processes occurring in the shallow aquifer of the EAS.

The recharge and flow processes dominating the EAS are slow as a result of regional processes present in the system. Infiltration of coastal rainfall can potentially lead to immediate recharge from the surrounded granite hills while infiltration through the calcrete layer can penetrate to the EAS near Geelbek. Timmerman (1985b) identified the high lying area between Langebaan Lagoon and Hopefield to be more favourable to recharge. Consequently, indicating that it is possible that the main source of immediate recharge can be derived from coastal rainfall and the rounded granite hills in the study area.

The possibility of groundwater flow from the Piketberg and Porterville mountain region to the EAS is likely, however, there is a correlation from Paarl which is in line with the faults that flow into the southern palaeochannel contributing to the EAS and then flows into the southern part of the Langebaan Lagoon (Figure 5.7). Borehole G46023 CRD 6/120 long term regional response is indicative of slow recharge processes being observed during a recharge event and shows that the deep borehole is situated far from the regional recharge area.

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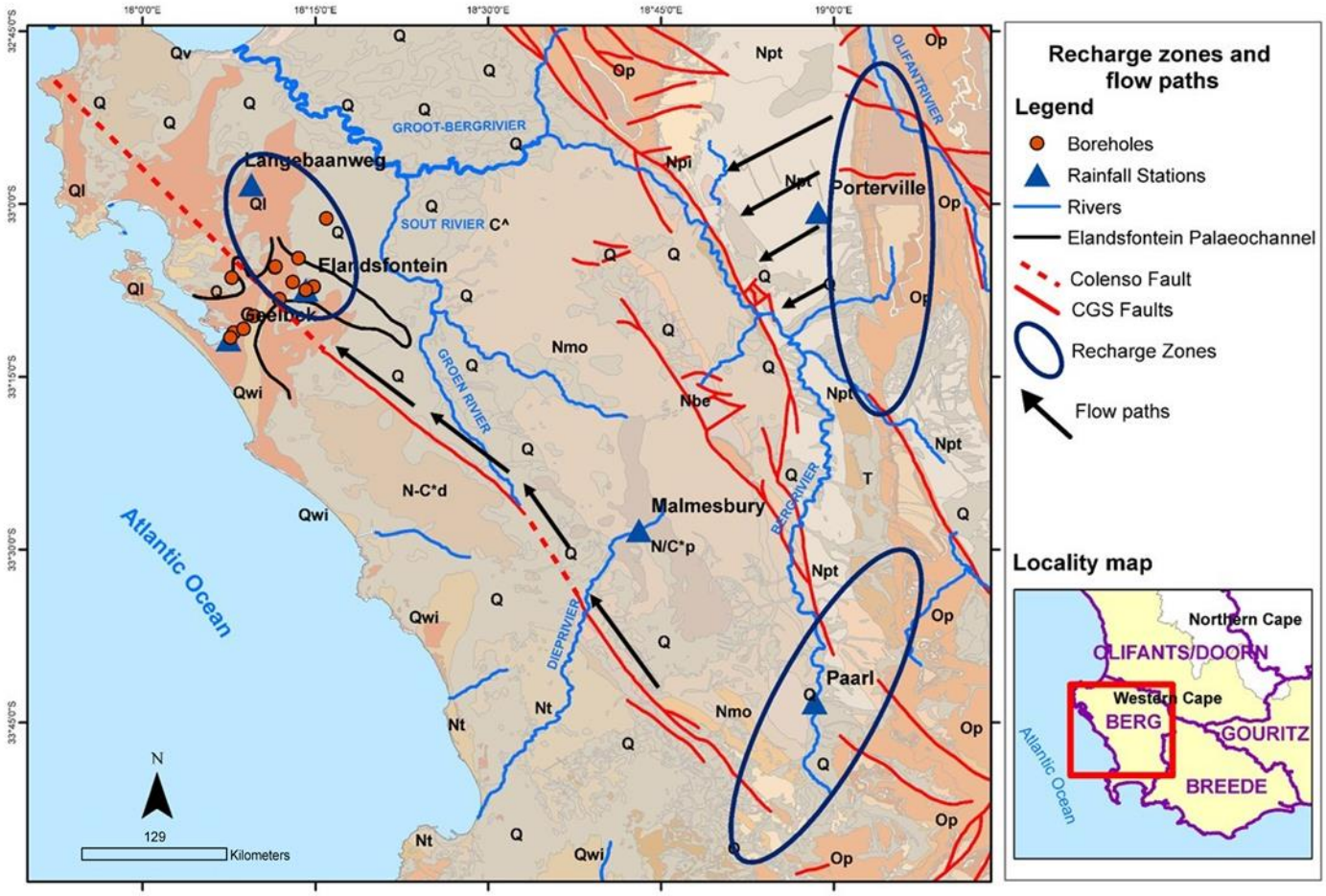

Figure 5.7: Recharge zones and regional flow paths for the Elandsfontein aquifer system and Langebaan Lagoon (geology from Council of Geoscience 1:250 000).

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CHAPTER 6
RESULTS AND DISCUSSION: HYDROCHEMISTRY CHARACTERISATION AND STABLE ISOTOPES δ^2H and $\delta^{18}O$

6.1 Introduction

This chapter will cover data and findings from the hydrochemical analyses of groundwater and rainfall within the Elandsfontein aquifer, as well as down gradient towards Geelbek near the southern part of the Langebaan Lagoon. The purpose of this chapter is to characterise and compare the physicochemical parameters of groundwater, rainfall and the lagoon in order to determine potential discharge of the Elandsfontein aquifer at Geelbek. The present chapter will also address the characterisation of groundwater quality in order to identify flow paths and recharge processes in the EAS, using hydrochemical analyses methods. Furthermore, stable isotopes will be used as a tracer to establish groundwater flow paths.

All the major ions and stable isotopes for the wet cycle in August 2015 are shown in Table 6.1 and the dry cycle from February 2016 in Table 6.2. The characterisation of groundwater hydrochemistry was done using Stiff and Piper diagrams; to determine the major factors governing the hydrochemistry and similarities in physicochemical characteristics of groundwater and the Langebaan Lagoon.

Stable isotopic analysis of δ^2H and $\delta^{18}O$ values was used to identify recharge and flow processes using the isotopic values of precipitation, groundwater and the lagoon. Therefore, the isotope approach was applied and compared to the recharge processes obtained from the CRD simulations. The isotope composition of the groundwater was used to establish whether recharge was of higher elevation, immediate or evaporated. The isotopic composition of the boreholes located at

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Geelbek was analysed to identify fresh groundwater and saline water interactions to establish if there are preferred pathways present from the EAS.

6.2 Results

6.2.1 Hydrochemistry characterisation

6.2.1.1 Electric conductivity (EC)

In 2015 all the Departmental boreholes in Geelbek, Elandsfontein, Hopefield Private Nature Reserve and Aurora, Piketberg mountain range was sampled and in-situ readings for EC were collected. An initial indicator of good groundwater quality was observed for EAS. The Geelbek EC readings ranged from ~115 – 7400 mS/m (wet cycle) and ranged from ~118 – 5566 mS/m (dry cycle). The EC readings for the Elandsfontein area ranged from ~52 – 125 mS/m (wet cycle) and ranged from ~47 – 100 mS/m (dry cycle). Hopefield Private Nature Reserve EC readings ranged from ~52 – 60 mS/m (wet cycle) and ranged from ~47 – 54 mS/m (dry cycle); and for Aurora the EC reading recorded was ~4 mS/m indicating a precipitation signature (see Tables 6.1 and 6.2). The dry cycle EC measurements reflect a fresher signature after the winter rainfall from the wet cycle that is an indication of the response to rainfall. The Hopefield Private Nature Reserve EC ranges present a freshwater signature as to that of the EAS and could be due to a source of local rainfall recharging the area.

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Table 6.1: Results of August 2015 hydrochemistry and stable isotope data for the wet cycle of all the monitoring geosites selected for the study area.

Parameters	Units	BH1A	BH2	BH2A	BH3	G30925	G33313	G33505	G33505B	G33316-VL1	G33316-VL2	G33317	G33320-VL1	G33320-VL2	BG00074	G33502A	G33502C	G46023	G46024	37/1	BG00074-RF	G46024-RF	G10K1-RF	Lagoon	Ocean
pH @25°C		6.2	5.7	6.0	6.2	6.5	5.7	6.5	6.7	6.3	6.8	6.2	6.1	5.9	6.4	7.2	7.3	7.3	5.8	3.9	5.9	6.2	6.7	6.0	
EC @25°C	mS/m	115.6	7400.0	298.0	131.5	105.5	119.5	52.8	61.0	80.6	87.5	83.8	80.6	109.4	81.5	125.4	100.8	60.9	52.2	7.5	7.1	12.7	4.4	4670.0	
TDS	mg/L	691.0	44330.0	1783.0	790.0	636.0	722.0	317.0	366.0	484.0	525.0	500.0	483.0	656.0	489.0	755.0	606.0	365.0	312.0	44.9	42.5	76.2	26.5	28000.0	
Sodium Na^{+}	mg/L	122.7	9652.5	473.8	161.7	173.5	162.7	74.6	75.6	84.8	107.8	101.5	93.1	141.0	92.1	232.8	122.2	64.9	52.4	7.8	5.9	6.0	10.1	7498.1	
Potassium K^{+}	mg/L	4.3	405.4	19.7	3.6	7.8	6.0	2.3	2.1	1.1	1.9	1.9	1.5	2.9	2.0	12.0	2.3	1.8	1.4	0.1	0.6	0.4	0.4	333.9	
Calcium Ca^{2+}	mg/L	98.4	562.4	122.4	101.6	27.0	57.1	20.0	32.8	71.2	71.6	59.3	52.0	67.3	60.3	64.3	73.7	52.6	32.0	0.3	2.0	9.0	5.1	348.0	
Magnesium Mg^{2+}	mg/L	15.0	532.3	47.9	13.1	2.2	21.0	5.9	6.0	9.3	11.7	8.6	8.1	12.8	6.3	30.8	16.7	5.4	5.9	1.0	0.6	3.5	1.5	471.7	
Chloride Cl^{-}	mg/L	219.5	114564.2	719.7	320.6	302.8	263.1	91.6	110.9	135.9	149.4	161.7	177.4	198.8	143.6	145.4	198.1	109.0	87.6	16.0	11.3	15.6	13.8	20048.7	
Bicarbonate HCO^{3-}	mg/L	215.1	367.9	255.1	202.0	32.1	162.0	111.5	131.8	179.0	205.9	181.0	102.3	134.4	223.6	194.7	193.4	112.8	64.3	0.0	18.4	25.6	19.7	290.5	
Sulphates $SO4^{2-}$	mg/L	32	3645	114	28	4	39	5	4	19	28	12	23	34	9	3	24	15	27	5	6	8	6	2093	
Oxygen $\delta^{18}O$	‰	-3.50	2.28	-3.50	-4.34	-3.85	-4.83	-4.43	-3.90	-4.50	-3.79	-4.50	-3.54	-3.45	-3.08	-3.57	-3.78	-3.45	-3.54	-3.59	-2.41	-1.91	-4.97	2.28	0.25
Deuterium $\delta^{2}H$	‰	-20.89	7.81	-17.52	-29.05	-20.82	-24.59	-13.39	-27.52	-14.95	-24.88	-19.12	-27.88	-15.08	-25.90	-16.33	-25.13	-19.05	-14.37	-9.16	-5.88	-2.90	-29.21	7.81	2.30

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Table 6.2: Results of February 2016 hydrochemistry and stable isotope data for the dry cycle of all the monitoring geosites selected for the study area.

Parameters	Units	BH1A	BH2	BH2A	BH3	G30925	G33313	G33505	G33505B	G33316-VL1	G33316-VL2	G33317	G33320-VL1	G33320-VL2	BG00074	G33502A	G33502C	G46023	G46024	G46024
pH @25°C		7.9	7.6	7.8	7.8	7.3	7.9	7.9	7.9	7.5	7.7	7.5	7.3	7.3	6.4	7.2	7.3	7.3	5.8	5.8
EC @25°C	mS/m	118.6	5566.0	307.0	136.5	108.6	119.0	47.6	56.1	79.3	85.3	75.4	62.0	93.7	61.0	84.5	100.2	54.4	47.9	47.9
TDS	mg/L	759.0	35624.0	1968.0	874	695.0	762.0	304.0	359.0	507.0	546.0	482.0	397.0	599.0	390.0	541.0	642.0	348.0	307.0	307.0
Sodium Na^+	mg/L	122.8	7434.2	524.3	190.7	192.1	174.6	69.1	82.7	92.7	92.1	103.3	76.4	108.9	64.3	109.1	113.3	63.9	55.2	55.2
Potassium K^+	mg/L	4.2	378.9	21.4	4.4	8.0	6.2	2.0	2.1	0.7	0.9	1.8	1.6	1.2	7.0	2.1	1.7	1.2	1.1	1.1
Calcium Ca^{2+}	mg/L	96.0	499.7	115.9	99.3	24.5	56.0	14.1	30.0	68.5	67.4	54.4	32.8	63.1	32.3	57.3	68.1	39.2	30.5	30.5
Magnesium Mg^{2+}	mg/L	14.3	535.5	53.7	15.9	3.4	21.0	5.3	6.0	9.6	9.6	11.3	6.7	9.3	9.7	6.9	15.9	3.7	5.9	5.9
Chloride Cl^-	mg/L	228.0	22140.0	790.0	286.0	295.0	300.0	87.0	96.0	151.0	147.0	181.0	145.0	203.0	119.0	158.0	216.0	106.0	104.0	104.0
Bicarbonate HCO_3^-	mg/L	237.0	277.0	261.0	228.0	18.0	156.0	116.0	161.0	194.0	241.0	170.0	77.0	148.0	87.0	241.0	205.0	111.0	59.0	59.0
Sulphates SO_4^{2-}	mg/L	30	2558	124	33	7	39	1.43	2	21	22	19	14	30	28	1.43	20	12	33	33
Oxygen $\delta^{18}O$	‰	-3.21	-0.87	-3.31	-3.50	-3.35	-3.53	-3.46	-3.58	-3.35	-3.43	-3.62	-3.55	-3.91	-3.35	-3.81	-3.81	-3.51	-3.35	-3.35
Deuterium δ^2H	‰	-13.14	-0.65	-9.61	-12.63	-13.03	-12.42	-12.83	-15.74	-14.80	-11.66	-14.83	-14.73	-12.95	-9.63	-10.96	-15.08	-15.48	-12.93	-12.93

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6.2.1.2 Macro elements analysis

In Figure 6.1 the physicochemical parameters of groundwater and the lagoon are displayed as Stiff diagrams plotting the various water samples in the study area. A polygonal shape is created by plotting ions in milliequivalents per litre on either side of a vertical zero axis; cations are plotted on the left and anions on the right hand side. The blue Stiff diagrams that were plotted represent a wet cycle water sample taken during August 2015 and the red Stiff diagrams display a dry cycle water sample that was sampled during February 2016.

The Stiff diagrams in Figure 6.1 represent a mixed signature of groundwater across most of the boreholes for the Elandsfontein water samples. The boreholes sampled indicate a water type of Na-Cl, Ca^{2}-Mg^{2}-Cl (mixed) and $Ca^{2}HCO_3$ and are the dominant water types within the study area. Borehole BG00074 is situated on the highest elevated area mamsl in the study area and could indicate direct recharge, as the wet cycle Stiff diagram display an increase of HCO_3^- concentration during the wet cycle rainfall period as opposed to the dry cycle Stiff diagram. Borehole G33502C displayed an increase concentration of calcium and bicarbonate ions during the dry cycle Stiff diagram, and could likely represent slow/indirect recharge processes and possibly regional recharge rather than immediate/direct recharge. Borehole G33316 VL1 is similar to that of borehole G33502C displaying a slow recharge process to the deep aquifer.

Boreholes G33316 VL2, G33317 and G33505B are located near granite hills and the wet cycle (G33317) as well as the dry cycle (G33316 VL2 and G33505B) Stiff diagrams, display a freshwater signature for these boreholes possibly also indicating direct recharge from the granite hills or high elevated areas.

Borehole G30925 is located ± 4 km from the lagoon and is situated within the southern portion of the palaeochannel of the EAS. The borehole shows lower concentrations of Mg^{2+}, Ca^{2+}, HCO_3^- and SO_4^{2-} having a Y shaped Stiff diagram representing a Na-Cl type groundwater, which could be an indication of stagnant

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water and/or less transmissive groundwater flow processes. The Na-Cl signature can also be a reflection of a subterranean groundwater flow path from the lagoon.

The Geelbek water samples for the Langebaan Lagoon boreholes BH2 and BH2A contains elevated concentrations of Na^+ and Cl^- having a Y shaped Stiff diagram for both wet and dry cycles that has a similar origin as the lagoon. The elevated concentrations for the boreholes were characterised as saline water and indicative of subterranean groundwater sources (refer to Table 6.3). Borehole BH1A is a shallow borehole situated at a depth of 13 mbgl adjacent to the lagoon at Geelbek, the groundwater collected for both wet and dry cycles represents a freshwater signature possibly derived from recent recharge waters and discharge of the Elandsfontein aquifer. Borehole BH1A consists of a hexagon shaped Stiff diagram, which represents a mixed groundwater source of both fresh and saline water. From Table 6.3 results for both wet and dry cycles indicate that BH1A and BH3 have similar concentrations of major ions.

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Table 6.3: Results for the Langebaan Lagoon boreholes indicating wet and dry cycles.

WET CYCLE						
Boreholes	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Na^+ (mg/L)**	**HCO_3^- (mg/L)**	**Cl^- (mg/L)**	**SO_4^{2-} (mg/L)**
BH1A	15	98.4	122.7	215.1	219.5	32
BH2	532.3	562.4	9652.5	367.9	114564.2	3645
BH2A	47.9	122.4	473.8	255.1	719.7	114
BH3	13.1	101.6	161.7	202.0	320.6	28
DRY CYCLE						
Boreholes	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Na^+ (mg/L)**	**HCO_3^- (mg/L)**	**Cl^- (mg/L)**	**SO_4^{2-} (mg/L)**
BH1A	14.3	96.0	122.8	237.0	228.0	30
BH2	535.5	499.7	7434.2	277.0	22140.0	2558
BH2A	53.7	115.9	524.3	261.0	790.0	124
BH3	15.9	99.3	190.7	228.0	286.0	33

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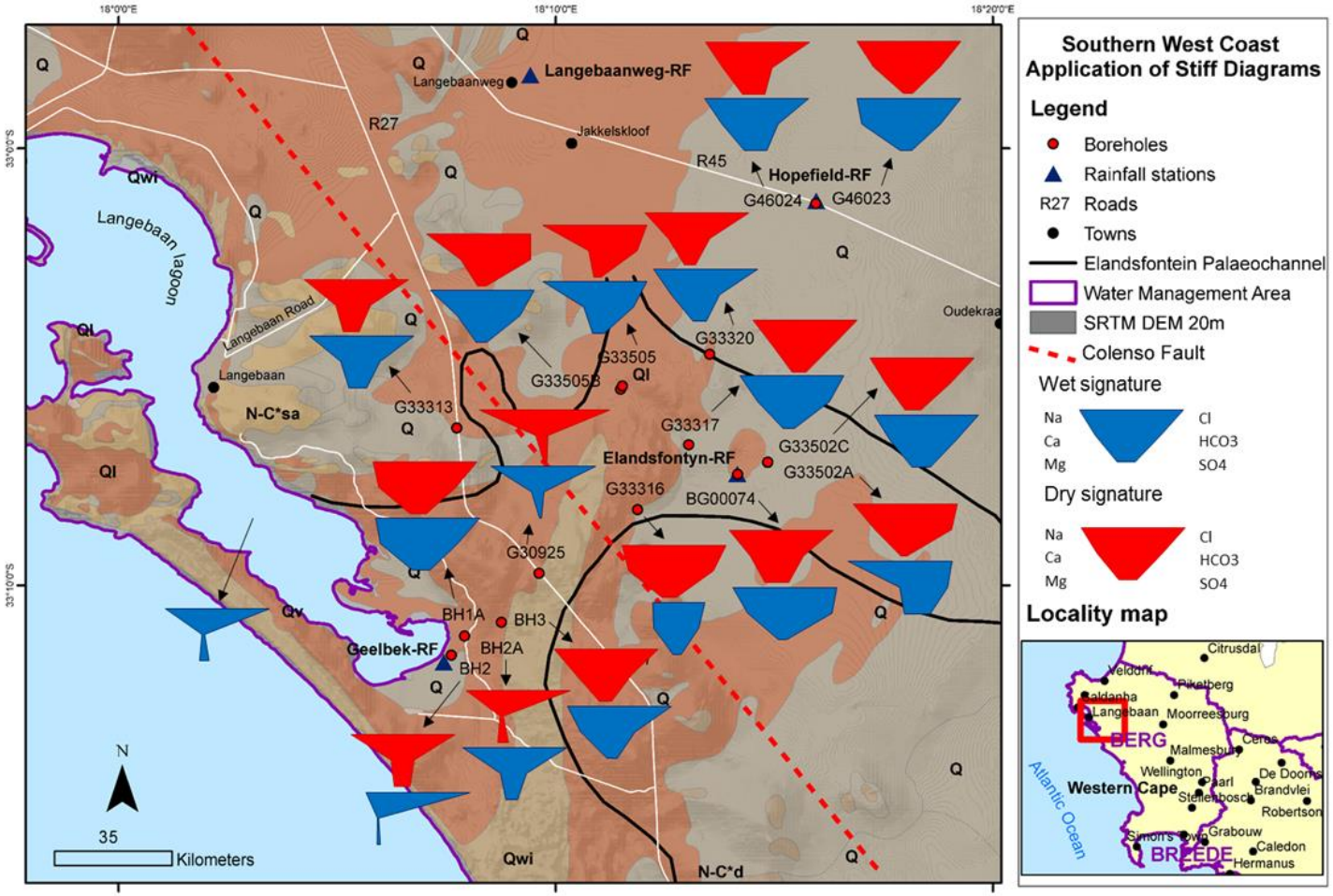

Figure 6.1: Results of Stiff diagrams for the Langebaan Lagoon and Elandsfontein Aquifer System (geology from Council of Geoscience 1:250 000).

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The Piper diagram was used to plot the Elandsfontein and Geelbek hydrochemical results for an entire hydrological year factoring all four seasons as shown in Figure 6.2. The GW_Chart v.1.29.0. software was used to generate all the Piper diagrams for 22 samples (boreholes and 3 rainfall stations) during winter; 19 samples in spring; 20 samples in summer and 19 samples in autumn. For all the sampling geosites 5 water types were identified for the study area in winter 2015, spring 2015, summer 2016 and autumn 2016. Based on the major cations and anions 5 water types were classified according to their chemical water type grouping on a Piper diagram (Piper, 1944). Figure 6.2 displays all 5 water types that were identified that comprised of Na-Cl, mixed Ca^2-Mg^2-Cl, Ca^2-Na-HCO_3-Cl, Na-HCO_3-Cl and Ca^2-Na-Cl. The dominant anion and cation for Elandsfontein were Ca^2-Na-HCO_3-Cl and mixed Ca^2-Mg^2-Cl represented by a solid black line ellipse, and as for the Geelbek was Na-Cl shown by a blue line ellipse for the study area as shown in Figure 6.2.

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The dominant water type for the winter season 2015 hydrochemical results were Ca^2-Na-HCO_3-Cl and Na-Cl as expected for a coastal aquifer, except for boreholes G33316 VL1, G33316 VL2 and BH1A that identified a mixed Ca^2-Mg^2-Cl type groundwater. The diminished black line in Figure 6.2 indicates a Na-HCO_3-Cl water type for boreholes G33502A, G33505 and G33505B that is situated in the EAS located on the Elandsfontyn farm 349. Rainfall stations were sampled and the sample water type for G10K1-RF presented Na-K-HCO_3, G46024-RF was Ca^2-HCO_3 and BG00074-RF was Na-HCO_3-Cl respectively.

The Na-HCO_3-Cl water type for boreholes G33505 and G33505B are similar for seasons: spring 2015, summer 2016 and winter 2016. Most of the sampling geosites for spring 2015 consists of Ca^2-Na-HCO_3-Cl and Na-Cl type groundwater except for boreholes G46023, G33316 VL1 and G33316 VL2 that identified a mixed Ca^2-Mg^2-Cl water type. Summer 2016 groundwater type was similar to that of the spring 2015 groundwater type. The dominant water type for most of the sampling geosites including the lagoon was Ca^2-Na-HCO_3-Cl and Na-Cl; except

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for boreholes G33316 VL1, G33316VL2 and BH1A indicating a mixed Ca^2-Mg^2-Cl water type.

The autumn 2016 hydrochemical results displayed 6 water types. The dominant water type across the sampled boreholes for the EAS showed a mixed signature Ca^2-Na-HCO_3-Cl and mixed Ca^2-Mg^2-Cl, as shown in the solid black line ellipse. Boreholes BH2, G30925 and G33313 displayed Na-Cl water type as indicated by a blue line ellipse. The red line ellipse illustrates a Na-HCO_3-Cl water type for boreholes G33505 and G33505B were classified. The diminished black line in Figure 6.2 indicates a Ca^2-Na-Cl water type for boreholes G46024. Borehole G33316 VL2 identified a Ca^2-HCO_3 type groundwater that had an increase in bicarbonate compared to other sampling geosites in the study area.

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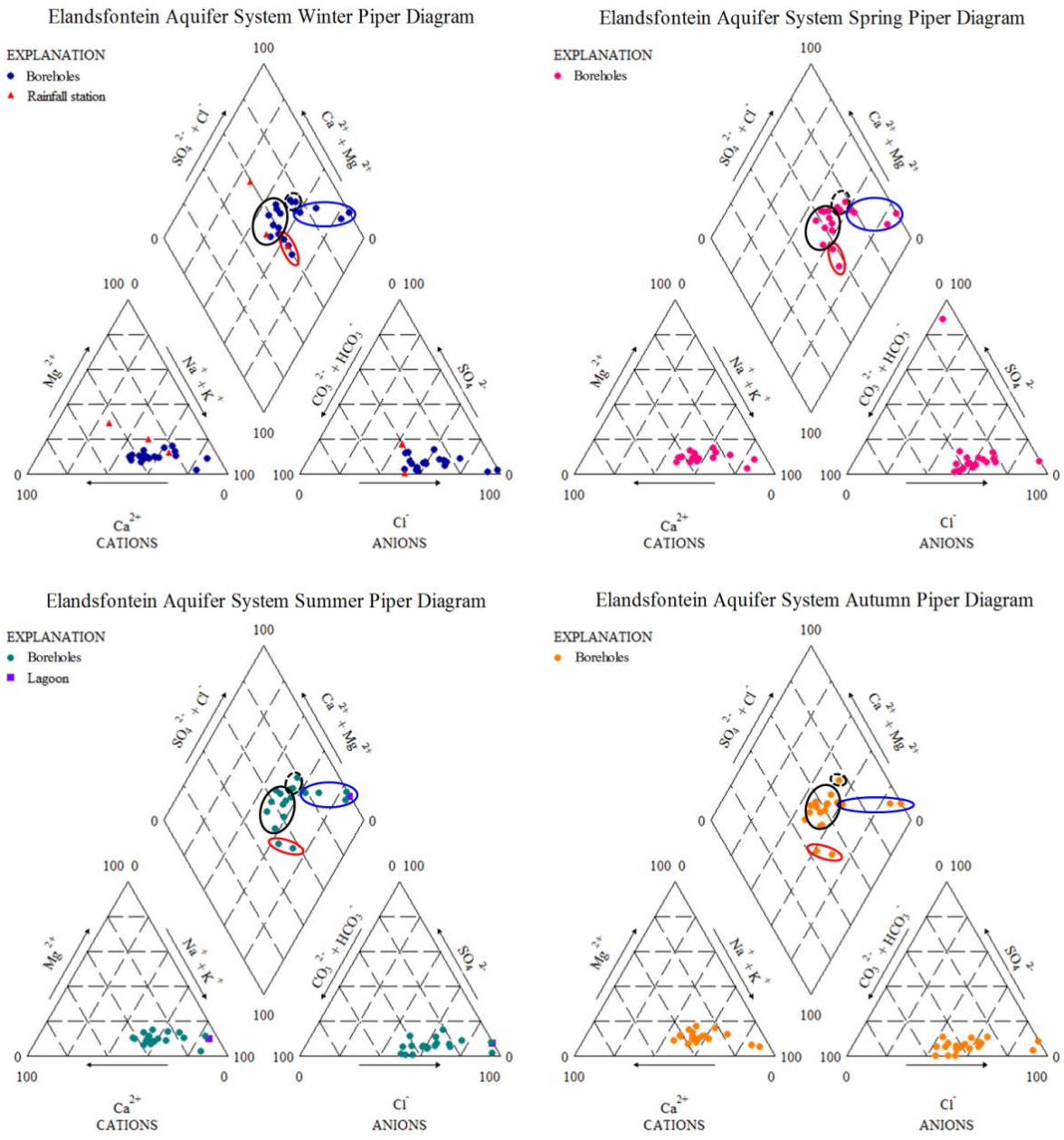

Figure 6.2: Piper diagram representing the Geelbek and Elandsfontein areas of the EAS - winter 2015 to autumn 2016.

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6.2.2 Stable isotopes δ^2H and $\delta^{18}O$

6.2.2.1 Winter

In order to supplement the hydrochemical data, rainfall and groundwater were sampled and analysed for environmental isotope (δ^2H and $\delta^{18}O$) signatures in August 2015. The resulting stable isotope plot of δ^2H verses $\delta^{18}O$ is presented in Figure 6.3.

The isotopic compositions of these samples ranged from -29.05 ‰ to 7.81 ‰ for δ^2H and -4.83 ‰ to 2.28 ‰ for $\delta^{18}O$; and most samples are scattered relatively close to the Global Meteoric Water Line (GMWL) in the bottom left quadrant whereby 4 groundwater samples plot on the GMWL. The Elandsfontein and Geelbek groundwater for the wet cycle shows a mixed signature, which is a result of recent rain water and evaporation enrichment. The winter isotopic compositions have more negative isotopic values for groundwater and could indicate recharge to the groundwater system that can be derived from both local and regional recharge. Borehole BH2 displayed positive isotopic values (7.81 ‰ for δ^2H and 2.28 ‰ for $\delta^{18}O$), which are indicative of a coastal lagoon signature being highly enriched. Lloyd (1966) described this type of coastal lagoon isotopic composition in relation of an evaporation basin whereby salinity increases through evaporation.

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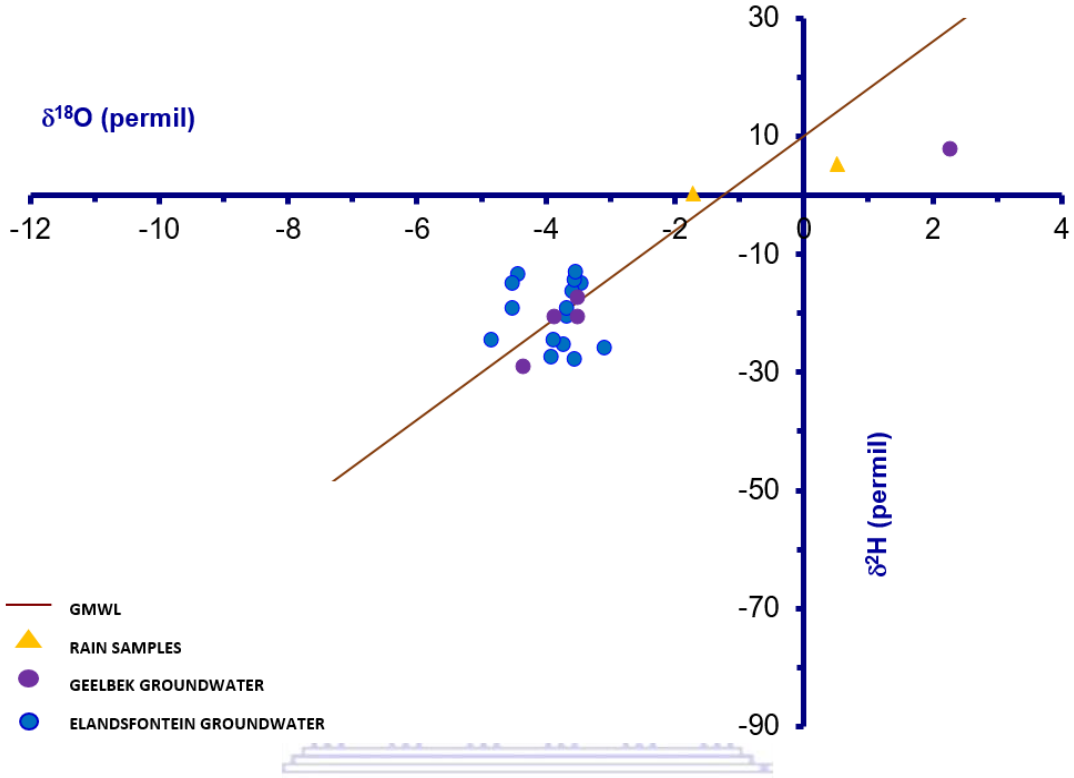

Figure 6.3: A plot of δ^2H verses $\delta^{18}O$ concentrations from groundwater and rainfall for August 2015 in relation to Craig's (1961) Global Meteoric Water Line.

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6.2.2.2 Summer

All stable isotope compositions are shown in Figure 6.4 for February 2016. The isotopic compositions of these samples ranged from -15.74 ‰ to 0.65 ‰ for δ^2H and -3.91 ‰ to 0.87 ‰ for $\delta^{18}O$; and all groundwater samples cluster relatively close to the GMWL. The closely clustered samples represent a dry cycle that was subject to evaporation where relatively low negative isotopic values are present, resulting in a slightly more enriched signature than that of the wet winter cycle. Therefore, indicating insignificant to no recharge of the area during that period.

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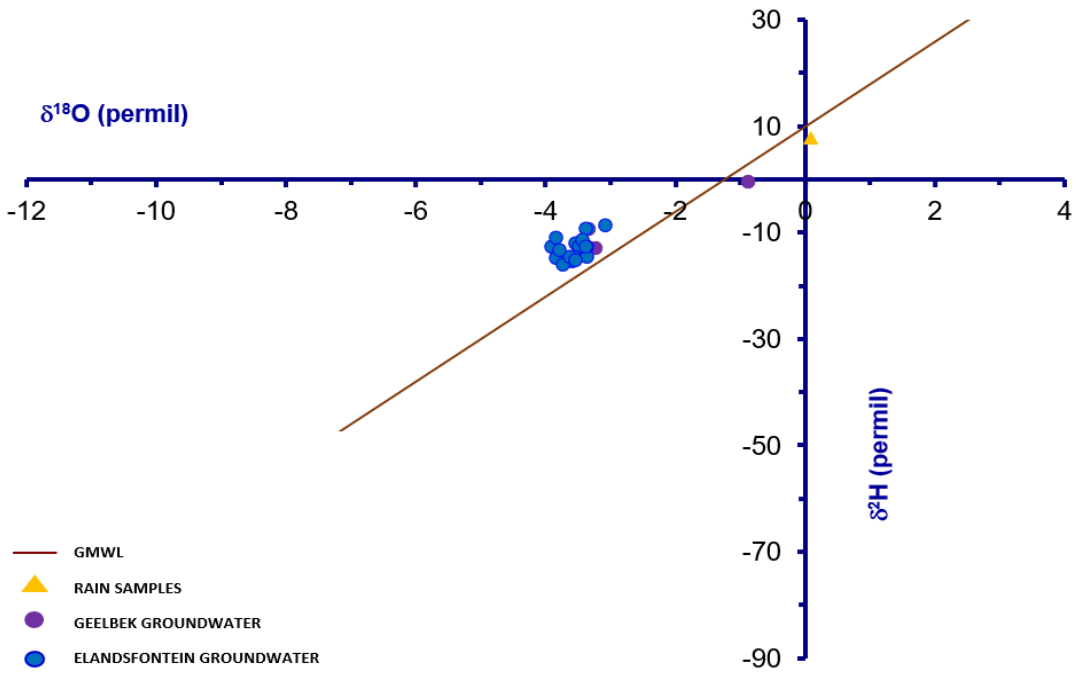

Figure 6.4: A plot of $\delta^{2}H$ verses $\delta^{18}O$ concentrations from groundwater and rainfall for February 2016 in relation to Craig's (1961) Global Meteoric Water Line.

Figure 6.5 presents a plot of measured delta values $\delta^{2}H$ verses $\delta^{18}O$ from literature and other sources. The Elandsfontein and Geelbek groundwater for the wet winter cycle shows a slightly enriched and depleted signature, which is evident of mixing waters and are of similar $\delta^{2}H$ and $\delta^{18}O$ content for both groundwater and rainfall.

The Rawsonville ($\delta^{2}H$, $\delta^{18}O$) and Sandspruit delta values (Galli et al, 2016), plot in the same zone as the Elandsfontein and Geelbek groundwater samples whereby the Rawsonville (TMG) has a depleted isotopic composition and Sandspruit a more enriched isotopic composition. The Table Mountain Group (TMG) rainfall samples plotted in Figure 6.5 are situated at a high altitude near Piketberg and show an expected isotope signature that is depleted.

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A Local Meteoric Water Line (LMWL) for the study area previously could not be calculated due to a limited amount of precipitation samples, with the aid of historical rainfall delta values from the Global Network of Isotopes in Precipitation (GNIP) for the Cape Town Airport (IAEA/WMO, 2006) sufficient δ^2H and $\delta^{18}O$ values were plotted, which derived a LMWL (R^2 = 0.79) for the area. Figure 6.5 also illustrates highly enriched delta values for sea water, lagoon and BH2. Boreholes situated in the deep aquifer along the Elandsfontein palaeochannel show a depleted isotopic signature.

The LMWL along with all the groundwater and rainfall delta values display a true reflection of a coastal δ^2H and $\delta^{18}O$ composition. In the bottom left quadrant of Figure 6.5 the isotopic composition signature displayed for groundwater of both Elandsfontein and Geelbek plots relatively closer to the TMG rainfall samples, which indicates similar water types and sources of local and regional recharge using the winter cycle isotopic dataset.

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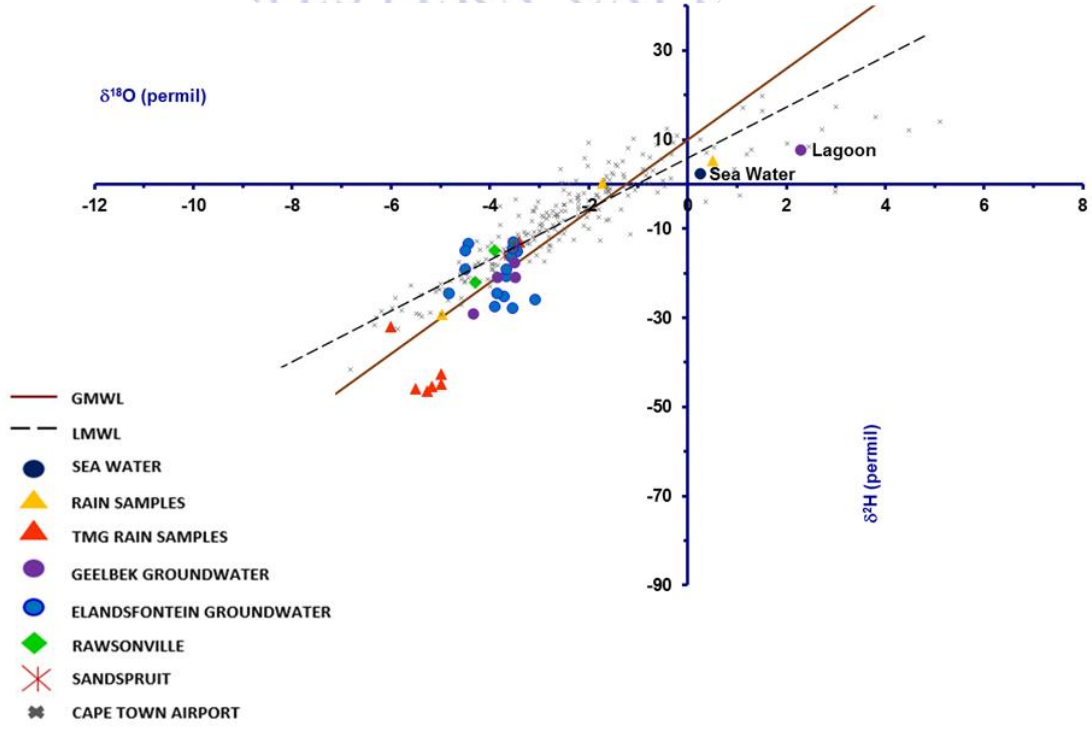

Figure 6.5: Winter cycle stable isotope data plot for water samples with respect to Craig's (1961) Global Meteoric Water Line and the Local Meteoric Water Line (LMWL) for the study area.

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6.3 Discussion

The hydrochemical analyses and stable isotopic analysis of $\delta^{2}H$ and $\delta^{18}O$ values were used to characterise groundwater recharge and flow processes to determine whether recharge is direct (local scale) or indirect (regional scale).

The Stiff diagrams for both wet and dry cycles of year 2015 to 2016 provided evidence that the dominant water types of the study area are Na-Cl, mixed Ca^{2}-Mg^{2}-Cl, and $Ca^{2}HCO_3$. The Stiff diagrams of the Elandsfontein aquifer situated on the Elandsfontyn farm represent a mixed signature of mixed Ca^{2}-Mg^{2}-Cl and Na-Cl, indicating similar shaped Stiff diagrams that are shown for the boreholes situated in the Elandsfontein palaeochannel. The dry cycle Stiff diagrams for boreholes G33316 VL2 and G33505B in the Elandsfontein aquifer unit are similar. The similarity of these boreholes identifies a freshwater signature that could be derived from direct recharge within the area. The Geelbek area represents a Y shaped Stiff diagram for all boreholes indicating Na-Cl water, except for BH1A that displays a freshwater groundwater signature. Therefore, higher concentrations of Ca^{2}-HCO_3^{-} for the Elandsfontein water samples G33316 VL2, G33317, G33505B and BG00074 are obtained and the opposite is displayed for the Geelbek water samples except for borehole BH1A.

The Piper diagram analysis for all four seasons show the water type characterisation for Elandsfontein to be (Na-Cl, mixed Ca^{2}-Mg^{2}-Cl, Ca^{2}-Na-HCO_3-Cl, Na-HCO_3-Cl and Ca^{2}-Na-Cl); whereby the dominant anions and cations indicated Na-Cl, mixed Ca^{2}-Mg^{2}-Cl and Ca^{2}-Na-HCO_3-Cl. The Geelbek water type characterisation was Na-Cl and mixed Ca^{2}-Mg^{2}-Cl. The Piper Diagram illustrated seasonal changes in the hydrochemistry data as indicated on the Piper diagrams in Figure 6.2. The elements migrate from the lower middle position of the diamond (Na-HCO^{3}-Cl, Ca^{2}-HCO_3, Ca^{2}-Na-HCO_3-Cl and mixed Ca^{2}-Mg^{2}-Cl water type) towards the right position of the diamond (Na-Cl), in an upward direction towards the Langebaan Lagoon. This is a typical piper representation of a coastal aquifer. Borehole G30925 displayed a different water type as to the other

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boreholes in the EAS, this might be due to the borehole being in the deeper part of the Elandsfontein palaeochannel comprising of weathered Malmesbury and granite material. A mixed water type of Ca^2-Mg^2-Cl is dominant amongst four boreholes namely; G46023 (lower LRAS), G33316 VL1 (lower EAS), G33316 VL2 (upper EAS) and BH1A (Geelbek) that could comprise of similar geology. The flow path identified from boreholes G33316 VL1 and BH1A mimics that of the Elandsfontein palaeochannel.

The chemical analysis for borehole G33316 VL2 revealed a Ca^2-HCO_3 water type for autumn 2016, which is indicative of fresh groundwater that was recently recharged after a rainfall event as a result of calcrete being present in the borehole. Younger (2007) identifies this water type from high elevated recharge areas that recharged the aquifer and as result comprises of a fresh groundwater signature. Borehole G33505B (autumn signature) also had a Na-K-HCO_3 water type, which was similar to the TMG rainfall station G10K1-RF (winter signature). It also had a Na-HCO_3-Cl water type that was similar to the local rainfall station BG00074-RF (winter signature) of which both autumn and winter water type signatures indicates recharge water. The above-mentioned is to be expected in coastal aquifers where the primary mechanism of recharge to the aquifer is of coastal precipitation (Jackson, 2007).

The dominant water type for most of the boreholes near the lagoon is classified as a Na-Cl, situated in a lower elevation area and forms part of the discharge zone for the EAS whereby stagnant water (marine origin) is prevalent. Therefore, Na-Cl water type is known to predominantly occur in lower elevated areas (Adams et al., 2001). The Langebaan Lagoon also indicates a high Na-Cl water type that plots similar to that of a seawater signature.

Figure 6.6 displays the winter isotopic results for the study area in the southern West Coast. The isotopic results provided evidence that most of the boreholes that were sampled for the study area represent a similar source of water for the summer isotopic compositions for $\delta^{18}O$ that ranges between -3.21‰ to -3.81‰.

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The isotopic results in Figure 6.6 illustrate the winter compositions for $\delta^{18}O$ that ranges between -3.08‰ to -4.83‰. The winter isotopic results also indicate that recharge processes are slow from prolonged rainfall events resulting further inland from highland areas. As shown in the following boreholes G33313 -4.83‰, G33316 VL1 -4.50‰, G33317 -4.50‰, G33505 -4.43‰ and BH3 -4.34‰ in $\delta^{18}O$ for the EAS. All these signatures are similar to that of higher elevation Rawsonville and the TMG rainfall delta values. This provides an indication of potential regional recharge flow processes as alluded to in Chapter 5 CRD. Furthermore, the boreholes located in Elandsfontein, Geelbek and Sandspruit have similar isotopic signatures, which is indicative of a similar flow path where direct recharge is present. The Colenso fault could also possibly contribute to regional recharge to the area as all the above mentioned boreholes provide evidence of indirect recharge that result in mixing of water types. Boreholes G33505B and G30925 illustrate $\delta^{18}O$ values of -3.90‰ and -3.85‰, respectively and are also situated relatively close to the Colenso fault.

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The isotopic results also provided evidence for preferential flow paths from the Elandsfontein aquifer towards the southern part of the lagoon through the Elandsfontein palaeochannel, as identified in Chapter 3 in the geology section. Borehole G46024 located in the shallow aquifer of the LRAS has similar $\delta^{18}O$ signature of -3.54‰ as G33320 VL2 located in the shallow aquifer of the EAS. This occurrence could provide an indication of a potential recharge zone and flow path from the shallow aquifer of the Langebaan Road aquifer by borehole G46024 to the shallow aquifer unit of the Elandsfontein aquifer at borehole G33320 VL2.

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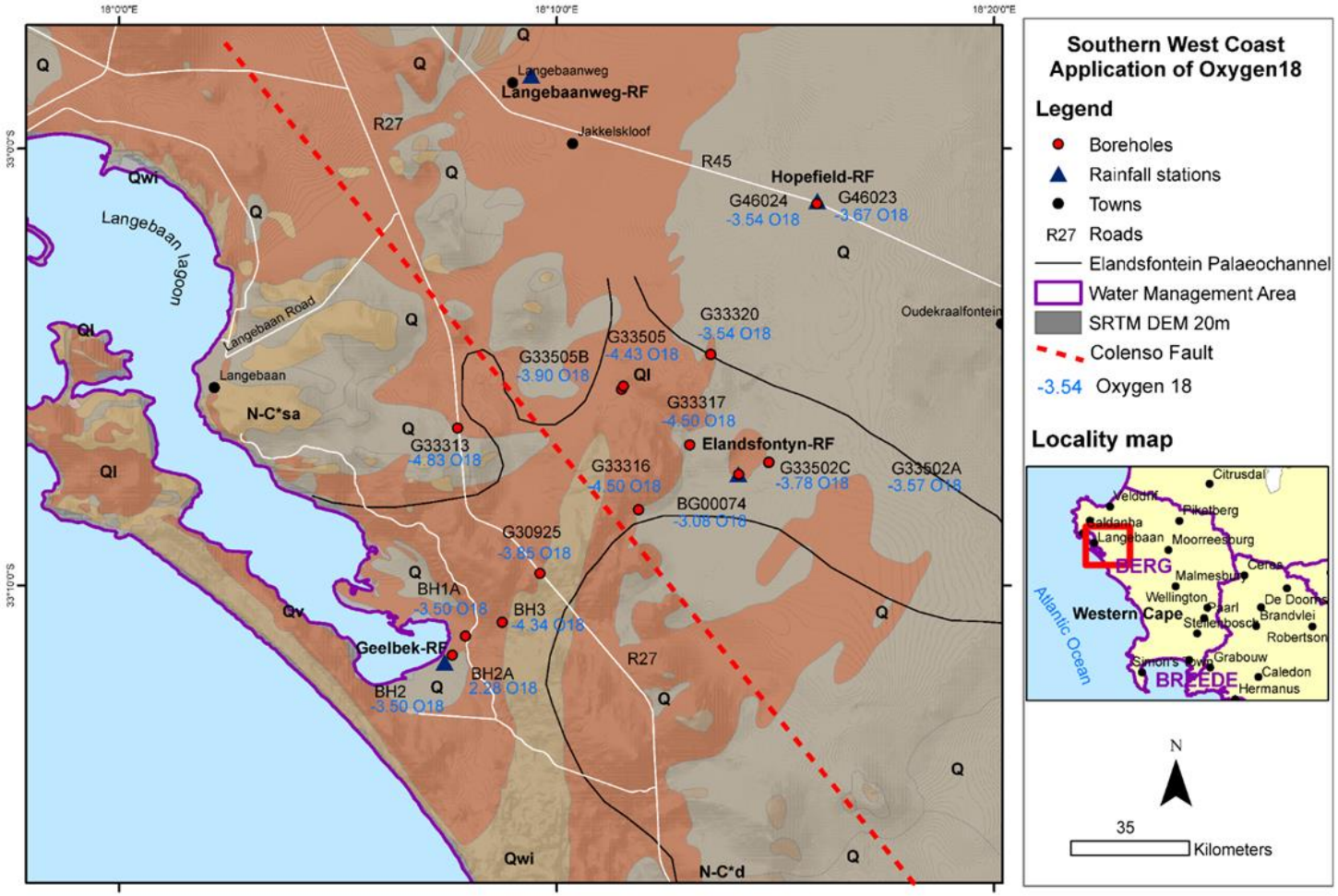

Figure 6.6: Results of $\delta^{18}O$ for the Langebaan Lagoon and Elandsfontein Aquifer System (geology from Council of Geoscience 1:250 000).

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CHAPTER 7
CONCEPTUAL MODEL

7.1 Introduction

A conceptual model was built on the understanding of how the EAS functions by the characterisation of the hydrological, hydrogeological and hydrochemical processes of the system. The model is a simplification of the real world complexities that is appropriate on either a regional or local scale of a project (Jackson, 2007). This conceptual model for the Elandsfontein aquifer consisted of the conceptualisation of the geology, geological structures, hydrogeology, hydrology and preferential pathways of the groundwater system. This chapter also tries to consolidate the findings presented in chapters three, five and six for the development of a spatial conceptual model; to assist in the understanding of dominant processes controlling groundwater recharge and flow dynamics within the EAS. The objectives of the conceptual model were to assess the local and regional scales of recharge processes of the delineated study area. Furthermore, the conceptual model will illustrate the flow paths of the EAS to evaluate the link between the shallow and deeper aquifers.

7.2 Conceptualisation

The overall conceptualisation for the Elandsfontein aquifer towards the Langebaan Lagoon is illustrated in Figure 7.1, displaying the plan view and cross section in Figure 7.2.

7.2.1 Regional scale

The higher lying areas of Paarl and Porterville are likely to be the dominant regional recharge mechanisms for the Lower Berg River Region. This was established from the CRD simulations (boreholes G33316 VL1, G33316 VL2 and G33502C) in Chapter 5 whereby the long term average rainfall near Paarl highland correlates well with the EAS

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water level response, indicating a response to recharge after 31 months to preceding cumulative rainfall events to the system. The EC indicates a more saline signature in the palaeochannel towards Geelbek for boreholes G30925 (~108 mS/m), BH3 (~136 mS/m) and BH1A (~118 mS/m). The macro elements analysis (Stiff and Piper diagrams) for borehole G30925 also represents a Na-Cl type groundwater indicating saline water.

The winter stable isotopes δ^2H and $\delta^{18}O$ displayed a more depleted isotopic composition (negative delta values of ± -4‰) for the deep aquifer of EAS (Figure 7.1). The deep aquifer is represented by borehole G33317 drilled into the clay (Malmesbury Group); and boreholes G33316 VL1, G30925 and BH3 are all drilled into the bedrock that is comprised of the Cape Granite Suite. Additionally, the hydrochemistry represents a mixed Ca^2-Mg^2-Cl water type for the above-mentioned boreholes. Boreholes G33317 (-4.50‰), G33316 VL1 (-4.50‰), G33505 (-4.43‰) and BH3 (-4.34‰) indicates similar $\delta^{18}O$ isotopic signatures; and therefore alluding that high elevation TMG recharge could be the dominant recharge process. These depleted values for the above-mentioned boreholes are all situated within the Elandsfontein palaeochannel. Therefore, these depleted isotopic values could also suggest that groundwater flow could possibly be derived from a regional flow system from higher lying areas (Gat and Gonfiantini 1981). The Colenso strike slip fault is evident in the study area and extends from the granite hills between Paarl and Stellenbosch to the West Coast, by which this geological structure could provide a preferential pathway for regional flow processes.

7.2.2 Local scale

Three potential local recharge zones are located near rounded granite hills of the Cape Granite Suite located near the Elandsfontein Aquifer System. The two LRAS boreholes G46023 and G46024 display lower ECs of (~54 mS/m) and (~47 mS/m) for the dry cycle suggesting fresh groundwater quality; and likely to be derived from immediate recharge to the aquifer system. The EC indicates a freshwater signature for boreholes G33505 and G33505B alike (~47 mS/m) as well as borehole G33505B (~56 mS/m) located on the edge of the palaeochannel. A water type of a Na-HCO_3-Cl water type for boreholes G33505 and G33505B were classified, however, higher concentrations of Ca^{2+}-HCO_3^- for borehole G33505B was identified.

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Boreholes G46024 (-3.54‰) drilled into the shallow aquifer of the LRAS have the same winter isotopic composition value as that of G33320 VL1 (-3.54‰) positioned in the deep aquifer in the EAS. Similarly, boreholes G46023 (-3.45‰) drilled into the deep aquifer of the LRAS have the same winter isotopic composition value as that of G33320 VL2 (-3.45‰) positioned in the shallower aquifer in the EAS. Therefore, the wet cycle stable isotopes validate that these boreholes are of the same water type and a potential pathway exists between the LRAS near Hopefield Private Nature Reserve and EAS. Figure 7.1 also displays that the stable isotopes $\delta^{2}H$ and $\delta^{18}O$, hydrochemical descriptors, EC and hydraulic head data support the preferential flow path of the southern palaeochannel that discharges into the southern part of the Langebaan Lagoon.

Figure 7.2 indicates that the conceptual model of the Elandsfontein and Geelbek areas consists mainly of the Elandsfontein Aquifer System, which consists of the Sandveld Group, Malmesbury Group and Cape Granite Suite. The dominant water types for the EAS are Ca^{2}-Na-HCO_3-Cl, mixed Ca^{2}-Mg^{2}-Cl and Na-Cl as displayed in Figure 7.2. The local groundwater flow direction is predominantly from an east to south-westerly direction as illustrated on the conceptual model in Figure 7.2, as well as in Figure 5.1. The geological logs provide evidence that the EAS layers are not according to that of traditional expected layers of an unconfined and confined West Coast aquifer (Figure 3.17). Therefore, indicating that the EAS could be viewed as one aquifer unit consisting of a shallow and deeper portion discharging towards the coast at the southern end of the Langebaan Lagoon.

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Plan view

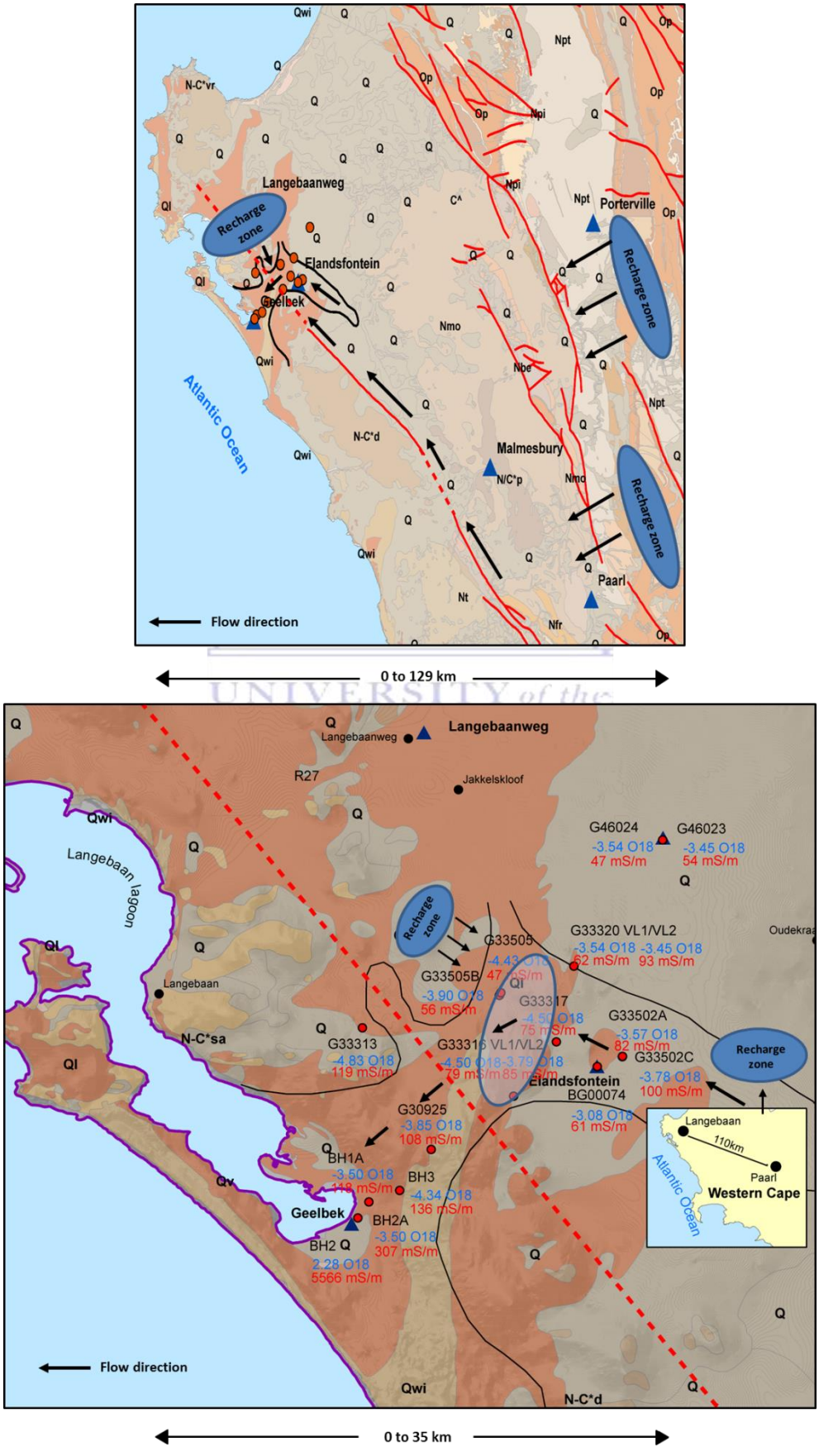

Figure 7.1 Plan view for the Langebaan Lagoon and Elandsfontein Aquifer System.

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Cross section

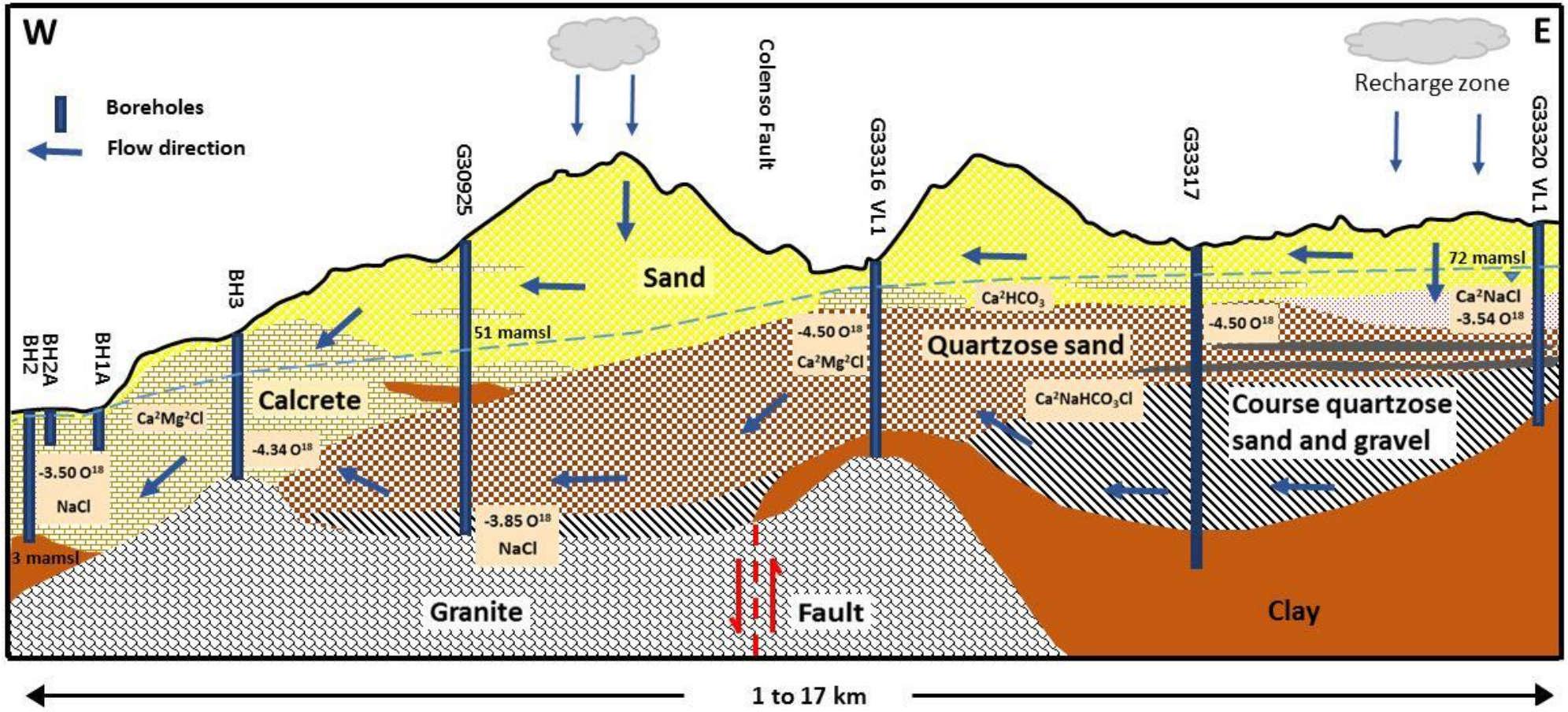

Figure 7.2: Cross section of the conceptual model for the Langebaan Lagoon and Elandsfontein Aquifer System.

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CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This chapter aims to combine and conclude all the findings that were achieved through the objectives, which aimed to characterise recharge sources as well as preferential flow paths of the EAS. The objectives are achieved as follows:

The thesis addressed the first objective that established groundwater recharge mechanisms through the CRD method. Based on the CRD simulation results there are evidence of both short and long term memory recharge processes present for the Elandsfontein aquifer. The short term memory provided evidence that the local groundwater recharge is derived from direct recharge from the surrounding rounded granite hills and high elevated areas through runoff. Regional long term average rainfall contribute to groundwater recharge mechanisms based on the long term memory responses, are interpreted as the predominant source of regional flow from the Paarl and Porterville high lying areas to the West Coast.

The second objective identified groundwater flow paths and recharge mechanisms using chemical methods of hydrochemistry and stable isotopes (δ^2H and $\delta^{18}O$) as a tracer. The hydrochemistry and stable isotopic analysis of δ^2H and $\delta^{18}O$ provided similar results to the CRD simulations. Both the hydrochemistry and stable isotopes (-4.50‰ to -4.43‰ for $\delta^{18}O$) also suggested that the study area receives recharge from high lying TMG areas. The major anions and cations also indicated that borehole G33316 VL2 located within the shallow aquifer located near a granite hill had a Ca^2HCO_3 water type in autumn 2016 of which is typical of recently recharged groundwater through the calcrete layer. The CRD simulation for borehole G33316 VL2 also correlates well with the Paarl rainfall station, therefore indicating a mixed water type of both saline and freshwater into the system. The isotopic evidence confirms various contributions from different flow

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paths with different isotopic signatures occurring within the Elandsfontein palaeochannel towards the southern part of the lagoon, which suggests a mixed isotopic signature.

The third objective of this study developed a conceptual model of the Elandsfontein Aquifer System. The conceptual model focused on the Elandsfontein and Geelbek areas, whereby conceptualisation of the EAS can be seen as one aquifer unit with a shallow and deeper part discharging into the Langebaan Lagoon. The results from chapters 5 and 6 also conclude that the lagoon receives a mixed water type signature from local and regional groundwater sources contributing to the Elandsfontein aquifer.

8.2 Recommendations for future research

Further research is required to understand the complexity of the EAS and the interconnectivity with the LRAS in the West Coast as a whole. The following recommendations are made based on the results acquired during the study:

- The relationship of the Colenso fault and other surrounding fault structures with regional flow processes must be investigated for confirmation as the dominant preferential flow path for regional recharge.
- Groundwater dating analyses in the EAS to determine the age of groundwater and confirm local sources of recharge.
- Simulate the dominant processes controlling groundwater flow and discharge by developing a numerical groundwater flow model of the EAS.
- The newly drilled SANParks boreholes are to be incorporated in the next assessment conducted for the EAS.
- Additional geological surveys and groundwater exploration drilling for the gap area between EAS and LRAS to understand interconnectivity and groundwater flow processes between aquifers.
- Dependence of other ecosystems on the EAS including the contribution of groundwater to the Sout and Groen Rivers.

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