Hydrogeophysical characterization of coastal aquifers for solution-based modeling, West Coast, South Africa

By

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Declaration

I, the undersigned hereby declare that this thesis entitled "*Hydrogeophysical characterization of coastal aquifers for solution-based modeling, West Coast Aquifer System, Western Cape, South Africa"*, is my own original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used, acknowledgements have been made.

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Signature

08/03/2022

Date

Dedication

This work is dedicated to my parents, Mr and Mrs Igwebuike for their love, support, and encouragement.

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Abstract

The need to improve groundwater security remains critical especially in urban areas where demand for groundwater as an alternative source of water supply increases. Declining trends in availability of surface water because of climate change effects further exacerbates problems of water supply shortage to meet the increasing demand for water, hence the need for groundwater sources. The use of hydrogeophysics data and derivative analysis in understanding aquifer dynamics remains limited and poorly understood therefore, the study argues that when hydrogeophysics data and derivative analysis are not used in aquifer characterization, it results in models that are not solution-based and cannot guide groundwater management. The study was aimed at providing improved understanding on characterization of aquifer dynamics for solution-based modelling while addressing the importance of integrating hydrogeophysics data and derivative analysis in amplifying the heterogeneities that exist in aquifer system. The electrical resistivity survey results indicated a clear layer of fine to medium grain sand with depths of about 60m in some areas, intercalated with coarse grain sand and thin layers of peat. The results from the derivative analysis plots indicated that the dominant flow regime is linear and bilinear flow. It also showed the presence of various double porosity dips during the pumping cycle, which indicated an unconfined aquifer, while aquifer heterogeneity and a no flow boundary were detected in the various boreholes. Double porosity or unconfined aquifer behaviour was portrayed by the stabilization of drawdown during mid-time of pumping, suggesting that the matrix blocks feed the porous opening made by the gravels with water at an increasing rate or the vertical delayed recharge from the overlying permeable part in the unconfined aquifer. Results from the study suggested that the transmissivity in the Hopefield ranges from small to moderate with values between 19.0 m^2/ day and 94.5 m^2/s while storativity ranges between 1.68E-04 and 1,18E-07. Further findings suggested that borehole T4/2240 and TA/1850 with moderate transmissivity value of 94.5 m^2/day and 50.4 m^2/day respectively indicated that these boreholes were likely drilled in the paleochannels of the Elandsfontein sand and gravel that runs along the coastline towards the Atlantic Ocean hence the direction of groundwater flow here is Southwest and controlled mainly by the bedrock topography. It is concluded that the electrical resistivity tomography method is an effective tool for characterization of subsurface aquifer system while derivative analysis of pumping test is key in amplifying the heterogeneities in aquifer system. The methods provided a more practical interpretation for the study area compared to the traditional

drawdown versus time curve hence results from this study are useful for groundwater usage, monitoring and management.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Overview of the study

The motivation for the study is the quest to augment the surface water supply sources. With the declining surface water resource due to increasing effects of climate variability, there is a need for alternative sources of water to meet the increasing demand for water supply and this has become crucial. Groundwater has been identified as an alternative source to augment the surface water supply. Therefore, assessment of groundwater resources to address the shortage of water supply remains fundamental. The use of hydrogeophysics and derivative analysis in the characterization of aquifer system have not been used comprehensively in understanding aquifer dynamics hence the development of groundwater models that do not represent or describe the realistic dynamics of aquifer. The study aims at improving the understanding on characterization of aquifer dynamics for solution-based modelling using hydrogeophysics and derivative analysis. The purpose is to improve interpretations of observed and modelled results on groundwater resource in the study area to improve actions on groundwater monitoring and utilisation. To achieve this aim, firstly aquifer units has been established using surface geophysics method. Secondly, aquifer flow regimes and boundary conditions were determined using derivative analysis for the improvement of solution-based models. Thirdly, aquifer hydraulic parameters were estimated as this is crucial in proper planning and management of groundwater resources.

1.2 Background of the study

Coastal aquifers are sometimes composed of different types of rock including fractured rocks, limestone (karstified) and loose materials such as sands. Since their geology can sometimes be complex due to its heterogeneity, a spatial knowledge of their hydrogeological properties is needed to ensure adequate utilization in achieving sustainable management of the resource. Many of the issues faced with aquifers around the world include conceptual understanding of coastal hydrogeological systems, characterization of subsurface hydrogeological properties and development of mathematical models (Werner et al., 2010). Busari and Mutamba, (2014) stated that in South Africa, the inadequate knowledge of hydrogeological properties of these aquifers have been concerning as most of the available knowledge do not reflect the condition in situ. This in-situ knowledge includes hydraulic parameters, establishments of groundwater units and depth, groundwater flow rates and flow directions, among others. Hydraulic parameters of aquifers make up the core of hydrogeology of the aquifer and this makes it related to aquifer hydraulics. One of the ways, aquifer hydrogeologic parameters can be determined is by field testing. The analysis of the field testing can result into a model hence it is important to have a thorough knowledge of aquifer hydraulics as it is required to select appropriate model or models for an aquifer or aquifer system. Almost all field-testing procedures are based on the vertical well methods. Pumping tests, slug tests, pressure pulse tests, and constant head injection tests are frequently used on vertical wells for the determination of aquifer hydraulic parameters.

A good example of this is pumping tests; it is mostly performed by withdrawing water at a constant rate from one well and observing the temporal variation of the water levels in the pumping well and in the nearby observation wells. The temporal variation of the water level in an observation well largely depends on the aquifer permeability and the magnitude of the pumping rate. Pumping test being a conventional approach to determine aquifer hydraulic parameters, does not give enough information regarding the in-depth conceptualization of the local aquifer properties (flow regimes). Ferroud et al., (2019) stated that this results in flow models with high degree of idealization, and it becomes impossible to show the real complexities of aquifers, hence the use of derivative analysis. Hydrogeophysics as a discipline has been also developed in recent years, basically to explore the potential that geophysical investigations are important in the characterization of subsurface properties and processes (Muchingami et al., 2021).

Since geophysics investigations can be conducted from many different platforms (such as aircrafts and satellites, at the ground surface of the earth and within and between well bore), integration of geophysical and direct hydrogeological data can provide information for characterization over a variety of spatial scales and resolutions. Geophysical methods provide spatially extensive information about the surface in a minimally invasive manner and at a comparatively high resolution. Due to its spatially coverage, it provides important details about complex hydrological processes, construction of transport and flow model is informed by geophysical data and the adequate utilization of subsurface water resources is also informed by geophysical data. Many different techniques exist to provide information about occurrence, depth, the quality, and quantity of groundwater. Geophysical methods detect anomalies of physical properties within the earth's crust. Magnetism, elasticity, density, and electrical resistivity are properties that are commonly measured by geophysical investigations. These properties are interpreted with a difference in their rock type, geologic structure, porosity, water quality and water content. Of all geophysical methods, geoelectric, and geoelectromagnetic methods are the leading ones in the exploration and management of groundwater because these methods aid planning efficient and informs proper drilling programs. They are especially well adapted for locating subsurface saltwater boundaries because the decrease in resistance when salt water is encountered becomes apparent on a resistivity spacing curve. When the conditions at the surface are relatively the same (homogeneous), these methods are used to detect the water table as the top of a relatively conductive layer. Successful groundwater management plan can be proposed after extensive geophysical investigations. A good example of where this has been applied is a study conducted by Andersen, (2018) at Gasværksgrunden in Horsens, Denmark, where different geophysics methods including the electro-magnetic method and the direct current profiling were used in a detailed subsurface characterization.

Groundwater exploitation and mapping that is based only on drilling, information might lead to many uncertainties in the models. One example of this uncertainty is the risk of hitting a dry well and this is because the role of hydrogeophysics data has been neglected. Coastal aquifers are important sources of freshwater supply in coastal areas, but the inadequate understanding of the hydrogeological and geophysical properties have led to the underdevelopment of some of these aquifers (Aladejana et al., 2020). The characterization of these aquifers which brings about a better understanding is therefore essential to bridge the gap. Vouillamoz et al., (2007) stated that it is important to use both hydrogeological and complementary geophysics investigation for the characterization of coastal aquifer as this integration gives an in-depth understanding of the system under study.

The combination of hydrogeological and geophysics investigations as ideal methods for characterising aquifers in coastal regions was also stressed in Werner et al., (2013). Investigations have shown that coastal aquifers have great quantities of water, and this requires proper utilization and management to minimize the intrusion of saltwater due to over abstraction (Babu et al., 2002). The first step towards the proper characterization and hence management of this coastal aquifer is the identification or establishment of such aquifers, and this is conducted either by geological methods, geophysics methods, chemical methods, or even a combination of any two of these methods. This study uses an integration of hydrogeophysics data and the use of pumping test data to better understand the aquifer flow system. Examples of studies that have used the above method/s include Frohlich et al., (1994), Okereke et al., (1998), Esu et al., (1999), Choudhury et al., (2001), Hodlur et al., (2002). Overtime, hydrogeological data are being complemented with sub-surface geophysics information and this allows an in-depth interpretation of the aquifer system (Kafri and Goldman 2005; Mota and Monteiro dos Santos, 2006). Rubin and Hubbard, (2005) reports that the continual combination of these studies leads to the development of hydrogeophysics as a discipline.

There has been considerable advancement in the use of geophysical data for subsurface hydrogeological characterization. These advancements include those associated with the migration from one-dimensional resistivity structure of the subsurface (vertical electrical sounding) to a much more better interpretation which gives a 2D-image of the resistivity distribution, both laterally and in depth (electrical resistivity tomography) as stated in Zarroca et al., (2011), instruments development (example, improvement from 4 electrode electrical survey to multi electrode system), interpretation procedures (from manual curve matching to software interpretation), integration of different methods for better understanding (transient electro-magnetic and vertical electrical sounding, vertical electrical sounding and ground penetrating radar, vertical electrical sounding and seismic) and coupled hydrological and geophysical modelling. In this study, the characterization of aquifer dynamics in the Hopefield is being investigated by first establishing the groundwater units using surface geophysics data, secondly, determining the flow regime, boundary conditions and heterogeneities within the aquifer system using derivative analysis and lastly, estimating of aquifer hydraulic parameters.

The sole aim of this integration is to show the influence that hydrogeophysics data play in the characterization of aquifer and showing that without the use of hydrogeophysics data and derivative analysis, the understanding of the aquifer dynamics remains oversimplified. The use of derivative analysis for aquifer studies is not fully explored in hydrogeology globally by many authors especially in the past decade but more recently Ferroud et al., (2018) modified the theoretical flow regimes and their associated flow dimensions from Ehlig-Economides et al., (1994). This gave way to a more recent publication by Garin et al., (2019) where derivative analysis and specifically the diagnostic plot method was used for the improvement of pumping test data in a carbonate aquifer located Southeast of France. The authors used this approach to define a conceptual flow model from the succession of flow regimes identified with the derivative of the drawdown. Beauheim et al., (2004) also used this method and the authors concluded that the flow-dimension diagnostic plots provide a simple and effective means for the evaluation of aquifer flow regime.

Globally, geophysics data have been used in the development of groundwater conceptual models. Dickson et al., (2015) integrated geophysics data in multiple point statistics simulations and this integration assisted the development of groundwater flow models. The Lagan Valley Aquifer study in Northern Ireland aimed at taking a practical example of the multiple-point statistics direct sampling method and discovered its usefulness in the investigation of aquifer heterogeneity and its use to parameterize groundwater flow models. The authors concluded that the integration of geophysics data with MPS significantly improves the resulting groundwater models. Therefore, this study is integrating both hydrogeophysics and derivative analysis to better understand the flow regime in the study area and hence a more practical conceptual model. Mogaji et al., (2015) also used geophysical parameters to model groundwater recharge using a multiple linear regression (MLR) along the boundary of Perak and Selango in Peninsular Malaysia. It was proposed that groundwater recharge should be modelled on a regional scale by correlating the estimated recharge rate with various aquifer parameters derived from geophysics data. They concluded that the proposed method could provide a quick, independent, and cost-effective recharge estimation by simple geophysical measurement. Andersen, (2013) and Masciopinto et al., (2017) also used geophysics data for groundwater modelling but their studies did not include the use of derivative analysis hence the gap.

A 3D geological model was developed from geophysics data for groundwater modelling and management in the Kribi-Campo sedimentary sub-basin, Cameroon (Yevalla et al., 2020). The aim of the study was to develop a clear geophysics data collection procedure and developing both geological and hydrogeological models to ensure the delineation of aquifer geometry and extent of connectivity. Models were developed and proper management plans were put in place. However, the authors stated that one of the shortcomings of the study was that borehole data have not been used especially for the validation of the geophysics investigation and that is a major advantage of this study which includes both geophysics data and borehole/pumping test data to understand the system thereby producing a more practical model output.

1.3 Problem statement

1.3.1 Research problem for the study

The use of geophysics data and derivative analysis in understanding the complexities that exist around aquifer system remains poorly understood. This is a problem because if derivatives are not considered in characterization of aquifers, we will have limited understanding of the flow regime and the heterogeneity of the aquifer hence it affects the utilization and monitoring of the system. Specifically, some of the problems that are seen in aquifer system includes.

1. Heterogeneity which is caused majorly by the difference in hydraulic parameters and geology of the area. In the Hopefield area, heterogeneity occurs as alluvial sediments which are been hosted by the paleo-channels that are present in the porous aquifer system.
2. The physical properties of the fractures, their position and interconnectivity as this affects the permeability which in turn impacts on the pattern of flow (flow regime) of the formation.
3. There is also complexity to investigate and define how they work in the field.

In many cases, geophysical techniques have been used to explore groundwater in various hydrogeological conditions but the use of derivative analysis of pumping test which amplifies the heterogeneity of the aquifer system and informs the choice of the groundwater conceptual model (Ferroud et al., 2018) has not been fully utilized. The magnitude of this type of problem is widely known. For example, the following models are conceptually and numerically developed without the use of geophysics data and derivative analysis (Kpegli et al., 2018; Nema et al., 2019; Samuel et al., 2020). Yevallaa et al., 2020 developed a groundwater model using geophysics data only and reports that the inclusion of geophysics and borehole data in the characterization of an aquifer produces a more reliable model. The implication of excluding the use of derivative is that the complexity of the aquifer in nature remain unknown (Ferroud et al., 2018) due to the simplicity of these models. In other words, if such a problem is not addressed, it means we have inadequate information on flow regime in aquifer system. As a result, in the current study, the focus is to explore the use of hydrogeophysics data and derivative analysis to improve knowledge on aquifer dynamics.

1.3.2 Research question

What are the advantages of using hydrogeophysics data and derivative analysis for aquifer hydrogeological characterization?

1.3.3 Research central argument

When hydrogeophysics data and derivative analysis are not used in aquifer characterization, it results in models that are not solution-based and cannot guide groundwater management.

1.4 Study aim and objectives

The aim of the study is to provide improved understanding on characterization of aquifer dynamics for solution-based modelling. Such improved understanding enhances practitioner's use of groundwater models for practice as they use and manage groundwater resources. The West Coast Aquifer System in South Africa is used as a case study. To achieve the stated study aim, three objectives are formulated as follows:

1] Establish the aquifer units for characterizing aquifer system

2] Determine aquifer flow regime and boundary conditions for the analysis of solution-based models

3] Estimate aquifer hydraulic parameters for hydrogeological characterization

1.5 Study rationale

This study is importantly because firstly, it is solely concentrated on enhancing the knowledge concerning the characteristics of the aquifer hydrogeophysical properties in coastal areas. Secondly, results from this study can be used in decision making and management of groundwater in the study area as it provides information on the hydrogeophysical properties of the area. Thirdly, since hydraulic properties are essential for groundwater quality and quantity assessment (transmissivity, storativity and sustainable yield), this study contributes to the existing knowledge for future assessment on the hydrogeophysical investigation in coastal regions. Lastly aquifer testing is one method of subsurface characterization, and it is related to other methods used by geotechnical and petroleum engineers, hence results from this study is broadly applicable to many other disciplines in understanding the complexities and hydrogeological characterization of aquifer systems.

1.6 Conceptualisation of the study

This study was conceptualized based on an extensive review of literature that was conducted in the major areas that aligns with the stated objectives. Groundwater flow regime, hydrogeophysical data, pumping test, derivative analysis, amongst others were the theme used in the literature search. Through this systematic review, suitable solutions to the research question became understandable. Renard (2005); Samani et al., (2007); Hammond and Field (2014); Ferroud et al., (2019) and Garin et al., (2019) were amongst several authors who demonstrated through their publications the influence or advantages of using derivative analysis in pumping test interpretation. Hammond and Field (2014) stated that the application of derivative plots is essential to determine the correct model to apply for a set of time-drawdown data. Their studies also included the use of geophysical logs while Garin et al., (2019) stated that the diagnostic plot method allows the definition of a conceptual flow model from the succession of flow regimes identified with the derivative of the drawdown.

More recently Ferroud et al., (2019) used the derivative approach to interpret non-uniform aquifers with a constant rate pumping test data. They concluded that the inclusion of derivatives and geophysical/geological survey can be helpful in selecting a non-unique flow model. The authors also stated that through the integration of derivative analysis and geophysical survey, the nature and the configuration of aquifer heterogeneity can be uncovered. However, with an aim of developing a better interpretation, this research during literature review realized that there is a need for a broader approach hence this study is being investigated by an integration of geological data, geophysical data, and the use of derivative analysis. Lastly since the choice of a conceptual model is informed by derivative analysis (Hammond and Field, (2014), Ferroud et al., (2019)) hence this study was conceptualized on the need to demonstrate the advantages of the derivative approach in enhancing understanding on the characterization of aquifer systems that will infirm solution-based modeling.

Within the scope of hydrogeology, which deals with the movement and distribution of water in the rocks pore spaces, fissures, faults, and lineaments, this study focuses on the flow of groundwater components of hydrogeology in terms of processes. It also focuses on the interpretations of the variations in the properties of aquifers as a major way into widening the understanding of aquifer properties. The flow of groundwater in terms of processes depend on the gradient and the properties of the aquifer. The study focused on the characterization of aquifer system using an integration of hydrogeophysics method and derivative analysis to better understand the aquifer dynamics in the Hopefield area.

1.7 Outline of the thesis

The thesis outline of this study is as follows: Chapter 1 provides a background on coastal aquifers, need for aquifer characterization in such regions and a background on the use of derivative analysis in the determination of flow regime in a system. In addition, the research problem, research question, central argument, study objectives and study rationale are stated. The study area and its features has been described in chapter 2 of this thesis. Chapter 3 presented the reviewed literature on the study to show what is known and not known from global to national context. The theoretical and conceptual frameworks that guide the study have been described. Chapter 4 provides the description of the research design, methods that were used to collect and analyse data. In addition, aspects of research integrity and limitations in the study have been described. Chapter 5 has presented and discussed results on 1] subsurface geophysical investigation, 2] determination of different flow regimes that were identified and 3] estimation of aquifer hydraulic parameters. Finally, chapter 6 provides summary and conclusions on the study and recommendations for future work.

CHAPTER 2: DESCRIPTION OF STUDY AREA

2.1 Location of the study area

The study area for this project is the Hopefield in the West Coast District Municipality (WCDM), which is in the Western Cape Province of South Africa. It is situated in the Berg River Catchment area. The WCDM comprises of 12 quaternary catchments that differ in sizes. The Hopefield is located in the G10L quaternary catchment with an area extent of about 1754.5 km^2. Geologically it is composed of Cenozoic sediments in the towns of Langebaan, Saldanha, Hopefield and Velddrif. Landscape in the region is generally flat and covered by sand plains, sand, and vegetated dunes. The study area has a coastal climate, and its hydrological environment is semi-arid with limited water sources. The land use is dominated by shrubland, low fynbos and large cultivated land. Built-up and industrial areas occur in the small towns of Saldanha, Langebaan, Velddrif and Hopefield.

Figure 1- Location of the study area within a municipality setting (GEOSS, 2019)

The complex hydrogeological nature of the West Coast Aquifer System makes it a good location for this study. Some concerns have been shown about the conceptual model of the Langebaan Road Aquifer Unit and Elandsfontein Aquifer Unit developed by Woodford et al.,

(2003) as it is not easily explained by apparent geomorphological process (DWAF, 2008b). The complexity of the West Coast Aquifer System was further shown by Conrad et al., (2004) using groundwater surface water interaction and the deep-seated inflow of aquifer in the Sandveld. The increased knowledge of aquifer systems as it helps in the management of groundwater resources in the West Coast (Jovanovic et al., 2017) is also a rationale for the chosen study location.

2.2 Drainage and hydrology of the study area

The Berg River is the only perennial river in the study area with its flow derived from the Drakenstein and Franschhoek Mountains, approximately 285 kilometres to the east and lies in a broad flat plain with elevation less than 20 meters above mean sea level (Seyler et al., 2017). The Berg River discharges north-westwards into the Atlantic Ocean near Velddrif and is located within the north-eastern boundary of the study area. Timmerman, (1985b) and Seyler et al., (2017) stated that the Groen and Sout River which are important non-perennial rivers in the study area are located on the eastern border and they drain northwards into the Berg River. Surface runoffs from the Vredenburg Koppies which have low permeability also supplement the Berg River (Umvoto, 2008). A section of the Langebaan Road Aquifer Unit groundwater flows in a northerly direction also towards the Berg River and this drainage section forms part of the Berg River Catchment.

At the Ramsar Convention of 1975, the Langebaan lagoon which covers an area of about 57 km^2 was classified as a wetland of international peace and this is solely because the wetland supports more birdlife than any other wetland in South Africa (Saayman et al., 2003). The Langebaan lagoon is surrounded by vegetated dunes, and these are areas where recharge occurs naturally. The Langebaan Lagoon is an extension of the Saldanha Bay, and the southernmost edge of the Lagoon is known as Geelbek with an average depth of about 1-2 meters. When Tidal fluctuations occur between Saldanha Bay and the lagoon, it generates high temperature (14°C in winter and 25°C in summer months) at Geelbek and this is due to the shallow nature of the lagoon. This results in high evaporation and greater salinity in Geelbek than in Saldanha Bay.

2.3 Climate features of the study area

The Hopefield area is considered semi-arid because evaporation exceeds rainfall. It also has a Mediterranean climate with warm dry summers and cool wet winters (Cobbing et al., 2013;

Seyler et al., 2017). Rainfall occurs during the winter from June to August which is the wettest month throughout the year. The amount of rainfall decreases from North to South with Atlantis and Velddrif experiencing an average annual rainfall of 532 mm/a and 253 mm/a respectively (DWAF, 2008). Clark, (2009) stated that the average annual rainfall found in the Langebaan Road Aquifer Unit (LRAU) is 310 mm and the Elandsfontein Aquifer Unit (EAU) is 400 mm per annum. The inter-annual changes between weather stations are also important, Seyler et al., (2017). This has been seen in the comparison between South African weather station (SAWS) rain gauges which was found at the coast and further inland where notable differences of ± 30% was noticed. Rainfall is highest at the coast during the winter months while minimum and maximum temperatures are highest further inland. The rate of evaporation is higher in the southern part of the study area while relative humidity is high in winter months than in summer months and highest at the coast because of the effects of excess oceanic water vapour.

2.4 Geology of the study area

The Cenozoic sediments in the Saldanha environs are richly endowed with paleontological and archaeological remains although it is limited in volume. These range from the diverse Mio-Pliocene fauna at the Langebaan Road phosphate quarry (Hendey, 1974, 1981a, b), the Middle Pleistocene Hopefield site where the partial cranium of early archaic Homo Sapiens were found (Singer and Wymer, 1968), and the Late Pleistocene fossil human footprints at Kraal Bay. There are many other significant sites that hold archaeological and paleontological remains, this is because of the calcareous nature of the coastal sand. Three major events informed the existence of this coastal platform of the south-western coast, and they are firstly; - deformation during the Late Permian Cape Orogeny, which has largely controlled the relief and structural grain of the pre-Mesozoic strata. Secondly, Headward erosion since the Late Jurassic to Early Cretaceous separation of western Gondwana and lastly, climatic fluctuations in large measure mediated by changes in global oceanic circulation systems.

The predominant geology of the West Coast is the Sandveld group which extends in a northward direction from the Cape Hangklip in the southeast to Elands Bay. It is composed of semi to unconsolidated Cenozoic sediments (65 Ma – present) and this overlies the Malmesbury group which are metamorphosed shale and the granites of the Cape granite suite. The formations present in the area are the Elandsfontein Formation, Varswater Formation, Langebaan Formation, Springfontein Formation, and the Witzand Formation. The Elandsfontein formation was exposed in a small, presently inaccessible peat quarry at

Kraaifontein, east of Cape Town (Cole and Roberts, 1996). It occupies Paleo-depressions in Precambrian bedrock and typically conformably to unconformably overlain by the Mio-Pliocene Varswater formation. Rogers (1980) stated that at Noordhoek, south of Cape Town, the strata occur as much as 50 meters below mean sea level. The Elandsfontein comprises upward-fining sequences of angular, fine to coarse-grained, quartzose sand, gravel, clay, and lignite, recording meandering river sedimentation (Rogers, 1980, 1982 and Timmerman, 1988). Thickness of up to about 70 meters has been recorded east of Langebaan lagoon (Southeast of Saldanha) and between the Berg River and Elands Bay. The Varswater formation is a marine formation bearing highly fossiliferous phosphate. The type area is the Varswater phosphate quarry near Langebaan Road, where the formation occurs up to 50 meters above mean sea level. It attains up to 60 meters in thickness (Timmerman, 1988) resting on the Precambrian bedrock. It is unconformably overlain by the Langebaan, Velddrif and Springfontein formations.

The rich and diverse fauna of the Langeberg and Muishond Fontein Members, which includes the only bear known in sub-Saharan Africa (*Agriothenum africanum*), a wolverine (*Plesiogulo monspessulanus*), short-necked giraffids (*Sivathenum hendeyi*) and five species of hyaena (Hendey, 1981a) suggests a Mio-Pliocene age. The type area of the Langebaan formation is on the western shores of the Langebaan Lagoon, where the strata are well exposed and precisely dated (Roberts and Berger, 1997). Commonly overlain by the Witzand formation, the Langebaan formation rests on a variety of Cenozoic and basement rocks. The formation comprises the Late Pliocene Diazvile Member, named after a town, west of Saldanha and the Quanternary Kreel Bay member, named after a locality on the western shores of Langebaan lagoon. The Diazville Member is distinguished from the Kraal Bay Member by its micro and marco faunal content and by its generally higher carbonate content (up to 90%). The former includes the calcareous sand member (Varswater formation).

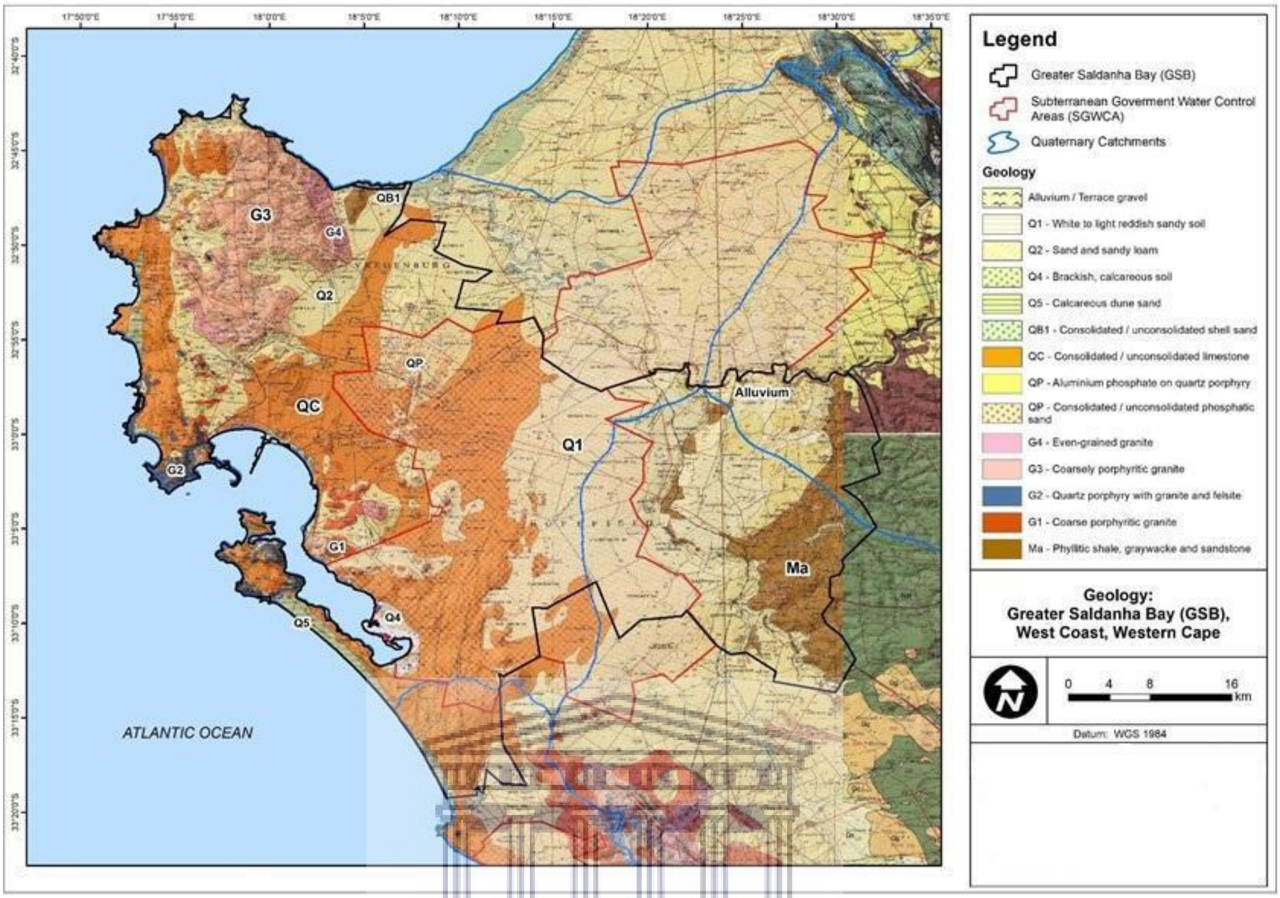


Figure 2- Regional geology of the study area (GEOSS, 2019)

The type locality of the formation is Springfontein Cliffs, 10 kilometres southwest of Atlantis (Rogers, 1980). The reddish to grey unconsolidated quartzose Aeolian sands of the Springfontein formation are muddy and peaty in places (Rogers, 1980). It has a maximum thickness of about 67 meters near Atlantis and 34 meters on the Cape Flats southeast of Cape Town. There is uncertainty in the age of the Springfontein formation, but Rogers (1980) stated that it ranges from Middle Pleistocene to Holocene and it is about 40 kilometres north of Cape Town where the sand is up to 28 meters thick (Rogers, 1980, 1982). The whitish grey to slightly reddish sands of the Witszand formation is mobile, pertly vegetated to unvegetated bioclastic-silicilastic and they also record the most phase of Aeolian activity in the Sandveld Group. The Witzand formation comprises about 20-85% detrital carbonate and they occur intermittently along the coastline.

2.5 Hydrogeological features of the study area

The stratigraphy of the West Coast Aquifer System is slightly complex with varying clay layers however groundwater occurrence in the area is grouped under four hydrogeological units (Figure 4). The deepest water bearing unit is the bedrock aquifer. The Elandsfontein aquifer unit (EAU) is the basal gravel of the Elandsfontein formation, and this forms the southern paleochannel. The northern paleochannel is called the Langebaan Road Aquifer Unit (LRAU). The aquitard of the Elandsfontein formation which is a clay layer superimposes the LRAU and EAU and it also confines these units (DWAF, 2008). These aquifer units (LRAU and EAU) both constitute the lower aquifer unit (LAU) of the West Coast Aquifer System (WCAS) while consolidated sands and calcrete with interbedded clay of the Sandveld group constitutes the upper aquifer unit (UAU). Since the study area is location in the paleochannel formation of the Elandsfontein, the transmissivity here is expected to be high.

There is a similar flow pattern between the lower and upper aquifer unit (Woodford et al., 2003). Although this is not entirely true because of the nature of the 2 aquifers and their aerial extents. It is suggested that the flow in the LAU is controlled by the bedrock topography and flow occurs along the axis of the paleochannels, towards their exits on the SW coastline. Flow in the UAU is more likely to be topographically controlled. According to DWAF 2008, the UAU is directly recharged from rainfall, which is concentrated in the dune areas west and southwest of Hopefield, where topography and water levels are highest.

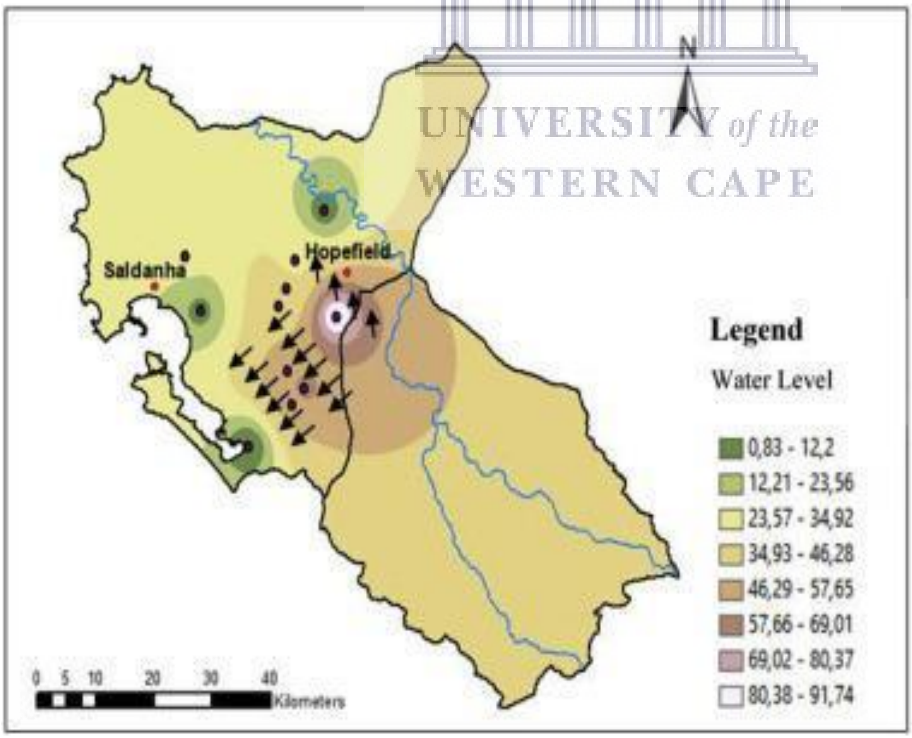


Figure 3- Movement of groundwater in the study area due to elevation in the water table (Van der Schyff et al., 2020)

The LRAU which is in the G10M quaternary catchment consist of loosed alluvial and reworked marine deposits and this is classified as a highly permeable formation (Saayman et al., 2004).

A well field which comprises of 2 production and 2 standby boreholes, which taps the LRAU was established in this aquifer during the late 1999 hence it is a major aquifer. Seyler et al., (2008) stated that the Elandsfontein Formation comprises of fluvial deposits which consist of white sand, gravels, fine sandy clays, and dark organic-rich peat. These deposits are more susceptible to erosion can be seen in the depressions of the paleochannels which are found extensively in the west coast region. Above the Elandsfontein Formation is the Varswater succession and it consists of alluvium, sandy calcrete and a quarzitic sand layer.

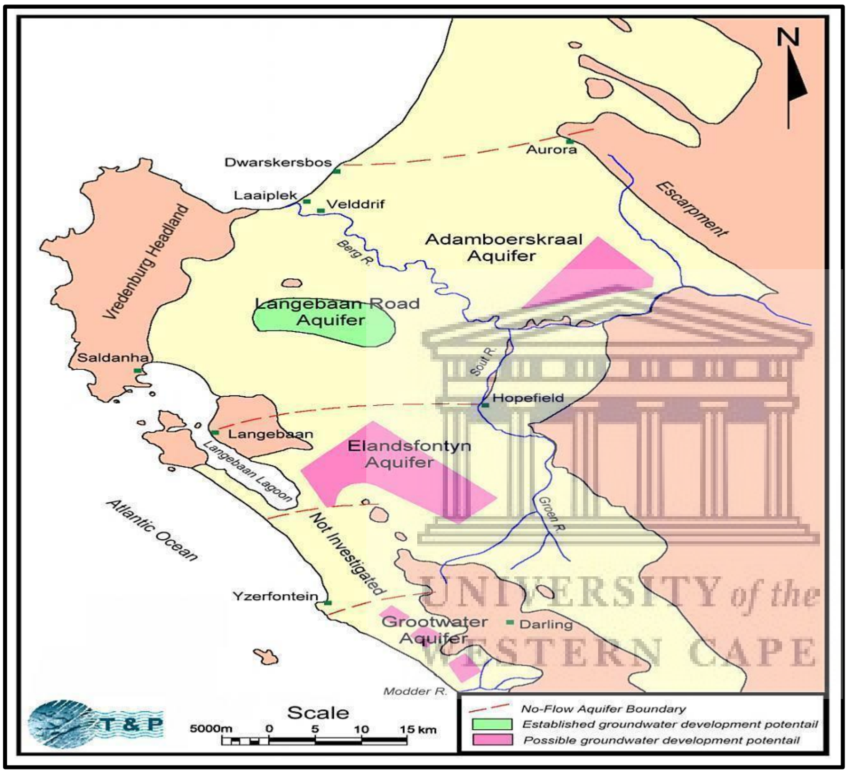


Figure 4- Map of the study area showing aquifer units (Du Plessis, 2009)

An exploration drilling conducted by Timmerman, (1985) supported the assumption that the west coast aquifer system is composed of four hydraulic layers. This assumption was also recently confirmed by a numerical modelling investigation by Seyler et al, (2017). Boreholes in this aquifer system are deep. This is because the Elandsfontein aquifer is much thicker when compared to the Langebaan Road aquifer. Seyler et al., (2016) reported that the Elandsfontein formation outcrops in the southeastern part of the area and has eroded and deposited sediments near the Atlantic Ocean. Timmerman, (1988) recorded that the most permeable zone has been described to be sand layer of the Springfontein Formation and this is because of the layer having a hydraulic conductivity value of 20.2 m/day and Transmissivity value of 237.4 m^2/day while the Noordhoek Formation has a clay and peat lenses with a range of hydraulic conductivity value of 1.4-8.7 m/day and transmissivity value of 23-202 m^2/day and this basically gives the semi-confine character to the unconfined aquifer.

A maximum thickness of 60 meters in the deepest sections of the paleochannel is reached by the Elandsfontein gravels (Kornelius et al, 2007). Woodford et al., (2003) stated that the paleo channels are filled with sand and gravel interbedded with silty fine sand. The LRAU is bounded by the Berg River, Sout River and has a zero-flow boundary between Langebaan and Elandsfontein aquifers, Timmerman, (1985). The paleochannel extends towards the coastline and it is released into the Atlantic Ocean. The clay aquitard is disseminated along the whole area of the west coast region, and it is thickest at the centre of the LRAU and EAU close to the Langebaan Road Wellfield. Seyler et al., (2017) stated that the thickness of the clay layers varies regionally, in some places about 40 meters and in some other; it can be less than 5 meters as the clay layer seems to have been eroded for distance much greater than 5 kilometres from the coastline.

Timmerman (1985a) investigated the geohydrology of the Langebaan and Elandsfontein aquifer unit in the Berg River region. The investigation comprises of the drilling of 54 exploratory boreholes, an electrical resistivity survey in the area north of the Berg River, 9 constant rate discharge test and some short duration test, water level and water quality monitoring. He stated that the Elandsfontein aquifer unit which is of a higher complexity than the Landebaan Road Aquifer unit has its base as a confined aquifer formed by the Elandsfontein sand and gravel, underneath a thick confining sequence of clay and peat, having a transmissivity range of 10 m^2/day and 400 m^2/day and average storativity value of 3.1×10^{-3}.

The coarse grained Elandsfontein Aquifer unit were deposited in series of paleo-river channels, the old courses of the Berg and other rivers in the area (Timmerman 1985a and 1985b). The aquifer unit alternates with clay and peat because of the fluviatile nature of the deposit. These clay and peats were deposited in the floodplain and swamp environment of the aquifer system. Lastly, Timmerman (1985) also indicated that there is a no “flow boundary” that exist between the Langebaan Road and the Elandsfontein aquifer system (figure 4) and this was concluded from the drilling results of boreholes G30871 and G29823. This further shows the presence of a high basement in the Malmesbury shale which separates the lower semi-confined aquifer, but Timmerman also stated that there is no sufficient information relating to the hydraulic nature and extensiveness of this “no-flow” boundary which divides the 2-aquifer system hence derivative analysis was used in this study to characterise the no-flow boundary and understand how it affects the aquifer dynamics.

2.6 Land use activities in the study area

Land use activities have a way of impacting the flow of water groundwater, since the West coast has an increase in migration and urbanization, the transition from vegetated land surface to industrial land surface has also change the groundwater recharge mechanism and hence the flow regime. Natural recharge has been slowed due to effects of urbanization and impervious surfaces increases runoff and hence an increased centred recharge which also in turn affects the flow regime through aquifers. The study area is characterised with low undulating relief dominated by open shrubland and low fynbos. Kornelius et al., (2007), stated that the increase in migration into the West Coast has created a demand for coastal developments and this has resulted in built-up areas consisting of small towns like Saldanha, Langebaan, Velddrif and Hopefield. Seyler et al; (2008) noted that the largest portion of the land in the area has been used mainly for commercial agricultural purpose. The area has been an important mining centre, with its main minerals consisting of phosphorites, primarily calcium phosphate. Accounting for the various land use activities and their interactions with the water cycle contributes to the understanding of the chemical character of the groundwater in the area.

2.7 Socioeconomic activities

The West Coast which covers an area of about 31,119 km^2 comprises of five local municipalities: Bergrivier, Cederberg, Matzikama, Swartland and Saldanha Bay. Saldanha and Vredenburg are the largest towns in the district and other major towns include Langebaan, Hopefield, Darling, St Helena Bay, Paternoster, Velddrif and Yzerfontein. Groundwater which contributes about 15% of all water resources been used in South Africa (DWS, 2016) is a major source in the study area. This area largely depends on groundwater for irrigation and source of water supply for local communities (especially in communities without surface water supply infrastructures) hence it is important to understand the aquifer dynamics and how it affects the flow regime.

For example, according to the Municipal Economic Review and Outlook (MERO) in 2015, Saldanha Bay Local Municipality which is the largest natural bay in South Africa with a land size of approximately 2,015 km^2 largely depends on farmland, industrial development, and tourism attractions. The rental value of land and high value commercial farms forms part of the economy but government expenditure, trade and manufacturing remain the primary drivers. Trade here includes tourism which is focused on the bay while Arcelormittal Steel Smelter is the primary manufacturing activity here. The agricultural sector here is also very efficient and this comes largely from animal products, wheat, fruits, and vegetables. The area is also known for other industries which include fish, mussels, oysters, seaweed, and others. Saldanha is also the location of the South African Military Academy as well as SAS Saldanha, a naval training unit.

The effects of both the socio-economic development and land use activity have impacts on the groundwater flow in the study area. For example, the mining industry in the area can cause the natural flow path of the groundwater to be diverted, dewatering of aquifer can occur and the groundwater table in the area can be lowered. The chemicals also used in the mine for processing and transportation of minerals also pose a point source contamination threat to the quality of the groundwater especially since the local aquifer has a high permeability. The effects of agriculture can also be noticed as large-scale abstraction of water for agricultural use in the forms of irrigation and livestock farming may lead to a depletion of groundwater available in the local aquifers.

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

Chapter one has provided an elaborate introduction of the current study of in terms of research problem, objectives, rationale including the study area where the research ideas were implemented. In this chapter three, previous studies have been reviewed in terms of what is known and what is not known about the use of hydrogeophysics methods to understand hydrogeological properties and the use of derivatives on understanding groundwater flow regimes. The reviewed literature has been presented systematically [objective by objective] and analytically [showing the gap in knowledge and practice] to show how the current study narrowed such gap. The general overview on aquifer characterization with focus on characterising hydrogeological systems of coastal aquifers has been presented. Principles and concepts that guide hydrogeological systems including characterization of aquifers in coastal areas are explained. In this chapter, the argument is that characterizing coastal aquifers using hydrogeophysics and derivatives methods lead to a better understanding of the aquifer system which provide practical solutions for planners, users, monitors and managers of groundwater resource [modelling for practical solution]. The previous studies have been reviewed from global, regional, and national perspective to contextualise the current study at such three levels. The chapter ends with a review on frameworks that guide the current study such as theoretical, conceptual and interpretation frameworks for the study.

3.2 Previous studies on hydrogeophysics of coastal aquifers

Hydrogeophysical characterization of aquifers must be a continuous process: geophysical characterization has been validated by drilling log, pumping tests and the calibration of geophysics has also been improved with new hydrogeological data. Aquifer characteristics (hydraulic conductivity and transmissivity) have been obtained from well pumping test data as previous studies have shown that it is one of the most appropriate techniques (Freeze and Cherry 1979; Kruseman and de Ridder 1994; Sattar et al., 2016). The natural flow of water through an aquifer and its response to the extraction of fluid can best be understood when these properties have been studied however conventional approaches do not allow a more in-depth conceptualization of the local aquifer properties (flow regimes) hence the use of derivative plots. Derivative analysis is a powerful diagnostic tool that enhances the interpretation of data from pumping tests. Features difficult to discern in drawdown data alone are often readily apparent through the application of the derivative procedure because derivative plots combine drawdown and derivative data on a single plot. Groundwater hydrologists use derivative analysis to firstly identify important flow regimes encountered during a pumping test, secondly detect aquifer boundaries, thirdly highlight heterogeneity in local aquifer characteristics and lastly select appropriate aquifer models (Ferroud et al., 2018).

Locally, Timmerman (1988) conducted a hydrogeological resource assessment of groundwater in the West Coast region and this assessment had a focus on the hydro-stratigraphy, geology, and water quality and aquifer delineation. In addition, an assessment of aquifer potential was conducted by Woodford and Fortuin (2002) and this study focused on analysing the aquifer characterization and recharge. A conceptual and numerical model were developed by the Department of Water and Sanitation (DWS) in 2008 and this was aimed at characterizing the Elandsfontein aquifer and providing a quantitative basis for resource assessment for water supply. The unpublished literatures in the form of government and consultant reports included groundwater resource impact assessment conducted by SRK Consulting (2008), geohydrological environmental assessment (2019) both conducted in the Saldanha area which is part of the West Coast aquifer system. However, a gap in knowledge has been identified in the use of integrated method using geophysics data and derivative analysis to characterize the West Coast aquifer system and this integration has led to an in-depth understanding of the complexity of the aquifer system globally.

3.2.1 Global context of hydrogeophysics of coastal aquifers

Numerous studies have been carried out and published globally on hydrogeophysics of coastal aquifers and many of these studies focused on seawater intrusion as this is the biggest issue facing coastal aquifers (Duque et al., 2008; Himi et al., 2017). Conceptual understanding of coastal hydrogeological systems, characterization of subsurface hydrogeological properties and development of mathematical models remain topical issues on coastal aquifers around the world (Werner et al., 2010). However, the emphasis on the establishment of hydrogeophysical properties is limited and not given the much attention it needs and presently in South Africa, the inadequate knowledge of hydrogeological properties of these aquifers remains worrisome (Adelana, 2008). This is despite the facts that a thorough knowledge of such assessment is essential in proper groundwater exploration and hence sustainable usage of such waters.

The role of geophysical, geochemical, and hydrogeological parameters in the exploration of fresh groundwater resource in a brackish terrain of Dharwar district in Karnataka State (South-

Western India) was explained by Hodlur, (2002). A later hydrogeophysical approach of investigation was also applied at Sasihithlu, Karnataka State, India by Vouillamoz, (2012) where aquifer properties were quantified, and freshwater resource was also mapped. Results showed that the combined interpretation of geophysical and hydrological results allowed estimating the aquifer properties and mapping the freshwater lens. These findings informed the approach for the present study where an integration approach was followed.

In Italy, Balia et al., (2003) carried out a study where geophysics data were used in the environmental study of the Muravera coastal plain, Sardinia. Complimentary geological investigations were also conducted. The study aimed at improving the available geophysical information which has been affected by drastic soil and water salination. Results from the study showed that the integration of both geophysical and geological investigation techniques can provide wide range and high-quality information and this is essential for realistic mathematical modelling while Martorana, (2014) used hydrogeophysical method for the 3D modelling of a coastal aquifer polluted by seawater in Petrosino, Italy. The authors concluded that the results obtained from the geophysical investigation can assist in the environmental protection of coastal aquifers with similar hydrogeological characteristics hence geophysics was applied in this study to understand the hydrogeological characteristics of the study area.

2D electrical imaging was used in the characterization of a sea water intrusion site in Almeria, Southeast of Spain by Nguyen et al., (2009). Geological information and logs from borehole were also used to compliment the geophysical data and results indicated that electrical imaging constrained seawater intrusion models if image appraisal tools are appropriately used to quantify the spatial variation of sensitivity and resolution. Farajat, (2009) characterized a coastal aquifer basin using gravity and resistivity methods in Aqaba, Jordan. Hydrogeophysical investigation investigated the groundwater potential in the Aqaba area, precisely the study aimed at the evaluation of the basin and its geometry, depths to groundwater, seawater-freshwater interface, and zone of different groundwater qualities. The result from the study stated that the combination of gravity and resistivity geophysical methods confirmed the 3D distribution of groundwater in the basin hence the resistivity method was chosen for this study to better understand the aquifer and hydrogeological properties under study.

A coastal aquifer assessment was conducted based on geological and geophysical survey in northwestern Crete, Greece by Soupios et al., (2010). The transient electromagnetic method

(TEM) and the electrical resistivity tomography (ERT) were used for defining the hydrogeological characteristics of the area under study. Detailed geological, hydrolithological and tectonic investigation was applied prior to the geophysical measurements and the authors concluded that the integration was successful for the determination of the major hydrogeological characteristics of the study area, as it provided information on the geometrical and hydraulic information of the aquifer. In China, Ma et al., (2019) spatially characterized the seawater intrusion in a coastal aquifer of Northeast Liaodong Bay. Results showed that the integration of geophysical and geochemical methods aided the characterization especially with areas having limited available hydrochemical data. Based on such results, the current study used same integration approach employing both hydrogeophysical method and derivative analysis in understanding aquifer dynamics in the study area.

Hydrogeophysical methods were used to contribute to the development of coastal aquifer hydrogeological conceptual model in the Algarve region (southernmost province of Portugal) by Francés, (2015). Complementary information such as boreholes logs, regional static piezometric map and analytical models of the freshwater-saltwater interface was used. Hydrogeophysical methods were employed to detect the freshwater-saltwater interface along the coast and identify the water bearing layers and aquitards and correlate them with the geological formations. The geophysical methods were successful in the detection of the position of the freshwater–saltwater interface (FSWI) and allowed redefining the boundaries and 3D structure of the aquifer, as well explaining the submarine groundwater discharge (SGD) location.

Sonkamble et al., (2016) used hydrogeophysical technique for the safe exploration of the fresh groundwater resource in the coastal belt of Cuddalore district, Southern India while Senthilkumar, (2019) used an integration of geophysical and geochemical methods to decode subsurface geologic pattern and delineate the seawater–freshwater zones in the coastal region of Thiruvallur district, Tamil Nadu, South India. Vertical electrical sounding techniques were successfully applied to identify the seawater and brackish water zones in the study area. From the sounding results, thickness of various layers and iso-apparent resistivity were successfully delineated. The current study followed a similar approach to delineate groundwater units in the study area, the West Coast aquifer system.

3.2.2 Regional context of hydrogeophysics of coastal aquifers

In Southern Africa, Meier et al., (2014) carried out a hydrogeophysical investigation in the western and north-central Okavango Delta (Botswana) using electrical and magnetic geophysical methods. The aim of the study was to delineate the sedimentary units of the Okanvango Delta. Despite numerous geologic, geochemical, geophysical, and hydrologic investigations over the past half-century, the sedimentary units underlying the delta are largely unknown while a later hydrogeophysical study conducted by Podgorski et al., (2015) also in the Okanvango delta aimed at having much information on the geology and hydrogeology of the Okavango Delta concluded that the results from the surface geophysical investigation was the principal data that was used to refine the hydrogeological model of the Okanvango Delta and hence a properly delineation of the study area was drawn from the model. The same approach was employed in this study as geophysics data was used in enhancing the knowledge on aquifer hydraulic.

In North Africa, Ibraheem et al., (2016) conducted a hydrogeophysical and structural investigation using the vertical electrical sounding and time domain eletro-magnetic data. The aim of the study was to delineate the subsurface structure and determine the groundwater regime of El-Nubariya–Wadi El-Natrun area (Egypt). The conventional hydrogeological techniques such as pumping test, exploration boreholes, water, and soil samples most times gives insufficient results to describe the complex flow and transport processes of fluids both in the saturated and unsaturated zones and this has been because of the strong heterogeneity in the subsurface (Kemna et al., 2006). In addition, these techniques are expensive, sometimes selective and they can impede with the flowing system hence geophysical investigation techniques which are spatially extensive and least minimally invasive are employed to provide characterization of the subsurface with high spatial resolution and monitoring of processes. A hydrogeological evaluation was conducted on the East Nile Delta, (Egypt) where a resistivity characterization of aquifer was investigated in the coastal semiarid area. Direct current resistivity method (DCR), induced polarization (IP) and available borehole data was used for the study. The authors concluded that the direct current resistivity method has a great importance for hydrogeological/hydrogeophysical assessment.

In Martil-Alila plain (North Morocco), geophysics data were used to characterize seawater intrusion in coastal aquifer by Himi et al., (2016). This characterization complimented the geological and hydrochemical data that were also used in the study. The vertical electrical sounding generated electrical resistivity models, and this allowed the characterization of the vertical and lateral extension of the aquifer formations. Ultimately, the frequency domain electromagnetic (FDEM) technique allowed delineating the extension of the saltwater intrusion. In northeast of Tunisia, Chabaane et al., (2018) used geophysics to characterize the freshwater-saltwater interface in the Maamoura region. The electrical resistivity tomography was used to obtain electrical sectional imaging which is of high-resolution, and this allowed the delineation of places characterized by a high salinization and recreates the geometry of the saline wedge front. The Wenner array which has a high resolution on detecting saltwater plume and a strong signal to noise ratio was used (Chabaane et al., 2017b). The integration of the geological and geo-electrical methods provided greater confidence in the inferred results.

In West Africa, hydrogeophysics has also been used largely. In Ghana, it was used in the delineation of aquifer units in the Tarkwa Mining Area. An integration of electrical resistivity imaging (ERI) and electromagnetic (EM) survey were used to determine the electrical resistivity and conductivity of the aquifer under study so that potential water-bearing zones can be identified. Seidu et al., (2019) concluded that geophysical studies should be integrated with either another geophysical method or a geological investigation as an integration of more than one geophysical method as it aided the identification of ambiguity in the study area and a success rate of 86% was recorded from the study. Hydrogeophysics and geochemical techniques have been used by Ayolabi et al., (2013), to map saline water intrusion at the University of Lagos campus (Nigeria). Electrical resistivity tomography (ERT) was used for the investigation alongside geological information of the study area, and it was possible to clearly see that the study area has been intruded by salt water from the lagoon adjacent to the university while hydrostratigraphic characterization of shallow coastal aquifers was conducted in the Eastern Dahomey Basin of Southwest Nigeria by Aladejana et al, (2020) using integrated hydrogeophysical approach. Electrical resistivity tomography (ERT) was used in combination with induced polarization (IP), borehole logging and data from groundwater sample for the study. The chosen approach demonstrated a high level of efficiency and effectiveness in delineating lithological layers hence the identification of the fresh water/ saltwater interface. The current study used similar methods groundwater units.

3.2. 3 National context of hydrogeophysics of coastal aquifers

The use of hydrogeophysics has also be used in many areas in South Africa and this due to its application in different geological environments. Soltau and Anderson (2006) used hydrogeophysics to explore groundwater in the town of Mamre which is situated about 50 km north of Cape Town on the semi-arid west coast of South Africa and falls within the Atlantis-Mamre water conservation area. Shallow seismic reflection, electromagnetics, and resistivity survey were used in this investigation. The authors concluded that the integrated geophysical survey was successful as priority locations were identified for exploratory borehole drilling. Wenninger et al., (2008) used hydrogeophysics in the classical hydrometric measurements aimed at identifying the hydrological processes in the semi-arid headwater catchment in the Eastern Cape Province of South Africa. The electrical resistivity imaging (ERI) surveys was combined with tracer sampling for this identification and the authors concluded that the ERI survey, in combination with time domain reflectometry (TDR) measurements, allowed the extrapolation of selective soil water content measurements hence the combination of different field methods led to the development of a conceptual model of the hydrological functioning of this catchment.

Another study conducted at the Sodwana area which falls within the Maputaland Coastal Plain, KwaZulu-Natal province of South Africa, Nweze Augustine of the university of Zululand, used hydrrogeophysics to delineate the coastal aquifer units. The aim was to use the electrical resistivity method to delineate the water bearing formations in the Lake Mgobolezeni Catchments, Sodwana and map their facies. Tessema et al., (2012) also used hydrogeophysics to assess groundwater potential of Mafikeng in Northwest Province, South Africa. Due to the hard rock and carbonate terrain of the study area, a combined analysis of airborne magnetic data, satellite imagery, borehole yield and ground-based time-domain electromagnetic soundings were used for the investigation and the authors concluded that the integration is best approach for groundwater assessment within the hard rock and carbonate terrains of the study area. Fourie et al., (2019) conducted geophysical surveys (ground magnetics and electrical resistivity tomography, ERT) across the Daskop dyke in the Free State Province and this was done to firstly determine the dip of the dyke and secondly test whether gravitational settling near the footwall of a dipping dyke could explain the unbalanced clast distribution. This study followed a similar approach using the electrical resistivity tomography to delineate groundwater units in the West Coast aquifer system.

3.3 Aquifer characterization

Aquifer characterization has been defined by Engdahl et al., (2010) as a quantitative description of the subsurface in terms of hydraulically parameters such as transmissivity (T), storage coefficient (S), hydraulic conductivity (K), specific yield (Sy) and porosity (φ). This definition shows that a good aquifer characterization can improve the conceptual knowledge of the aquifer system under study. Aquifer characterization was conducted by firstly establishing groundwater units using surface geophysics method, secondly determination of flow regime and boundary conditions of aquifer systems using derivative analysis and lastly estimation of hydraulic parameters for hydrogeological characterization. Aquifer characterization should be the starting point before decision is made because it leads to proper management of our groundwater resource and, hence ensuring sustainability.

Aquifer characterization entails delineating or mapping of lateral boundaries and spatial lithology definition, thickness, water table elevation and groundwater flow direction, Tooley and Ericksen (1996). It also constitutes the establishments of geological units and hydraulic properties such as porosity and transmissivity, fractures, faults, patterns of groundwater flow, the aquifer geometry, and the rock type (Vereecken et al., 2006). Hence, for a proper and descriptive conceptualization of the hydrogeological environment or properties of an aquifer, the characterization of such aquifer should be of paramount importance. Peach (2000) stated that characterization of aquifer can be either preliminary or more advanced and depending on the needs of the investigation, it can also consist of basic geological information and hydraulic properties. Thus, the approach applied in Tooley and Erickson (1996) serves more as a primary approach that generate information of which later can be used to carry out the activities indicated in Attandoh et al., (2013). Thus, it can be argued that the focus of the characterization of aquifer should primarily be on the hydraulic and physical properties as well as groundwater flows which results in a better understanding of the aquifer and that is the approach that was used in this study.

The components that make up the characterization process are dependent on the aquifer type under study. Dippenaar, (2008) and Lasher, (2011) reported that in fractured rocks, faults and fracture sizes are established during characterization while primary porosities are the focus for inter-granular aquifers. Nevertheless, Falga’s et al., (2011) stated that in all case of aquifer characterization, adequate level of characterization of the aquifer is needed for gaining the right knowledge on the aquifer property. Various approaches have been applied for aquifer characterization, these include geological mapping, cross-section, drilling, core or well logging, pumping test, surface and borehole geophysics, remote sensing as well as groundwater models (Paillet and Reese, 2000; Lasher, 2011). However, application of a single method of investigation does not allow for full characterization as inadequate data will lead to inadequate knowledge of the aquifer, hence an integrated approach that involves pumping test data, lithologs from well/data and geophysical logs proves to be useful for full productive characterization as stated by Paillet and Reese (2000). Falga’s et al., (2011) also stated that the integrated application of hydrogeological and hydrogeophysical data provides adequate information about the aquifer properties. The type of approach needed towards the characterization of aquifer is dependent on many factors including the specific data needed for the project, the state of the chosen method at the site and the budgetary constraints. Nevertheless, the specific usage of the data should be the main consideration for choosing the appropriate methods or approach (Maliva, 2016). In this study, an integrated approach was used in characterizing the aquifer system.

3.4 Establishment of aquifer units

Establishment of groundwater units in coastal areas have been conducted by several methods. One of such methods used is the geophysical investigation and with methods such as seismic, gravity, magnetic and electrical resistivity. The most usual parameters used in characterizing groundwater are the porosity, the permeability, the transmissivity, and the conductivity. Since the depth of aquifers varies from place to place due to variational geo-thermal and geo-structural occurrence, it is important to use the most suitable method for the investigation. The electrical resistivity technique which is a subsurface investigation method is well established and the most important method for groundwater investigation and aquifer delineation. By driving a direct current signal into the ground and measuring the resulting potentials created in the ground, the resistivity of the subsurface has been measured by this direct current (Dahlin and Zhou, 2006). Since different formations and structures underground have different resistivities, from the data generated, the electrical properties of the earth can be derived, geological/aquifer characteristics can then be inferred from the generated electrical properties.

The electric resistivity tomography (ERT) has been identified as the most popular method in the geophysical community as shown by the numerous applications during the last decades, involving both the geologic field, that is, aquifer characterization, hydrogeophysics investigation, identification of freshwater seawater interface, landslide modelling, and soil layering, (Günther and Rücker, 2012). This method is broadly used because of its theoretical, operational, and interpretational simplicity. Instrument/device portability, depth of investigation and refined interpretation techniques are part of why this method is widely used.

The use of multi-electrode system and multi-channel equipment makes this method rapid as it covers large distances with good resolution (Dahlin & Zhou, 2006). Globally, this method has been used in the characterization of aquifer system. The influence of angled survey lines on 2D ERT surveys using the Wenner array and implications it has for groundwater exploration in the Karoo rocks (South Africa) was investigated by Mukhwathi and Fourie, (2020). The results of field surveys show that apparent resistivity data sets recorded along angled lines may be partially corrected by calculating the true geometric factors and by adjusting the apparent resistivity data accordingly. Significantly improved inverse resistivity models are found for corrected data sets. The data used for this study was collected using the Wenner-Schlumberger array which is useful for characterizing aquifer system in coastal environments.

A multi layered aquifer was delineated and mapped for groundwater salinization by Galazoulas, (2015) using the ERT method in Rhodope, Northeastern Greece. Lithological, physicochemical, and geophysical log data calibrated with ERT profiles were used to delineate the aquifer geometry and this enabled the extent of seawater freshwater to be identified. Conclusions drawn from the study was that the broad usage of high resolution deep geoelectrical sections which is calibrated with many hydrogeological data can successfully delineate aquifer geometry dimensions, identify hydraulic boundaries, and clarify ambiguous field measurements, thus allowing the development of a thorough hydrogeological conceptual model. Electrical resistivity tomography was used to characterize heterogeneity in the Port-Miou coastal karst aquifer in France. Precisely, Tassy et al., (2014) used this method to image the karstic conduits, locate secondary springs within the aquifer and detect the saltwater-freshwater interface. Geological information was used alongside the geophysics data. Karst and fracture corridors were detected from the study, saltwater-freshwater interface was delineated, and the study showed that the integration of geophysics data and geological information was useful in characterizing underground heterogeneities in complex karstic aquifers. This study also integrated the geological and geophysics information for the characterization of the aquifer system in the Hopefield.

A strongly weathered rock aquifer in South Guangdong, China, was evaluated by Gao et al., (2018), using a combination of the ERT method, magnetic method, joint profile method (JPM) and borehole data. The study was conducted to determine the geological units associated with the water-bearing formation of the aquifer systems in South Guangdong, China. The weathered and partly weather layers linking the terrain and the substratum yield maximum aquifer potential in the study area. Through this study, the ERT method is seen to be efficient in aquifer delineation even in a weathered environment with complex geology. In the coastal plain region of Alt Empordà, (Northern Spain), the vertical electrical sounding (VES) and electrical resistivity tomography (ERT) were used for the identification, mapping, and monitoring of the contrasting saline domains. The study which was conducted by Zarroca et al., (2011), showed that the VES allowed the solving of the one-dimensional resistivity structure of the subsurface while the ERT offered a much better interpretation, giving a 2D-image of the resistivity distribution, both laterally and in depth. The investigation demonstrated the effectiveness of the electrical methods in subsurface mapping. The surface geophysics method has been widely used in ensuring a detailed characterization of aquifers globally, proper management of groundwater resource and an extensive knowledge of the aquifer parameters which this method is efficient (covers large distances with good resolution) in providing.

Adagunodo et al., (2018) stated that despite the indispensable characteristics of groundwater and its role in the daily activities of people, it is still often associated with low yield, and this is due to inappropriate planning which includes drilling without conducting a geophysical investigation. In a study conducted in Western Nigeria, they noted that the expanding demand for water and the cost involved in drilling boreholes therefore requires the application and the proper use of groundwater investigation techniques to locate high yielding aquifers. They concluded the study by detecting the drillable zones and depths for optimum groundwater yield in Aaba, Western Nigeria, using the vertical electrical sounding and hence further stated that this technique is efficient in characterization and delineation of groundwater layers. The geoelectrical sounding which has been widely used for aquifer delineation can also be used accurately for the determination of aquifer hydraulic parameters (Keller and Frischknecht, 1966; Zhody, 1989). The main reason for this is because the physical conditions (tortuosity and porosity) controls both the flow of electric current and the lateral flow of water in porous media.

3.5 Determination of aquifer flow regime using derivative analysis

A variation exists between the convolution of actual behaviour of flow and the simplicity of analytical flow models, and this makes the interpretation of well-test ambivalent and impossible to realistically represent the complexity of aquifers in nature. This ambivalent nature has led to minimal knowledge of aquifer hydraulic properties. Although, slowly this customary practice is changing, most hydrogeologists still interpret most cases of constant-rate pumping test by matching theoretical type-curves obtained from Theis (1935) and Theis-derived models (Cooper and Jacob, 1946). By regularly fitting these curves, hydrogeologists put forward as a fact that this pumping test produces cylindrical-radial flow regimes and the actual flow regime that is occurring within the aquifer is been ignored. Due to this variation in the behaviour of flow, the derivative analysis is employed to amplify the heterogeneity of the aquifer system using derivative plots.

Derivative analysis is used because of its sensitivity to small variation in the drawdown plot during aquifer testing and this variation is sometimes not noticeable using the standard drawdown/time analysis. Because of this limitation of the traditional method for analysis pumping test, derivative analysis method was adopted for the present study. Derivative analysis method provides an intervention to improve aquifer test interpretation and it was introduced to the groundwater literature by Karasaki et al. (1988), Spane (1993) and Spane and Wurstner (1993). The use of diagnostic plot of drawdown derivative which has proven to be highly sensitive to drawdown behavioural changes has been facilitated by the model identification. Chow (1952) first introduced the derivative plot of ds/dlgt as a guide for the interpretation of dynamic drawdown from an artesian aquifer, even though it has a limitation of interpreting drawdown data with the Theis solution.

Despite this limitation, derivative analysis has been extensively used and much helpful research has been done mainly in the petroleum industry and subsequently has been used by groundwater hydrologists for several years (Karasaki et al., 1988; Ferroud et al., 2018; Garin et al., 2019). Ehlig-Economides (1988) described the features of the pressure derivative plots obtained, which could be used to compute reservoir parameters. Characteristic time-drawdown and derivative curves are integrated with geology to identify the nature of heterogeneities and assess their impact on long-term aquifer response to pumping (Parks and Bentley, 1996). Several studies have been carried out on the use of derivatives in describing different hydrogeological formations. For example, studies by Djebbar and Kumar, [1980]; Bourdet et al., [1983, 1989]; Beauheim and Pickens, [1986]; Ehlig-Economides, [1988]; Horn, [1990]; McConnell, [1993]; Spane and Wurstner, [1993]; Goode, [1997]; Renard, [2005] and Samani et al., [2007]; Garin et al., [2019] and Ferroud et al., [2019]) demonstrated how the pressure derivative plot was used to describe different hydrogeological formations which include inner boundaries (wellbore storage), outer boundaries (inflow and no-flow) and various flow regimes (radial flow) during constant rate and its following recovery tests.

Based on accurate identification of radial flows in constant rate tests, the derivative plots of ds/dlgt could be used in place of the traditional semi-log drawdown plots to determine aquifer transmissivity (Spane and Wurstner, 1993). The application of derivative plots created using the drawdown data has become a common practice in the investigation of aquifer parameters for all types of aquifer settings and pumping test methodology. This means that due to the sensitivity of the drawdown derivative plot, it has been used in many geological environments and in the study of aquifer hydraulic parameters. For example, the drawdown derivative plot was used in investigating the hydraulic behaviour of the Karoo aquifer at the campus test site of the University of the Free state, South Africa, using the Flow Characteristic (FC) method. One of the objectives of the study conducted in 2017 was to get the flow regime of the boreholes using diagnostic, specialised plots, and derivative drawdown plots. The flow regime and flow diagnostic analysis using diagnostic, specialised and derivative plot shows that, there was no wellbore storage neither linear flow. Except for borehole UO23 that first has linear flow than later bilinear flow. Whereas the rest of the boreholes were showing that there was a bilinear flow since the pumping started, then later a radial flow. So, the matrix feed the fracture first then the borehole and the author concluded that the hydraulic behaviour of the aquifer is influenced by its fractured network.

The diagnostic plot method was also used when Hernández-Espriú et al., (2016) reinterpreted an aquifer test conducted in the Spiritwood channel-aquifer (North Dakota, USA) by Shaver and Pusc (1992). The aim of the study was to adapt the linear flow analysis in fractured reservoirs for the estimation of channel-aquifer width from pumping tests, using derivative analysis. Beauheim et al. (2004) developed diagnostic plots for the scaled first or second derivative of the pressure or flow-rate response for each type of hydraulic test (constant rate, constant-pressure, or slug/pulse) for well testing in fractured media while Trinchero et al., (2008) proposed the double inflection point method based on the derivative of time drawdown curve to determine leaky aquifer parameters. The diagnostic plot method was used in a study by Garin et al., (2019) to improve pumping test interpretation in the carbonate aquifer of the Huveaune watershed near Marseille city in southern France. The study was aimed at carrying out pumping test and applies diagnostic plot method in two geological settings to improve the hydrogeological understanding of the karst aquifer and identify conceptual flow models of the heterogeneous aquifers. The method was successful in identifying the conceptual flow model and the authors stated that the diagnostic plot method allowed the definition of a conceptual flow model from the succession of flow regimes identified with the derivative of the drawdown and they concluded that the diagnostic plot method can be used in karst, fractured and alluvial aquifers indifferently.

Drawdown log-derivative time series analysis was early recognized as a major improvement in pumping test interpretation, due to its drastically enhanced sensibility to flow conditions, allowing for the detection of various forms of non-uniform, heterogeneous or bounded reservoirs (Gringarten, 2008). This means that the enhanced responsiveness of this method has aided its usefulness firstly in the petroleum industry and later in hydrogeology and in several aquifer/geologic environments. For example, studies by (Chow, 1952; Bourdet et al., 1983; Tiab and Kumar, 1980a) have established further interpretation of transient tests by analysing the drawdown log derivative time series *ds/dlogt*, more commonly referred to in the petroleum literature as the pressure derivative *t.dp/dt.* Bourdet et al., (1989) suggested that while plotting the pressure data *p*, modellers and practitioners should also plot the pressure derivative signal *dp/dlogt.* Renard et al., (2009) stated that this is easily achieved in hydrogeology as a drawdown log-derivative signal *ds/dlog.*

Instead of using the conventional drawdown signal *s*, the derivative approach makes the signal much more sensitive to small variations of drawdown. The diagnostic plots, representing the combined plots of both s and ds/dlogt versus time, are thus used to improve the interpretation of constant-rate pumping tests. The traditional way of interpreting derivative analysis using the semi-log drawdown derivative (*ds/dlgt*) has been described by conceptual methodologies and computerized methods. There are 2 distinct methods used in the interpretation of the drawdown log-derivative signal; the first method is a quantitative approach, and this employ matching theoretical curves obtained from analytical flow models, over the entire observed signal. Matching the curves can be done manually or automatically using best fitting codes (Kuusela-Lahtinen et al. 2003; Verbovšek 2009). The second method is a qualitative approach, and this is done by the selection of an appropriate conceptual model by means of similarity between observed and theoretical signals. The curve matching approach originally introduced by Walton (1962) but was criticized by Mattar (1999) for not having enough precision hence Mattar and Tiab alternatively proposed the sequential analysis approach. The sequential analysis approach also known as the diagnostic plot method (Garin et al., 2019) involves the separation of the drawdown log-derivative signal into a sequence of straight lines whose slopes are interpreted separately in terms of flow regimes (Ehlig-Economides et al. 1994; Tiab, 1995; Mattar, 1999; Renard et al. 2009;) or flow dimensions *n* (Barker, 1988). In this study, the flow regime sequential analysis approach also known as the diagnostic plot method was used and the reason for this method is because according to Ferroud et al., (2018), it provides a general hydrodynamic conceptual framework in which each value of the flow regime / flow dimension *n* represents a specific stable flow behaviour.

Another reason why this method was chosen is because in a natural media, many responses from derivative that are obtained from constant rate test consist of an array of different sections with flow dimensions that are stable from different geologic environments (Ferroud et al. 2018). A change in hydraulic state is caused when there is a change in the flow dimension value and in a mixed aquifer system, these complex signatures are produced, and their interpretation cannot be possible using the conventional type-curve methods, but it is possible using the sequential analysis approach. To select the analytical model that most suitably represents the real flow regime, *ds/dlogt* is considered. The bilogarithmic projection of the drawdown log-derivative versus time makes it possible to distinguish between changes in flow regime caused by subtle variations in aquifer conditions. For example, Issaka and Ambastha, (1999) in their studies found, changes that are less visible on drawdown-only plots. Another example been made by Ferroud et al., (2018) showed where the late flow regime is identified and characterized by a change in the log-derivative slope. The drawdown-only response only made it possible to diagnose a departure from the early Theis function, or eventually to fit a Theis function to the late stage, which would be inappropriate, as the derivative signal clearly indicated that this was a non-radial flow regime. The change in flow regime reflects changes in aquifer conditions in a generic fashion, at distance from the pumping well. In this case, this may be related to the influence of a fault or a variously fractured domain, disconnected from the well.

The use of derivative analysis for the determination of flow regime however has its limitations and one of such is the issue of non-unique interpretations. This means that different flow behaviours can produce the same flow dimension and various conceptual models may produce an identical flow dimension value. This is termed non-unicity in flow regimes (Ferroud et al., 2018). For instance, the spherical flow regime (n = 3) can be produced in a partially penetrated aquifer (Moncada et al., 2005; Escobar et al., 2012a), in an aquifer of increasing thickness (IS aquifer) (Rafini et al., 2014; Ferroud et al., 2016) while Sui et al., (2007) stated that this flow behaviour also exits in a narrow aquifer influenced by a constant head boundary. Another limitation identified by Ferroud et al., (2019) is the noise in data. Since the choice of an appropriate conceptual model should be based on the quality of the derivative signal, if the signal is too noisy, the determination of the flow regime will be unreliable and therefore the selection of a conceptual model questionable. Also analysing series of flow regimes aid the choice of an appropriate conceptual model (Ferroud et al., 2019) and this is done by countering the non-uniqueness of the derivative signal. However, it is important to note that to conduct a comprehensive investigation, the derivative response should be analysed with respect to the geological environment as this defeats the non-unicity of the derivative signal.

3.6 Estimation of aquifer parameters

There are lots of analytical solutions to estimate aquifer parameters (Transmissivity T, and Storativity, S). Two of the common methods used in the estimation of these aquifer parameters are the Theis method (1935) and Cooper-Jacob (1946). These methods assume that the aquifer under study is confined with homogeneous, isotropic, and uniform properties (Kruseman and de Ridder, 1990; Van Tonder, et al., 2001). Despite its assumption, a study was conducted by Meier et al., (1998) and this study focuses on how the Cooper-Jacob can be used to estimate transmissivity in heterogenous aquifers, especially on the late time pumping test data. Vivier and Van Tonder, (1997) conducted another study where they suggested that the Cooper-Jacob method could be applied to fractured rock aquifers. This suggestion was drawn from the fact that during the plotting of the drawdown curve of a fractured system, two different flow regimes are identified by the slope namely, the fractured flow and the matrix flow.

During the identification of these flow regimes, it is possible to estimate the T and S for the different flow regimes hence it is possible to use the Cooper-Jacob and Theis methods for aquifers which do not align with the stated assumptions. These methods have been applied to estimate aquifer parameters for fractured, porous, and multi-layered aquifer system. Park et al., (2012) used Theis solution for a fissured aquifer with freshwater and saltwater. Chachadi and Gawas (2012), Sabtan and Mohanty et al., (2012) and Lee et al., (2014) also applied the Theis solution in detrital coastal aquifers. Diamantopoulou and Voudouris (2008) applied the Theis and the Cooper-Jacob method to characterize a multi-layered coastal aquifer while Mastrocicco et al., (2013) applied the Cooper Jacob method to interpret pumping tests in detrital coastal aquifers.

A study on the methods used for hydrogeologic characterization of a heterogeneous aquifer system was conducted by Alexander et al., (2011). The study was aim at identifying the of the accurate methods to describe the distribution of the hydraulic properties in the heterogenous aquifer system. The study was also conducted to check if the common methods used by hydrogeologist to predict flow regimes in heterogenous aquifer were accurate. Pumping test data were used to estimate aquifer parameters while the Neuman's analytical solution was selected for the analysis. This is because most of the late-time drawdown fell below the Theis (1935) solution, and this suggests a leakage in the aquifer system. This indicated that the aquifer is heterogeneous, therefore, the Hantush (1960) analysis methods was not suitable as it assumes homogeneity. Alexander et al., (2011) highlighted that applying a simplified analytical method to a complex geological environment yield averaged hydraulic parameters and these parameters vary from point to point. Despite the assumption of simplification, the model was applied because it has been commonly used by researchers (Marechal et al., 2004; Illman, 2006) to interpret pumping test data in strongly heterogeneous media. Meier et al., (1980) showed that the Cooper Jacob method leads to a good approximation of transmissivity, and this was confirmed by several other studies including Indelma, 2003; Copty and Findikakis, 2004; Wu et al.,2005. Sachez-Villa et al., (1999) showed analytically that storativity estimated by Cooper-Jacob method provides information on flow connectivity which was further investigated by Trichero et al., (2008) and Fernandez et al., (2011).

Anomohanran and Iserhien-Emekeme (2014) estimated aquifer hydraulic parameters for the Erho area in Delta State, Nigeria. The investigation aimed at determining the aquifer parameters of the study area, a total of 6 wells were used for the investigation (3 production and 3 monitoring). Data obtained were subjected to graphical and analytical evaluation using the Cooper-Jacob method. Aquifer transmissivity, storativity and specific capacity were estimated, and the results showed that the aquifer produce enough quantity of water for people in the area. Furthermore, the investigation confirmed the type of aquifer to be confined hence a good water quality. A study that was conducted by Hoppe et al., (2016) in Nairobi, Kenya, used Cooper-Jacob and Theis recovery method to analyse pumping test data from 84 boreholes. AQTESOLV software was used for the analysis by fitting analytical solutions for pumping test to measured pumping test data and it was concluded that the area under study produced high T values hence a maximum sustainable yield value

Al-Sudani (2017) conducted a hydrological investigation in the Khanaqin Basin, east of Iraq to calculate hydraulic parameters. The Cooper-Jacob and Theis Recovery method were used for the investigation to estimate transmissivity and storage coefficient. Out of 90 wells used in the investigation, results showed that 38 were unconfined while 52 were confined and average transmissivity for the unconfined and confined aquifer ranges between 273-4590 m^2/day and 14.97-249.35 m^2/day respectively. In 2018, Al-Sudani conducted a research to evaluate the hydraulic properties of the groundwater aquifer in Khan Al-Baghdadi, Iraq and this was aimed at achieving sustainable management of water in the area. Using the Cooper-Jacob and Theis Recovery, average transmissivity and storativity values were calculated using 2 wells and values were 33.966-1171 m^2/day and 2.2 x 10^{-4} - 2.07 x10^{-2} respectively dependant on Cooper-Jacob and Theis Recovery solutions.

The Neuman's method of 2004 was applied to estimate transmissivity in an aquifer near Tu¨bingen, Germany from a sequence of pumping tests conducted in four wells. The results from the investigation were compared with estimated transmissivity values obtained from 312 flow meter measurements of hydraulic conductivity and eight other wells at the site. The study which was conducted by Neuman et al (2007) concluded that four well was enough to provide the true transmissivity estimates using the distance-drawdown method of Neuman et al. (2004). Pumping test in coastal areas are highly complex and this is because of the several conditions that influence the results which includes the presence of both freshwater and seawater, Calvache et al., (2011). Tide-induced fluctuations can also alter the data or drawdown information obtained from coastal area hence Chapius et al., (2006) proposed correcting tidal effects in drawdown data for confined aquifers by subtracting the net tidal effects measured before pumping

In response to the Theis and Cooper-Jacob method, the Theis Recovery method which may produce accurate results for heterogeneous aquifer was proposed by Willman et al., (2007) and this method was based on the assumptions of the Theis and Cooper-Jacob. The authors further investigated using numeric modelling to explain the meaning of T estimates from recovery data. The results from the investigation showed that the T estimated from the recovery data identified useful information for the aquifer. On the bases that pumping test data may be influenced by pressure from pumping and increasing discharge head, Ballukraya and Sharma (1991) also agreed on the efficiency of the recovery T as it may yield even more information that are reliable because the system is not under pressure and in its natural state. Kruseman and de Ridder, (1990) also stated that the recovery T is more consistent, hence more reliable results than the pumping test T. One of the limitations of the Cooper-Jacob and Theis method is that it cannot fully account for complexities or heterogeneities that exist within aquifer hence Copty et al., (2011) proposed the use of derivative analysis method for parameter estimation from heterogenous aquifer. More so, it was stated that the time dependent estimates of T provide information about the underlying heterogeneity of aquifer system.

The rate of discharge (yield) from a borehole is of particular interest to hydrogeologist as it informs decisions around usage and management of water resources. The yield of the borehole is also referred to as the safe yield or reliable yield. The shift towards the use of “sustainable yield” in groundwater management indicates the development of the discourse of sustainability as a standard for addressing environmental management practices. The Brundtland Report (1987) amongst others played a major role in this process and defined sustainable as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987). In South Africa, the term Sustainable Yield is typically used. Due to the increasing number of dry boreholes, an investigation into the sustainable yield of the boreholes is therefore required. Methods commonly used in the estimation of sustainable yield in South Africa were summarized by Samie and Murray (1998) and the methods include-

1- The Recovery method
2- The late T-method
3- The Drawdown to-boundary method
4- The Distance to-boundary method

The above methods were compared by Naafs (1999) using the FC-method (Van Tonder et al., 1998). The results indicated that the Recovery method and late T-method of estimating sustainable yield were too high in most of the cases tested hence these methods are not to be used. Naafs adapted the late T-method by the introduction of a variable available drawdown. In this case, a similar result was gotten when compared to the Drawdown to-boundary and Distance to-boundary methods. Both the adapted late T-method and Drawdown to-boundary methods are special cases of the FC-method.

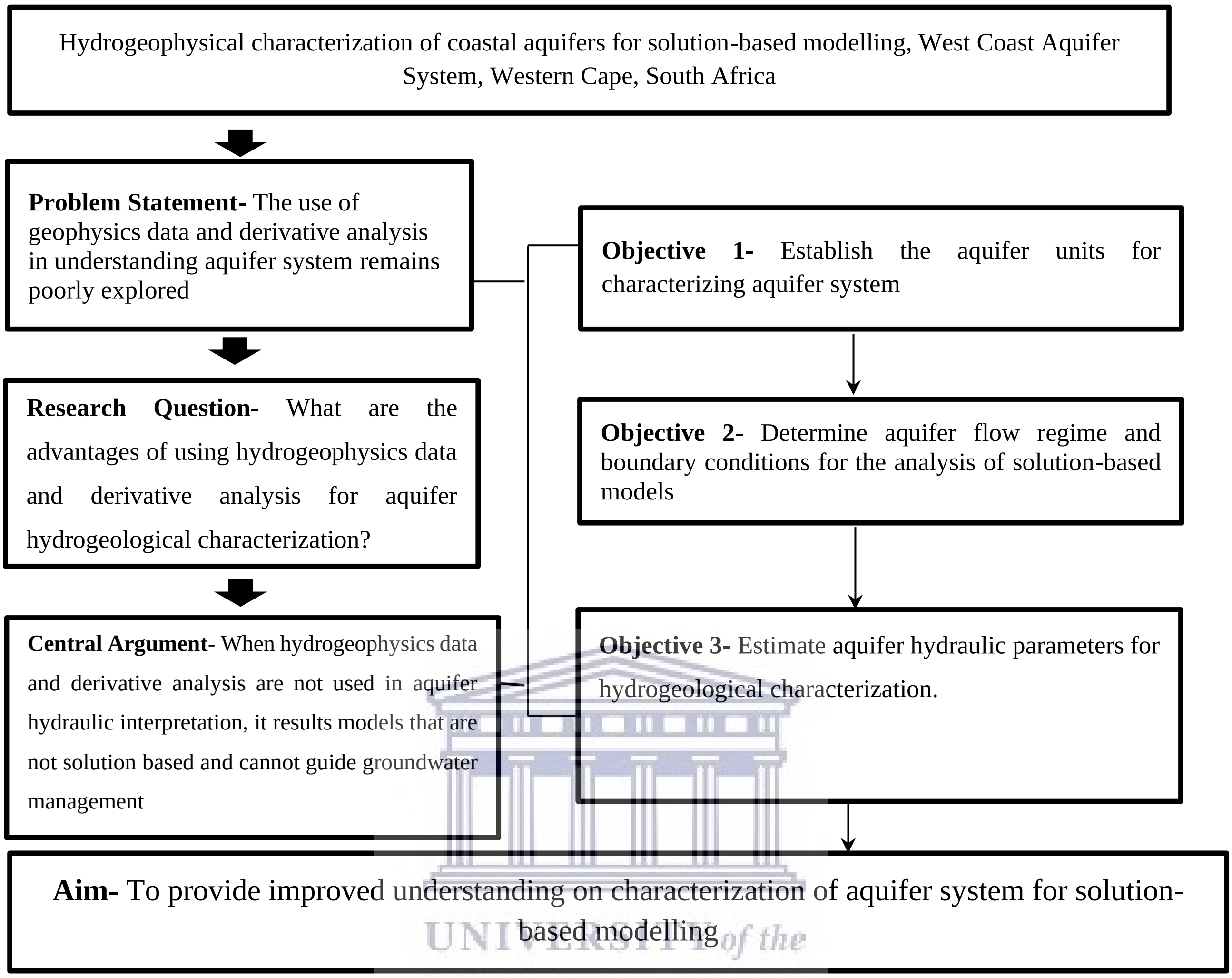
3.7 Theoretical framework

Ohm's law and Darcy's law both are employed as the theoretical framework for this study as they explain the principle of flow between different mediums. Ohms law states that the current passing through a conductor between two points is directly proportional to the voltage/potential difference across the two points. This basically means measurement of potential difference between other two electrodes in the vicinity of current flow. The resistivity (ρ) depends on the property of the material and is a geometrically- independent quantity that describes a material’s ability to transmit electrical current. The value of (ρ) is measured in ohmmeter (Ωm). Darcy law also explains the flow of fluid through a porous medium. It works on the fact that the amount of fluid flow between two points is directly related to the difference in hydraulic head between the two points, the distance between the points, and the interconnectivity of flow pathways in the rock between the points (Younger, 2007). Darcy's Law provides a basis for description of groundwater flow in all hydrogeological environments. These are homogeneous and heterogeneous systems, isotropic and anisotropic media flows, fractured rock or granular media, steady state and transient flows, flow in aquifers and aquitards as well as for saturated and unsaturated flows (Freeze and Cherry, 1979). Since Ohm's law and Darcy's law describes the flow of current through mediums and the flow of fluid through porous mediums, these theories have been used in this study to interpret data and understand groundwater flow system in the study area.

Methods for analysing and interpreting the results have been selected on the bases of being the most common, current, and appropriate for the study area. The electrical resistivity tomography (ERT) has been chosen as the surface geophysics method over its swift response especially in coastal areas and its presentation of 2D interface of the aquifer system. In addition, the flow regime sequential analysis approach has been selected as the most suitable method for interpretation of pumping test data because of its specialty in interpreting the various segments of flow regime that occur during the pumping cycle.

3.8 Conceptual framework

Hydrogeological characterisation is employed as a conceptual framework for the current study, and this involves the evaluation of the different characteristics of the aquifer using various forms of data. The characterization of the aquifer in the study area which is in the coastal region is important because in South Africa, aquifer characterization is poorly understood, and this characterization of aquifer involves evaluating the structure and hydraulic properties of the aquifer. The aquifer structure was evaluated by delineating the groundwater units, identifying the various flow regimes and boundary conditions using diagnostic plots and estimating the aquifer parameters (Transmissivity, storativity and specific yield). These hydraulic properties determine how much the aquifer can release water and the rate of release. Pumping test data was used for derivative analysis, and this was done to have a better understanding of the flow regime. In general, hydrogeological characterization was carried out to help inform the sustainable use and management of aquifers and their interaction with other water bodies. This study used the concept of hydrogeological characterization to answer the research question “What are the advantages of using hydrogeophysics data and derivative analysis for aquifer hydrogeological characterization?



Hydrogeophysical characterization of coastal aquifers for solution-based modelling, West Coast Aquifer System, Western Cape, South Africa

Problem Statement- The use of geophysics data and derivative analysis in understanding aquifer system remains poorly explored

Research Question- What are the advantages of using hydrogeophysics data and derivative analysis for aquifer hydrogeological characterization?

Central Argument- When hydrogeophysics data and derivative analysis are not used in aquifer hydraulic interpretation, it results models that are not solution based and cannot guide groundwater management

Objective 1- Establish the aquifer units for characterizing aquifer system

Objective 2- Determine aquifer flow regime and boundary conditions for the analysis of solution-based models

Objective 3- Estimate aquifer hydraulic parameters for hydrogeological characterization.

Aim- To provide improved understanding on characterization of aquifer system for solution-based modelling

Figure 5- Research framework for the study indicating the key elements of the current study

Chapter 4: Research Design and Methodology

4.1 Introduction

The chapter one and two has provided the general introduction and description of the present study respectively while chapter three has provided the reviewed literature in terms of what is known and unknown about hydro-geophysics of coastal aquifers among other aspects. The present chapter four explains methods that were used to collect and analyse data in addition to presenting the research design that was followed to answer the research question and the set objectives in chapter one. Therefore, this chapter four covers the research design approach, data collection and analysis, data assurance/quality control, research integrity and limitations of this study.

4.2 Research design

Leady (1997) defined research design as a study scheme that provides the overall framework for data collection while MacMillan and Schumacher (2001) defined research design as a subject selecting plan, research sites and procedures for data collection in answering the set research question(s). The authors further stipulated that the goal of a sound research design is to provide results that are considered credible hence the choice to characterise the aquifer with the chosen methods which are appropriate for the study in ensuring that the set question of this research is answered, and the identified problem is bridged. Detailed description of the design employed in this study is presented below.

4.2.1 Research design approach

Any type of research that employs numerical information to explore individuals or group characteristics to produce findings is termed a quantitative research methodology. The data used for this type of research are in form of numbers hence it is an empirical research. Keskinocak and Tayur (2001) stated that data required for this type of research includes experimental designs and non-experimental designs and the sources of data includes: surveys, observations and secondary data while qualitative research methodology allows the researcher to get close to the data thereby developing the categorical, analytical or conceptual components of explanation from the data itself. Berrios and Lucca (2006) stated that the data required for this type of research methodology includes narrative research, phenomenologies, ethnographic methodology, grounded theory and case studies and the sources of data includes: interviews, postcards, secondary data, and observations. The mixed research methodology refers to a developing methodology of research that advances the formal integration or mixing of quantitative and qualitative data within a single study. Quantitative and qualitative type of data are both collected, analysed, data are mixed in different forms and priority is given to one or both forms of data. Creswell (2017) stated that the mixed methodology can be used in a single study or in multiple phases of a study.

This study followed an integrated approach. Some preliminary ideas about aquifer properties in the study area were established and this was done with the aim of improving understanding on the hydrogeology of aquifers in coastal regions. A desk study was done to review the available records, information, and data on hydrogeophysics and the use of derivative analysis in the determination of aquifer flow regime and this was conducted so that the current and appropriate methods for collecting and analysing information were identified, selected, and used in the study. A record review method was also used to identify other hydrogeological and geophysical information in the study area, and this formed the basics of the study.

4.2.2 Sampling design and data required

The information retrieved from the interpretation of the surface geophysics exploration gave an understanding of the subsurface system and it was used to estimate aquifer parameters while the aquifer flow regime was determined using derivative analysis. The use of derivative amplifies the heterogeneity of the system and signatures that are not easy to detect in the normal drawdown/time curve which become apparent when derivative is used. This helps to determine the type of flow in the system and hence a much more better understanding. Information on aquifer hydraulic parameters such as transmissivity, storativity and resistivity value were derived. Coordinates of the geophysics survey location were obtained and used in the generation of the location map to enhance the location accuracy.

4.3 Research methods

Globally, methods that are commonly applied in the characterization of aquifer include geologic mapping and cross-section, geophysics methods, drilling, hydraulic test and remote sensing (Lasher, 2011; Vouillamoz et al., 2012; Dippennar, 2018;). An integration of surface geophysics method (resistivity survey) and hydraulic study (pumping test and aquifer hydraulic parameters) was employed as the standard for the characterization of aquifer in this study. Record review approach which formed the basics for the interpretation of results was also used in this study. The major strength of this integration is that these methods complement each other in terms of the data types (qualitative and quantitative). Other advantage of this integration is that it is applicable to many other geological environments and not restricted only to coastal aquifers. Despite such strengths, these methods are sensitive to noise in the data; hence the acquired data went through quality control/quality assurance. Details of the methods that were used in this study are given below.

4.3.1 Data collection and analysis for delineating groundwater units

Geophysics methods (surface and invasive), remote sensing, core and well logging are some of the methods used in the study of the hydrogeology of the subsurface. In surface electrical geophysics method, three techniques are used which include induced polarization (I.P), resistivity and self-potential (S.P) but in this study, the resistivity method was selected as the most current and appropriate method for the delineation of aquifer units (Shishaye and Abdi, 2016; Nazifi and Gulen 2018,). Amongst other geophysics methods, the electrical resistivity was chosen as the most preferred method because it has close relationship with electrical conductivity and some hydrogeological properties of aquifer. It is rapid, non-invasive and can provide good spatial coverage in comparison with other methods.

Electrical resistivity technique involves the passing of artificially generated current into the ground through a pain of electrodes. The electrical resistivity of a formation limits the amount of current passing through the formation when an electric potential is supplied. This method was based on the fact that any subsurface variation in conductivity alters the current flow within the earth and this affect the distribution of electric potential, the degree to which it affected depends on its size, shape, water content, location and electrical resistivity of the subsurface formation (Keller and Frischkenct, 1966). The electrical resistivity techniques are predominantly used in mineral, groundwater investigation and they are used based on the electrical properties of rock materials. These electrical properties include resistivity and conductivity. There are 3 sub-techniques used in carrying out electrical resistivity survey; vertical electrical sounding (VES) for 1-d information of depth-wise resistivity variation, profiling for information of lateral resistivity variation and imaging which combines sounding and profiling for 2-d and 3-d information on subsurface resistivity variations. Based on the availability of these methods, secondary data from the imaging method was chosen for this project.

Resistivity can vary both laterally and vertically, neither VES nor electrical profiling may give the desired results. Electrical imaging is used to image both lateral and vertical changes (Loke, 2001). This can be done by merging both sounding and profiling with the use of the multi-electrode profiling system by close gridding. This technique of simultaneous measurement of vertical and lateral resistivity variation in the subsurface through multiple-electrode arrangement is known as multielectrode electrical resistivity imaging (MERI) or electrical resistivity tomography (ERT). Due to its strength and reliability, the ERT has become the most used method applied in earth sciences and especially in hydrogeology (Chalikakis, 2006; Al-Fares, 2011) while Casas et al., (2008) noted that the ERT is considered as the modern evolution of the classical geoelectrical methods, such as vertical electrical sounding (VES) and electrical trenching.

After the 2000, the ERT swiftly substituted the one-dimensional VES and electrical profiling. The ERT which was developed at the end of the 1970s works on the principle that when a continuous electric current of intensity I (in mA) is generated between two current electrodes A and B – where A is the injection electrode (positive), and B is the reception electrode (negative) – placed at the surface of a ground, which is theoretically considered as homogeneous and isotropic, a semi-spherical electrical field is created, and its volume is a function of the distance between A and B (Scapozza and Laigre, 2014). The more the two electrodes are spaced the more the spatial extent of electrical field is. Kunetz, (1996) stated that if we add at these two current electrodes two potential's electrodes, M and N, allowing the measurement of the difference of potential ΔV (in mV) due to the join action of A and B, the resulting quadripole allows measuring the ground apparent resistivity ρa (in Ωm), using equation 1 below

$\rho a = (\Delta V / I)\, k$**………………... Equation 1**

Where k= Geometric factor (in m) and it depends on the geometry of the electrode array and the topography.

The most used array configuration in ERT include Wenner, Wenner-Schlumberger and Dipole-Dipole arrays. The Wenner array has a good investigation depth and its vertical resolution in terms of subsurface structure is very good. The Wenner-Schlumberger array is a combination of the Wenner and Schlumberger arrays. In this type of array, the MN distance is normally lower than 1/5 of the AB distance, whereas the AM and NB distance is the same (Scapozza and Laigre, 2014). The investigation depth of the Wenner-Schlumberger array is lower in respect to the Wenner array, but it has a better horizontal resolution of the subsurface structures. The dipole-dipole array, finally, is constituted by two dipoles (AB and MN). It has the best horizontal resolution by comparison with two other studied arrays, but the investigation depth is the lowest (Marescot, 2006). Hauck and Kneisel, (2008) stated that globally, due to the data acquisition run-time and the depth of investigation, the Wenner-Schlumberger array constitutes the best compromise between the Wenner and the Dipole-Dipole arrays.

While acquiring data, it is possible to obtain a pseudo-section in apparent resistivity. Along the acquisition line, the measurement of the apparent resistivity is automatically repeated for every possible combination of the quadripole for the selected array (Scapozza and Laigre, 2014). The physical principle is the same, but in this case instead of using only four electrodes (two current and two potential electrodes), computer-controlled multi-electrodes are used that change automatically and are fixed in the soil surface (Casas et al., 2008). The resistivity meter, which is a digital electronic device, used to send current into the ground through the pair of current electrodes was used, multi steel electrodes were used. The electrodes possess conductive properties. Global positioning system (GPS) was used to collect geographic coordinates of where survey was conducted; sledgehammer was used to drive the electrodes into the ground to ensure proper contact with the earth, as partial contact may lead to error in the data acquired. measuring tape was used for accurate measurement of the electrodes.

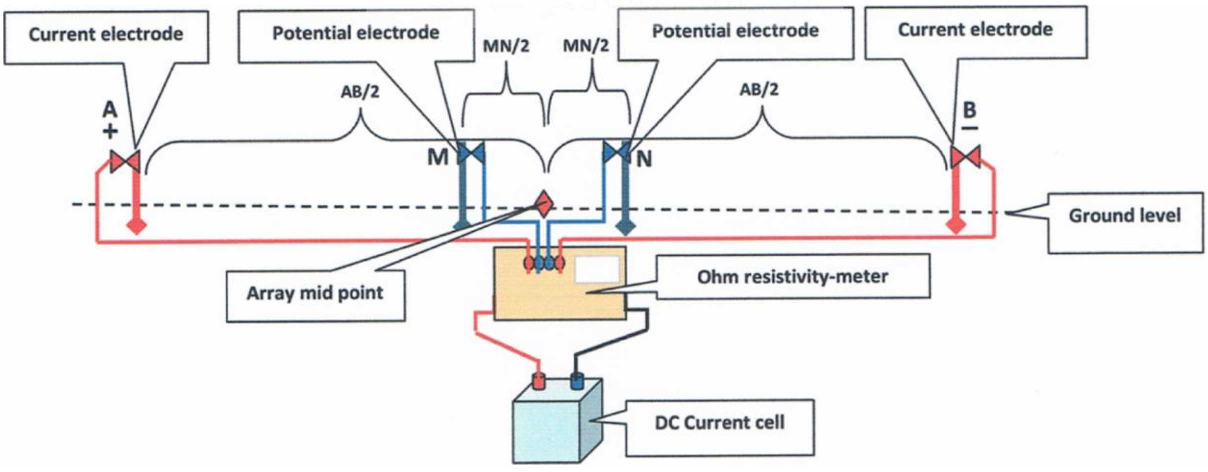


Figure 6- Electrode array for Wenner-Schlumberger configuration (Al-Khafaji, 2014)

Analysis of field resistivity data, including model interpretation were carried out using RES2DINV software program. The generated 2D resistivity models were used to identify and interpret the aquifer hydrogeologic units and features.

4.3.2 Data collection and analysis methods for flow regime determination

Secondary pumping test data were provided, and the analysis of the data began with the elimination of noise. Interpretation of derivative signals can be altered by poor data quality (Nobakht and Mattar, 2009) coming from imprecision from operation, fluctuations from pumping rate, earth tides and wind effects. The selection of an appropriate method to remove the negative effects of noise during the numerical differentiation of drawdown data is a crucial segment of performing derivative analysis (Spane and Wurstner, 1993; Bourdet, 2002). For proper interpretations and making sure that real flow regimes are recognized, pre-processing and data smoothing are often needed.

Remover of outliers has been suggested as the first step to the processing of derivative signal (Nobakht and Mattar, 2009), followed by the application of an algorithm which improves the derivative signal pumping rate adjustments. Ferroud et al., (2019) proposed different algorithm namely, convolution, deconvolution, variational regularization and multirate. The deconvolution algorithm is an algorithm-based process that is aimed at looking for solutions around convolution equation. It is an inverse approach recreate an identical constant-rate drawdown. Unlike the convolution method which assumes a conceptual model, the deconvolution processing method does not need to assume a definite conceptual model and that is one of its major advantages. Another major advantage of this processing method is that it allows more precise and unique interpretation by decreasing the ambiguity of the data observed (Cumming et al., 2013). This process also assists in the identification of a conceptual model (Gringarten, 2008) as a much better estimations of hydraulic properties and boundary conditions are produced by generating clearer reconstructed derivative data. The Flow Characteristic (FC) software was used in the study because it can simultaneously analyse and visualize pumping test data in all types of test conditions.

Calculation of log derivative

The concurrent plot of drawdown and the logarithmic derivative of drawdown as a function of time is the main tool of the derivative analysis method. This method has been considered the best for the identification of an appropriate conceptual model to use when analysing aquifer test data. An algorithm developed for the petroleum industry by Bourdet et al., (1989) calculates the first derivative of the pressure change with respect to the natural logarithm in change of time according to

$$\left(\frac{dp}{dx}\right)_i = \frac{\Delta p \;\; \Delta x_2 / \Delta x_1 + \Delta p_2 \, \Delta x_1 / \Delta x_2}{\Delta x_1 \, \Delta x_2} \, , \qquad \textbf{(2)}$$

Where p is pressure,
Subscript 1 = point(s) before the point of interest, i;
Subscript 2 = point(s) after the point of interest, i;
X is the natural logarithm of the time function, t*.

Because drawdown (*s*) during an aquifer test is related to pressure, Equation (1) may be applied to piezometric head φ(t) or drawdown with time s(t)

$$\phi t = \int_{p_0}^{p} \frac{dp}{\rho g} + z \, , \qquad \textbf{(3)}$$

$$s(t) = \phi t - \phi(t_0) \, , \qquad \textbf{(4)}$$

To estimate the logarithmic derivative of the drawdown (ds dx = tds/dt) for a reference elevation z, and an elapsed time *t* since the beginning of the pumping test (t_0) is a suitable time. Fitting the derivative of a conventional type of curve directly to the first divided differences of the observed drawdown data may be accomplished using

$$\frac{\Delta s_i}{\Delta t_i} = \frac{s(t_{i+1}) - s(t_i)}{t_{i+1} - t_i} \, . \qquad \textbf{(5)}$$

or as described by Renard *et al.*

$$\frac{\Delta s_i}{\Delta \ln t_i} = \frac{(t_i + t_{i+1})}{2} \frac{\Delta s_i}{\Delta t_i} \, . \qquad \textbf{(6)}$$

Derivative analysis of drawdown can be used to identify the different flow regimes in an aquifers system, the types of aquifers, presence of boundaries and to access the influence of well-bore storage. There is need to analyse different segments of an aquifer test separately and this is because contrasting flow boundaries can take place throughout the period of pumping as the increasing drawdown encounters boundaries and heterogeneities.

Determination of aquifer flow regime using diagnostic plot method

The principle of universally interpreting various types of flow regimes from bilog plots of the drawdown log-derivative vs time was formalized by Bourdet et al., (1983). The analysis of the ds/dlogt signal in hydrogeology was promoted by Renard et al. (2009) and this was done by highlighting its usefulness in detailed interpretations of aquifer. Beauheim et al., (2004) and Beauheim and Roberts (1998) also introduced the concept of flow dimension diagnostic plots. The concept incorporates the flow dimension theory with the straight-line sequential analysis promoted by Tiab and Mattar. Pressure derivative time series are decomposed into sequences of flow regimes (figure 7) marked by constant flow dimensions that can be either sublinear (n < 1), linear (n = 1), bilinear (n = 1.5), radial (n = 2), spherical (n = 3), hyperspherical (n > 3) or fractional (n is a non-integer).

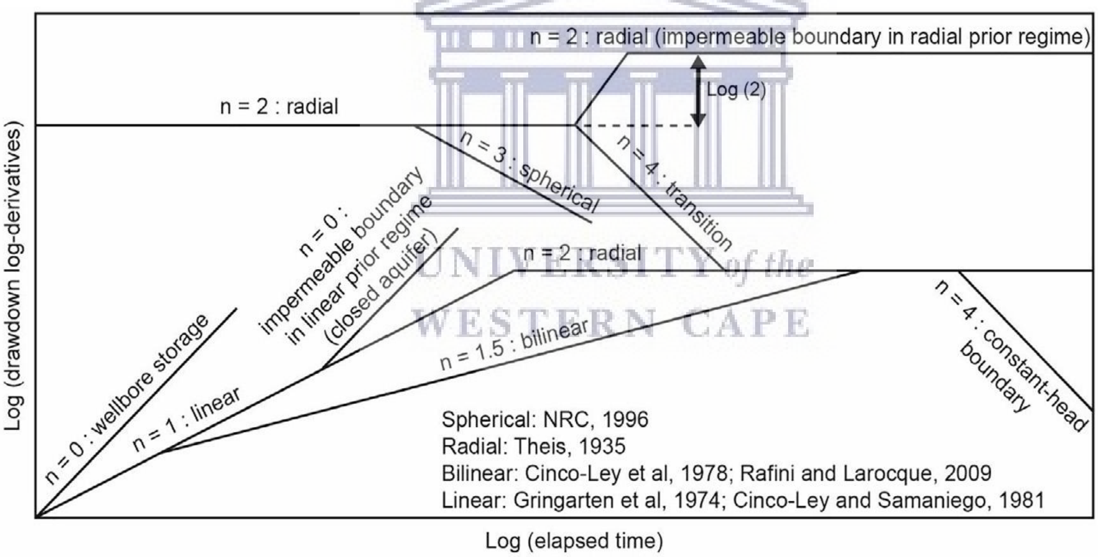


Figure 7- Summary of published theoretical flow regimes and their associated flow dimensions, n (Ferroud et al., 2018)

Positive and negative unit slopes also are commonly identified, which are classically interpreted as representing internal and external hydraulic boundaries rather than flow dimensions but may also represent transient behaviours. Several successive distinct flow regimes can be analysed and interpreted as a succession of stable hydraulic conditions occurring in the aquifer as the pulse run through it (Ferroud et al., 2018). The identification of a sequence of flow regimes essentially constitutes a hydraulic diagnosis (for instance in Figure 7, the n sequence is 2–1.18). The process of determining the sequence of flow regimes makes it possible to then proceed to a qualitative interpretation of these regimes which involves the selection of an appropriate conceptual model by means of similarity between observed and theoretical signals. To identify which model is accurate to interpret the data, a comparism is done between the diagnostic plot derived from the analysis and the set of typical diagnostic plot used in hydrogeology as illustrated in figure 8 (Renard et al., 2009).

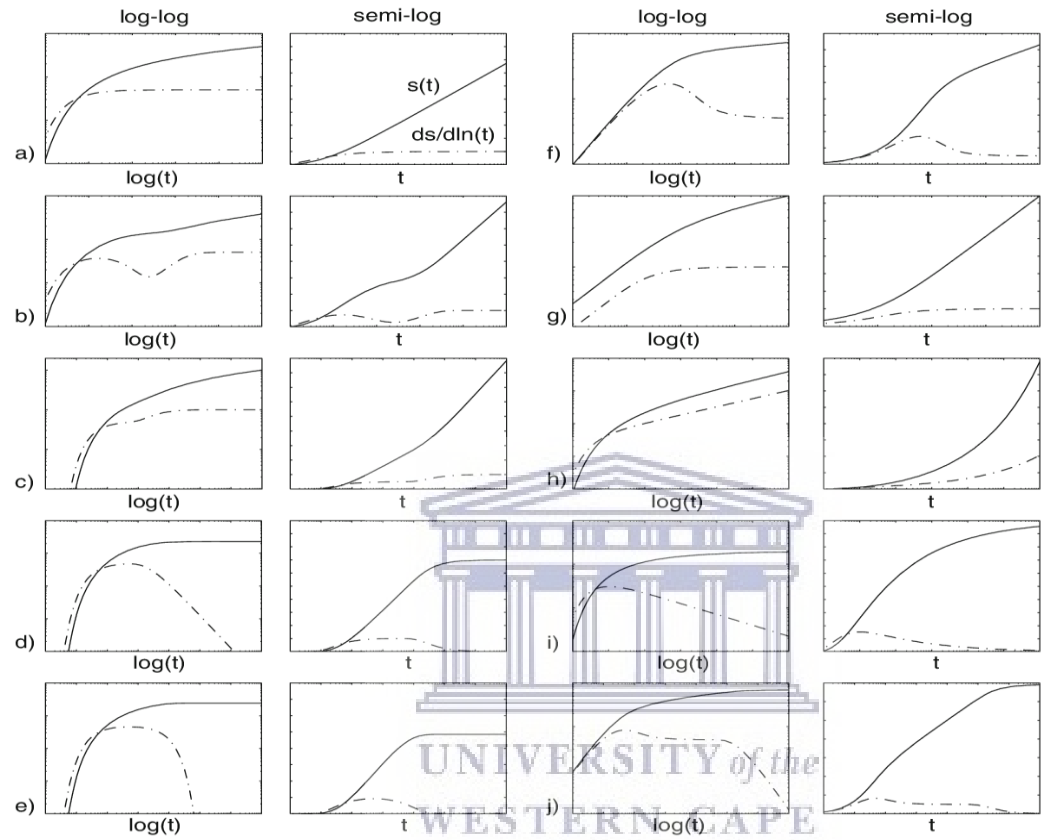


Figure 8- Most typical diagnostic plots encountered in hydrogeology (Renard et al., 2009)

4.3.3 Estimation of aquifer parameters

Cooper-Jacob (1946) Time-Drawdown

The computation of drawdown (S) from the difference between the water level in meters below ground level (mbgl) and the static water level (SWL) is the main process involved in the analysis of the constant discharge test. It is plotted on a semi-log graph with S alongside corresponding time since pumping started. A line of best fit is determined once the curve is plotted on the semi-log graph, then the slope is obtained for the drawdown over one log cycle. Transmissivity (T) and Storativity (S) may be estimated by equation 1 and 2 respectively, as long as this follows the average discharge value from the constant rate test.

$T=2.3Q\,4\pi\Delta s$**……………….... *Equation 7***

Where T= Transmissivity (m^2 /d)

Q = Discharge (m^3 /d)

Δs= Change in drawdown per log cycle.

$S=2.25Tt0\ r2$……………….... Equation 8

S= Storativity

T =Transmissivity (m^2/d)

t0 =Time at which the straight-line intercepts zero drawdown

r = Distance (m) between the pumping borehole and observation borehole.

Theis Recovery (1935)

To estimate T using the Theis recovery involves calculating the residual drawdown (S) as the difference between the static water level (SWL) and water level (WL) after pumping stopped. The residual drawdown is then plotted against t/t' on a semi-log plot, then a straight line that appears good depending on the early or late T is fitted. The slope (AS) is obtained for the straight line as the change in S' for one log cycle. Since T is the product of the saturated aquifer thickness and hydraulic conductivity (Kruseman & de Ridder, 1990), the above values are substituted in equation 3

$\Delta s' = 2.3Q\ 4\pi KD$……………….... Equation 9

Where Δs'= the slope in residual drawdown for one log cycle (m)

Q= discharge (m3/d)

K= Hydraulic conductivity (m/d)

D= aquifer thickness (m)

The flow characteristic (FC) method was employed in this study and used for the analysis of both Cooper-Jacob Time-Drawdown for T and S estimation and Theis Recovery for T estimation based on the line of best fit.

Estimation of sustainable yield

Caro and Eagleson (1981) defined sustainable yield as the long-term rate at which water can be withdrawn from a borehole without resulting effects such as reservoir exhaustion or water quality decline while Kendy (2003) defined sustainable yield as the rate at which water can be pumped from a borehole so as not to exhaust the water source. From both definitions, it is apparent that sustainable yield has more to do with the borehole understudy and less of other boreholes within or in proximity of the tested borehole. To obtain the sustainable yield of a borehole, a constant discharge test is conducted and aquifer under study is stressed to get the maximum potential yield which the borehole can be pumped especially for a longer period without dewatering the aquifer. The estimation of sustainable yield involves the use of time-drawdown data plotted on a semi-log plot (Van Tonder, et al., 2010). The FC spreadsheet was used for estimating the sustainable yield and it is given by dividing the available drawdown (difference in SWL and main water strike position) by the extrapolated drawdown values and multiplying the obtained value by the abstraction rate.

4.4 Research quality control / quality assurance

One of the main requirements of any research process is the reliability of the data and findings. Reliability deals with the consistency, dependability, and replicability of "the results obtained from a piece of research" (Nunan, 1999). Obtaining the similar results in quantitative research is rather straightforward because the data are in numerical form. To ensure adequate validity and accuracy of results, some measures were put in place to checkmate the estimated errors. They are quality control (QC) and quality assurance (QA) measures. QC/QA control measures are those activities one undertakes to demonstrate the accuracy (how close to the real result one is) and precision (how reproducible results are). Quality assurance generally refers to a broad plan for maintaining quality in all aspects of a program while quality control consists of the steps taken to determine the validity of specific sampling and analytical procedures. Quality assessment is assessment of the overall precision and accuracy of one's data, after the running of the analysis.

In this study, since secondary data were used, data error was checked and corrected. The geophysics data used for objection 1 have a high iteration error and this was because the field survey was conducted over the clean windblown sand, and this caused poor electrode coupling and very high contact resistance. To correct for this error, the resistivity model was interpreted alongside previous geophysical investigation results of the study area, existing literature and geological map which gave a clear indication of what should be looked at. Anomalous signature which might have been caused by an artifact in the data acquisition, instrument problem, noise or interference was also checked for. Data from pumping test (objective 2 and 3) are sometimes noisy, and this may be due to complications from operator, pumping rate variations, recharge effects and heterogeneity fields that are randomly diffused hence to ensure that the data was free from noise, processing and checking for repetition of data collected was done using excel document. The processing of the data was conducted having the geology of the study area in mind. The aim of a quality assurance and quality control is to make sure the data/research were free from errors hence having a data that is reliable and that was achieved after the QC/AC process in this study.

4.5 Research integrity

According to Singapore statement on research integrity, the integrity of any research should be based on four principles: Honesty in all aspects of research, accountability in the conduct of research, professional courtesy, and fairness in working with others and good stewardship of research on behalf of others (Resnik and Shamoo, 2011). Access to the data that was used for this research was granted, the principle of honesty was applied because the data and findings were shared openly to the research team. The principle of integrity was also applied here as the interpretations of data was completed to answer the stated objectives. Everyone associated with the different aspects of this research were all treated with dignity and respect, and everyone was duly informed on the research procedures.

4.6 Study limitation

Due to COVID-19 and movement restrictions, primary data collection was not possible hence some contour maps from surface resistivity data that would have enhanced the interpretation of the results were skipped. The collection of primary geophysical data would have also given way to estimating aquifer parameters using geophysics data and correlate with the estimated aquifer parameters from pumping test data as this would also enhance the interpretation however secondary data were used to meet the stated objectives. Another limitation encountered is lack of previous studies in the study area particularly on the use of the flow characteristic (FC) method in a porous aquifer system as this method has mainly been used in fractured rock environment hence part of the literature review was from regional and global context. Lastly this study was only focused on the key hydrogeophysical properties (transmissivity and storativity) of the aquifer under study and does not provide a full characterization of aquifer because there are many other methods used in aquifer characterization.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents and discusses results obtained from aquifer characterization, aquifer hydrogeological mapping using the electrical resistivity tomography geophysical method and aquifer hydraulic information in the study area. The first objective was to establish the aquifer units in the study area. The aim was to describe the hydrogeophysical conditions of the study area and their groundwater potential. The second and third objective were also aimed at determining the flow regime in the study area and estimation of aquifer hydraulic parameters respectively. Detailed description of methods is presented, followed by the results and interpretation of the finding. Finally, a synopsis of the chapter is presented.

5.2 Establishment and description of aquifer units

5 selected electrical resistivity sounding data were acquired in the study area at a 20m station interval. A minimum electrode spacing "a" of 20m, and n=1 to 10, was used while the maximum current electrode spacing was 800m and apparent depth of investigation (DOI) of up to 160m was obtained. The ABEM LUND resistivity terrameter was used for the investigation using 64 active field electrodes. The field measurement was in terms of apparent resistivity when interpreted as the electrical resistivity of a homogenous equivalent medium. The acquired data were inverted using RES2DINV software, this program allowed for producing 2D geoelectrical or resistivity model of the subsurface, showing formation with varying resistivities and resistivity variations up to a nominal 120m below surface were generated. The Lund imaging system is a completely automated resistivity data acquisition system, and its pre-designed protocols are used to optimise data coverage for specific profiles. For example, for groundwater flow regimes, data quality and resolution/coverage must be comprehensive. It comprises of an ABEM resistivity meter, an electrode selector or switching unit, multi-core cables and electrodes. A pseudo-section of apparent resistivity data is acquired that shows both lateral and vertical changes in resistivity along the profile.

The Wenner array was used for all profiles and the investigation procedure involves rolling out the multi-core electrical cables in the pre-selected areas. The electrodes were then inserted next to the electrode take-outs on the cables. The electrodes were pushed into the ground to minimise disturbance of soil around the electrode and thus maximising electrode contact. The electrodes were then connected to the electrode take-outs on the multi-core cables using the earthing cables. This was also the opportunity to ensure that electrode grounding is optimum, ensuring good quality data. The cables were then plugged into the electrode selector, which was connected to the ABEM resistivity meter. The resistivity meter was then connected to the battery and the system started.

The results of the investigation were used to identify groundwater units in the study area and when matched with the geological map of the Hopefield area, it also assisted in identifying geological features. Special attention was given to hydrogeological layers and features and groundwater zones. Around the Hopefield area, 3 ground geophysical traverses were carried out. The investigation was carried out around existing monitoring borehole locations in the Hopefield. Resistivity models were interpreted based on existing geological map of the West Coast aquifer system, past geophysics survey conducted in the Hopefield area and present geological and borehole records. Known resistivities for geological materials and water type as provided in Palacky (1988) were also used to make interpretations of the models (figure 9).

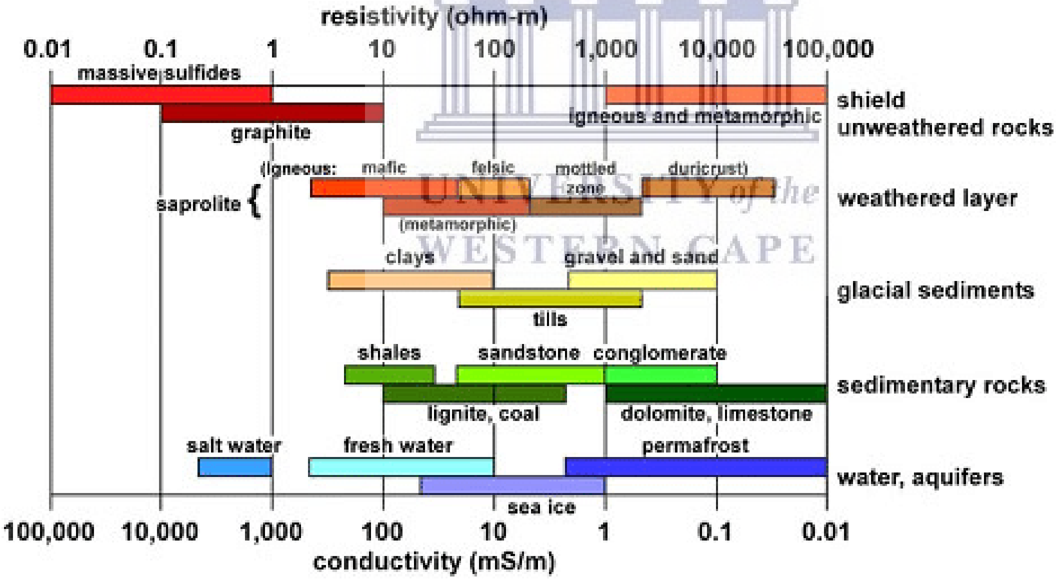


Figure 9- Typical range of electrical resistivities of selected earth materials (Palacky, 1988)

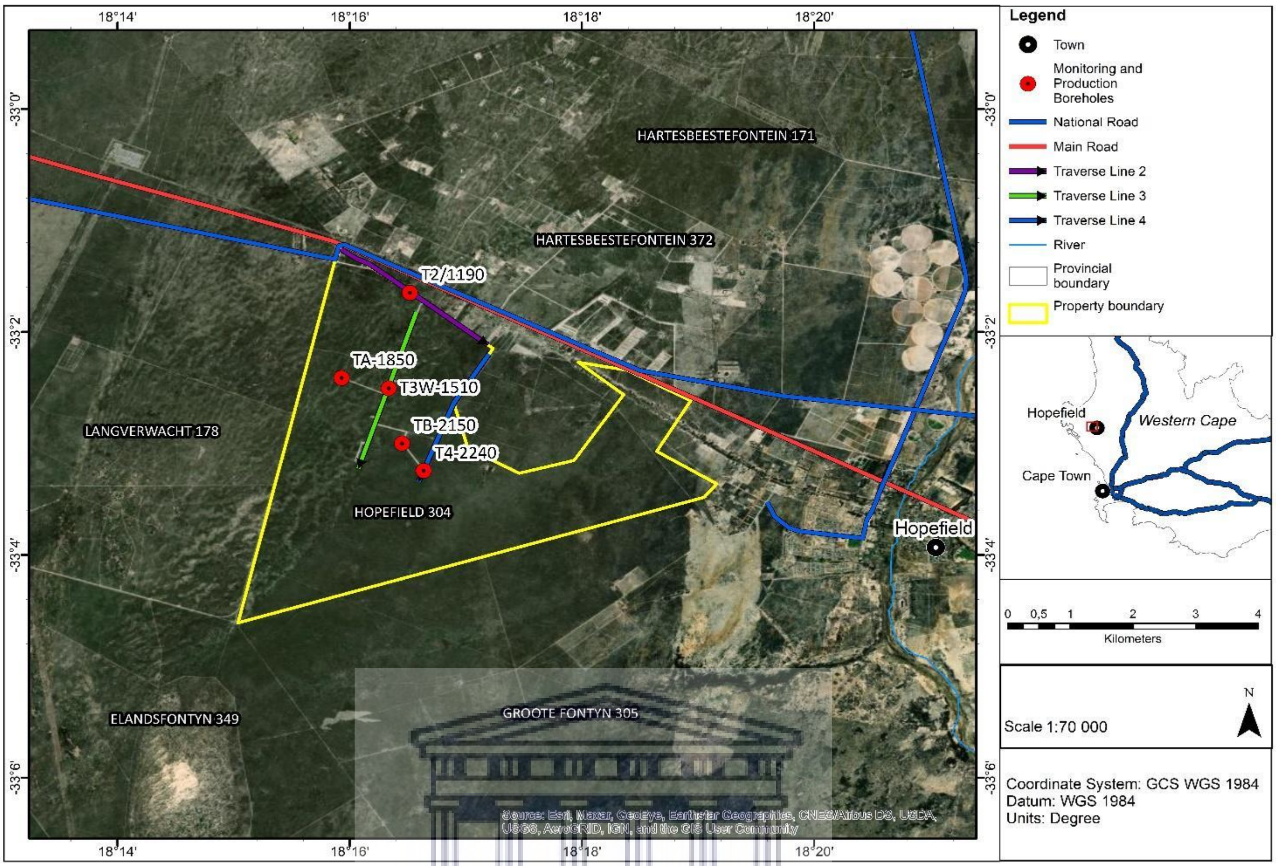


Figure 10- Satellite image of the study area showing geophysics traverse and borehole locations

The investigation comprised of four near parallel NNE traverse lines and one ESE traverse with lengths of 2,560m, 2570m, 3,200m, 3,000m, and 1,990, respectively. The apparent resistivity, which is the normal quantity determined from the field measurement, is not a physical constant, but reflects the distribution of the true resistivities in the subsurface and depends on the spatial configuration of the measuring systems. Of the eight-resistivity surveys that were carried out, five traverses were chosen for the result presentation. This was mainly because production boreholes were dug along the chosen resistivity profiles hence this made the interpretation more reliable. These were traverse 2, 3R, traverse 4, traverse A and traverse B. Soil condition and topography on site have been provided with the resistivity models.

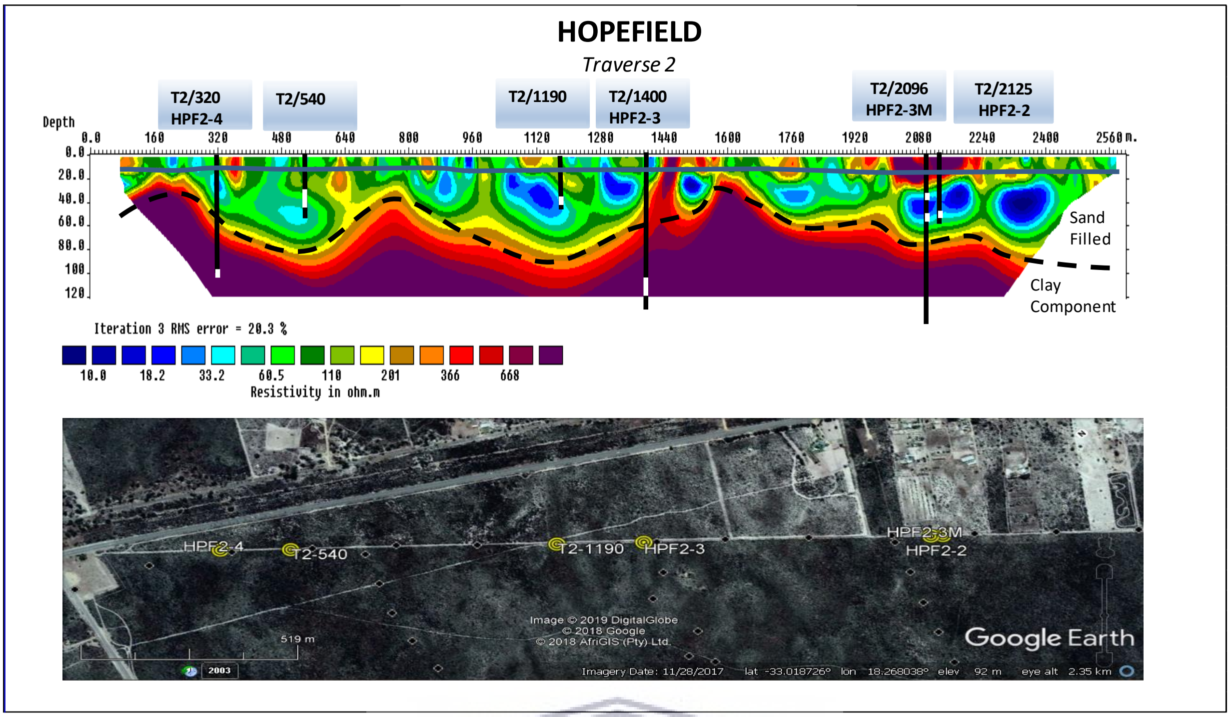


Figure 11- Resistivity model of Traverse 2 with borehole location and depth

The topography of the transect lines showed a slight undulation as seen on the google earth image in figure 11. Resistivity data were collected over 2570m to display a subsurface profile at the Hopefield site. The profile showed high variability in subsurface layers with clay component being the dominant lithology. To achieve a higher yield, 4 boreholes were drilled into regions with lower resistivity (around 33.2 ohm.m). Production borehole T2/1190 was chosen from this profile, its lithology ranges from white to brown fine sand at the top with peat intercalation later occurring. The screen of this borehole which was drilled at a depth of 49m was placed at the layer where an intercalation exists between brown fine-grained sand and coarse grain sand at a depth of about 30-42m.

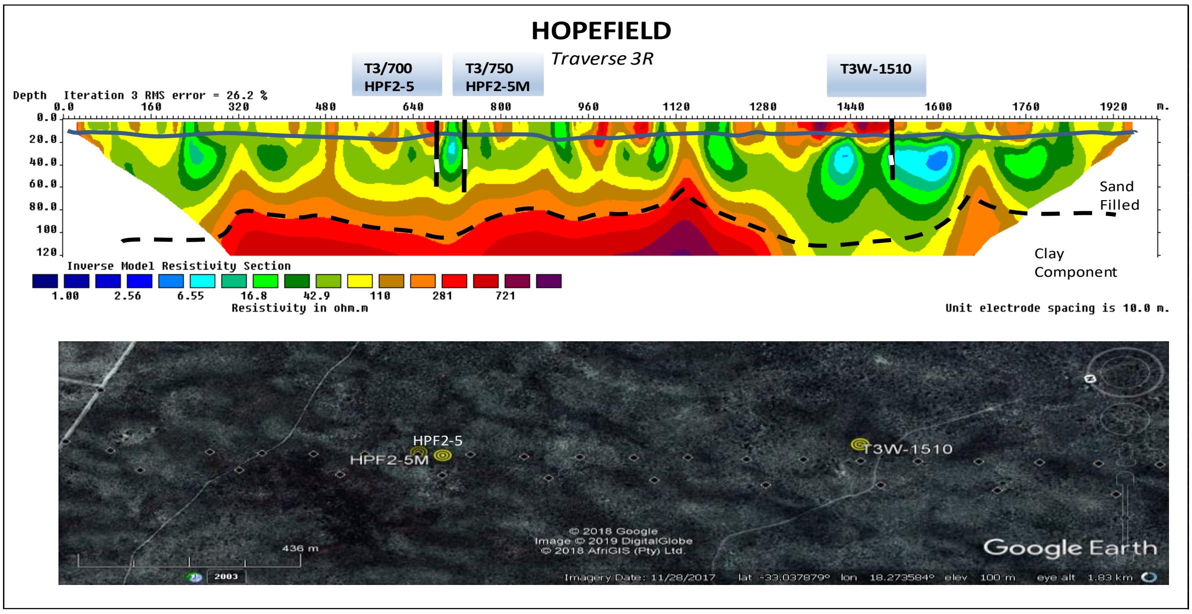


Figure 12- Resistivity model of Traverse 3R with borehole location and depth

The topography of the transect lines showed a slight undulation as seen on the google earth image in figure 12. Resistivity data were collected over 1990m to display a subsurface profile at the Hopefield site. The profile showed high variability in subsurface layers with sand-filled being the dominant lithology. A production borehole (T3W-1510) was drilled along transverse 3R, with a depth of 50m and its lithology comprises of fine-grained brown sand ranging up to depths of about 10m from topsoil, white fine-grained sand followed up to another 10m. The screen of this borehole was placed at the layer where an intercalation exists between brown fine-grained sand and coarse grain sand at a depth of about 31-40m.

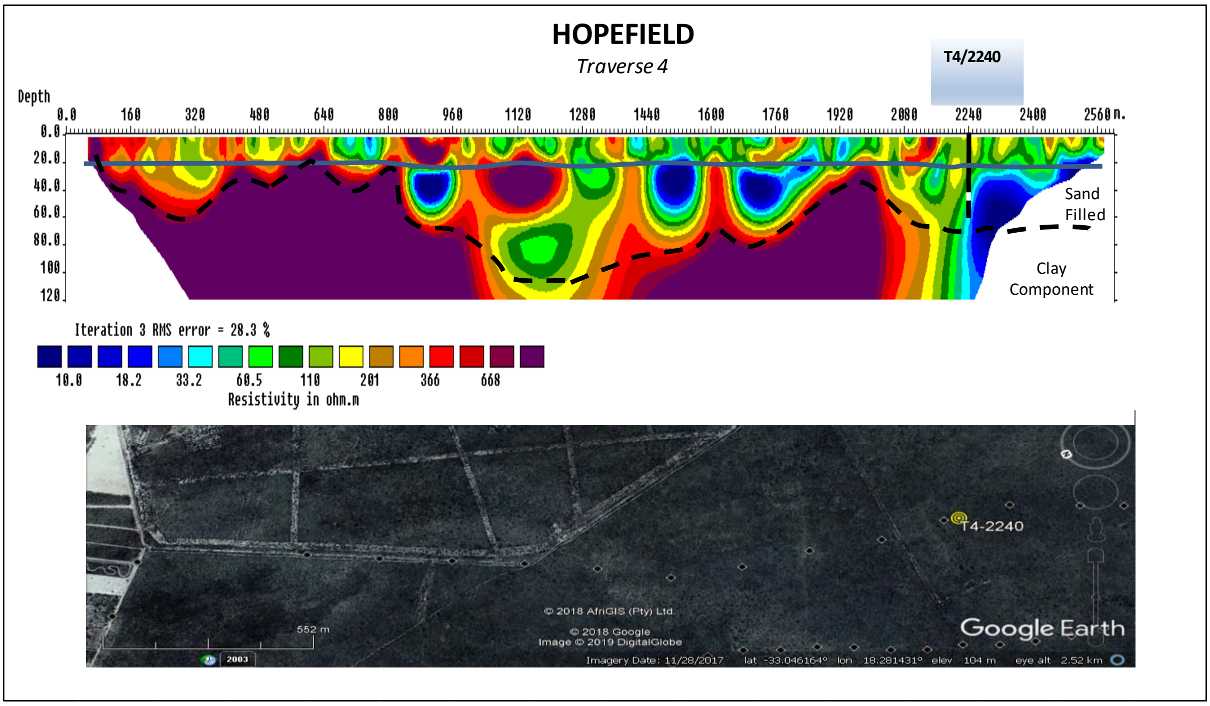


Figure 13- Resistivity model of Traverse 4 with borehole location and depth

The topography of the transect lines showed a slight undulation as seen on the google earth image in figure 13. Resistivity data were collected over 3000m to display a subsurface profile at the Hopefield site. The profile shows high variability in resistivity with a clay component dominating most of the profile. 1 production borehole (T4/2240) was drilled in a region of 33.2 ohm.m to generate a high yield, drilled to a maximum depth of 60m, it showed layers of sand that are poorly to well sorted, brownish to whitish in colour and they occur up to a depth 20m from the topsoil. The well was screen at a depth of about 28-40m where fine to coarse grain, well sorted brownish sand occurred. Below 40m is a layer of fine brown sand with peat intercalations of up to about 20% in composition.

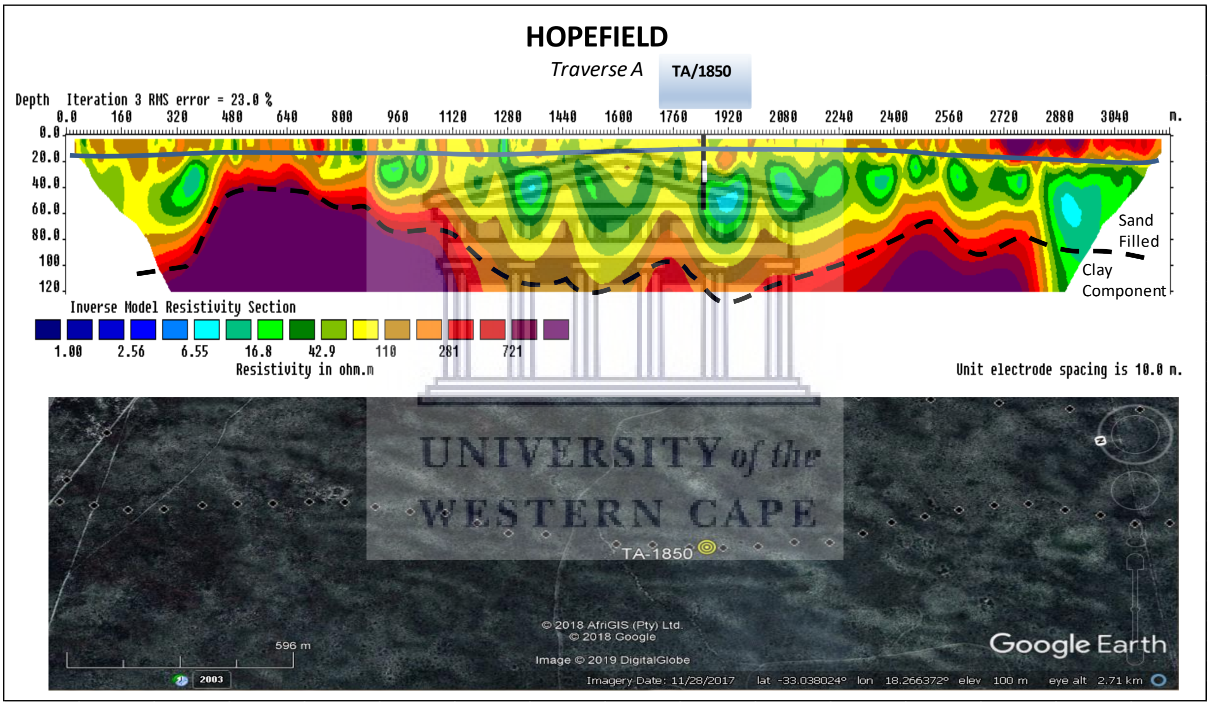


Figure 14- Resistivity model of Traverse A with borehole location and depth

The profile showed high variability with the sand-filled and clay lithologies clear differentiated. The resistivity data were collected over 3200m, and 1 production borehole (TA/1850) was drilled at 1850m in a region of low resistivity (33.2 ohm.m) on the profile to generate a high yielding borehole with a maximum depth of 55m. Lithology comprises of well sorted brown to white sand with intercalations of medium grained sand of about 10% in composition. The screen of the well was placed about 23-38m where well sorted fine to coarse grained sand that are brownish in colour occurred. Below 38m is the coarsest section containing brown sand that are well sorted with peat intercalations of about 35% in composition.

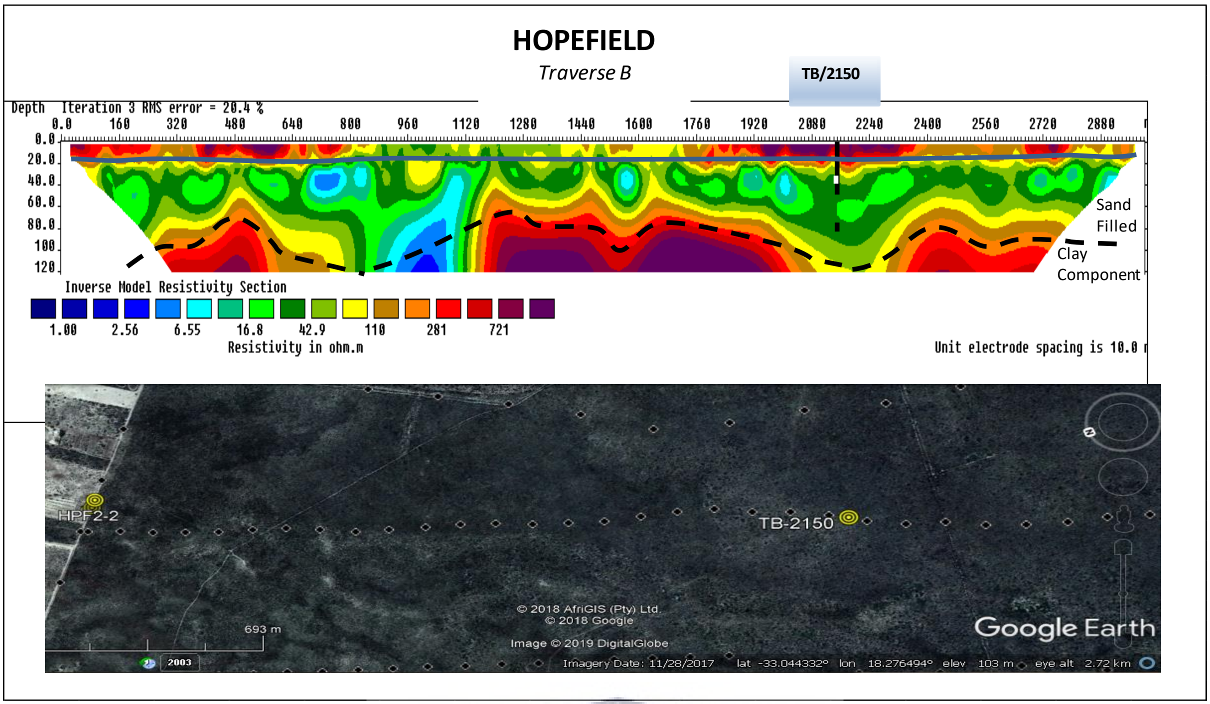


Figure 15- Resistivity model of Traverse B with borehole location and depth.

Resistivity data were collected at about 2040m. Like other profile above, this also showed high variability between the different lithologies also with sand-filled being the dominant layer. 1 production borehole (TB/2150) was drilled at 2150 m along the profile in a region of low resistivity (42.0 ohm.m) at a maximum depth of 48m. Lithology comprises of well sorted brown sand of about 28m from topsoil. The screen of the well was placed about 30-39m where well sorted fine to coarse grained sand that are brownish in colour occurred. Some medium grained sand of about 10% in composition also intercalated this layer. Below 39m is a brownish fine-grained sand.

Though the electrical resistivity method showed limitation in providing a clear distinction between layers of similar resistivity range as observed on the resistivity model portrayed in figure 9, the method was suitable for investigating groundwater units in a coastal area. Resistivity of geological units differ majorly because of the variation in either salinity of the pore fluid or changes in porosity hence the resistivity method is efficient in differentiating between different lithologies when there is a change in the porosity or salinity of the pore fluid. When different resistivity values were considered and since high voltages represent the very low resistivities and low voltages represent the high resistivities, it was concluded that the high voltages on the resistivity models represented water i.e., aquifer. This was true because water has a high conductivity which means that it allows current to flow, so inversely, it will have a low resistivity. The interpretation of the different traverses was done in assistance with geological and borehole information and the separation process between the electric zones depended on the differences of the resistivity.

The existence of clay was an aquiclude in this case because of its extensiveness in some traverses and it caused variation which was differentiated along the geological beds which had a decreasing effect on the resistivity values for these beds. The results showed is an investigation of the groundwater units at the Hopefield in the Saldanha Bay Municipality using Electrical Resistivity method. Overall, a maximum of two layers of different resistivity value ranges were observed. These were interpreted as fine to coarse grained sand which is extensive and clay layer with fine sand intercalation. However, the models provided a clear distinction between the sand layer and the clay layer based on resistivity difference. The investigation showed the usefulness of the resistivity method alongside geological information in characterizing subsurface.

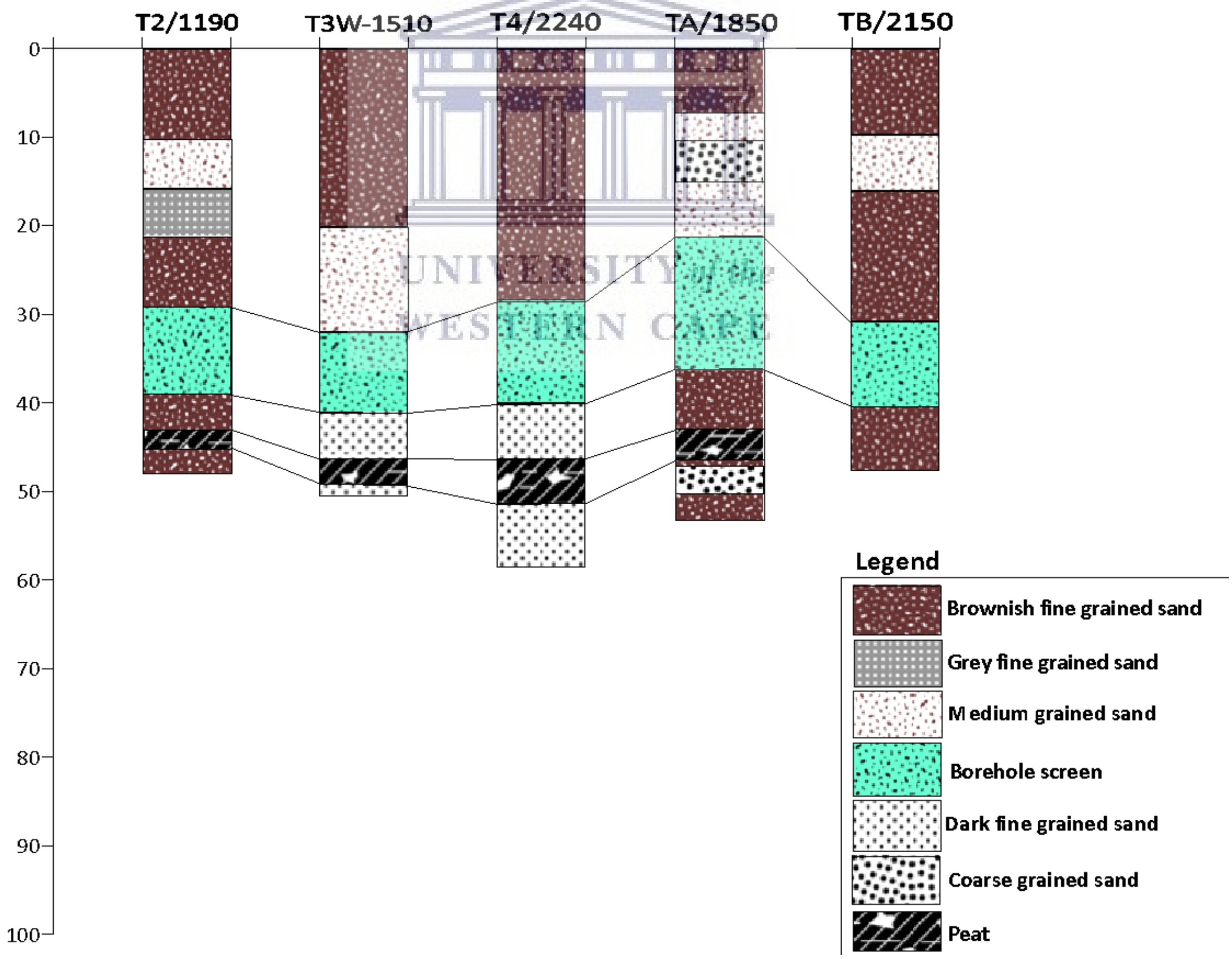


Figure 16- Lithological logs for groundwater boreholes in the Hopefield.

Figure 16 shows the lithological correlation between the 5 selected boreholes showing their screen depth and where the peat intercalation occurs. A combination of thick sand and deep weathering fractured areas was targeted for drilling. High conductive clayey areas were avoided. Borehole T2/1190, T3W-1510, T4/2240, TA/1850 and TB/2150 were screened at depths of 30-42m, 31-40m, 28-40m, 23-38m, and 30-39m, respectively. This shows the depth at which water was struck for the different boreholes. The correlation also shows close similarity in the geology and the peat intercalations can be found in the first 4 boreholes. The fact that the last borehole is the shallowest (48m) might be the reason for the non-occurrence of the peat intercalation.

Table 1- Geophysics and borehole locations in the Hopefield

Borehole Number	**Latitude**	**Longitude**	**Geophysics Traverse**	**Distance on Traverse**	**Borehole Depth (m)**	**Screen Depth (m)**
T2/1190	-33.02749	18.275532	Traverse 2	1190	49	30-42
T3W-1510	-33.04177	18.27227	Traverse 3R	1510	50	31-40
T4/2240	-33.05409	18.277729	Traverse 4	2240	60	28-40
TA/1850	-33.04022	18.26551	Traverse A	1850	55	23-38
TB/2150	-33.05001	18.2742	Traverse B	2150	48	30-39

From the geophysical investigation and borehole correlation, the predominant geology was of the Elandsfontein coarse sand and gravel aquifer and in some places confined by the Elandsfontein clay and peats as seen in the geophysical transverse and borehole log correlation above. The clay member of the Elandsfontein Formation is about 20 to 30 meters thick while the sand unit of the Elandsfontein Formation is more extensive (Figure 17) and, in some places, occurs up to depth of 40 to 60 meters thick, also seen in the borehole. The borehole details can be found in Table 1 above.

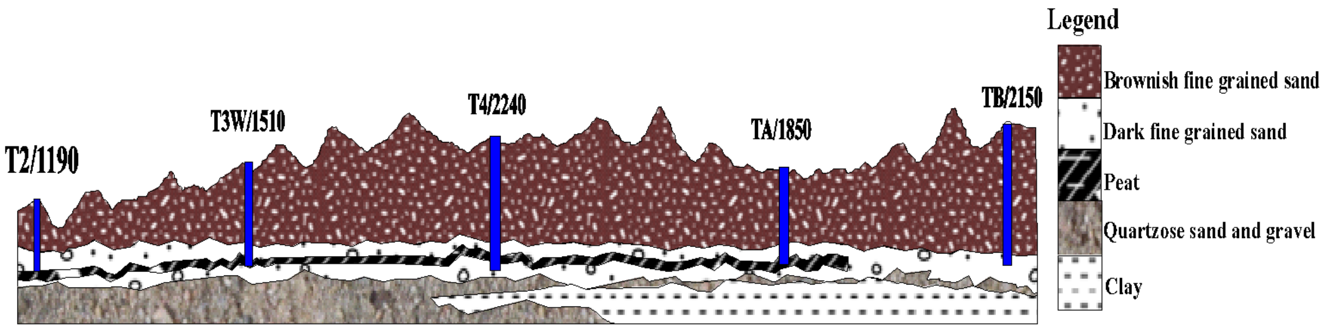


Figure 17- Cross section displaying the interpreted geology of the boreholes in the Hopefield

According to the 1:500 000 scale groundwater map of Cape Town (3317), the West Coast does host a range of aquifer types (fractured aquifers, intergranular aquifer, and a combination of the two), with varying associated yields. Regionally to the west of the study area, intergranular aquifers have been recorded with increasing yields towards the east while most of the inland areas which is where the study area falls under overlie fractured aquifers (Meyer, 2001). Specifically, the Hopefield area overlies fractured granitic bedrock (Figure 18) which can yield between 0.5 – 2.0 l/s. Please note these classifications are based on a regional scale and boreholes do occur within the Saldanha Bay with yields > 5 L/s. Groundwater in the primary intergranular aquifers store water moving through pore spaces, while groundwater in fractured aquifers are characterised by water stored and moving through fractured host rock.

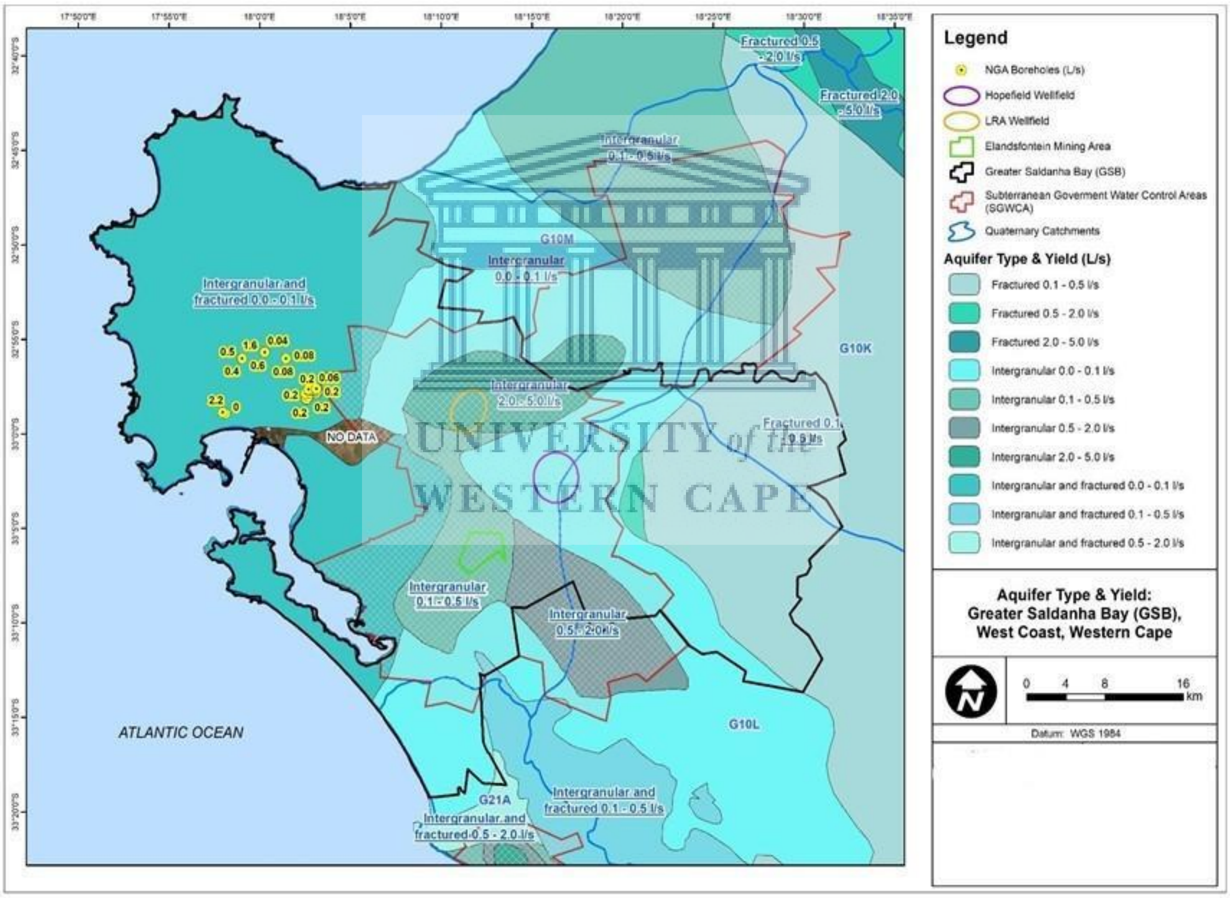


Figure 18- Regional aquifer yield from the 1:500 000 scale groundwater map (3317 –Cape Town) (DWAF, 2000)

The Department of Water Affairs and Forestry (DWAF) conducted a study on the aquifer system model of the Langebaan Road Aquifer and Elandsfontein aquifer in 2008. Specifically, the assessment of water availability in the Berg catchment by means of water resource related models was ensured and the study confirmed that two larger Sandveld aquifer systems situated in Paleo-drainage channels south of the Berg River are designated as the Langebaan Road

Aquifer System and the Elandsfontein Aquifer System. Another study by the Division of Water, Environment and Forestry Technology, CSIR in 2004 was conducted along the Langebaan Lagoon where the groundwater and surface water interaction were assessed. The investigation was conducted using the Electrical Resistivity Tomography (ERT) and it was successful. However, the resistivity interpretation was stated to be ambiguous and ground truth was recommended for control. The result from the geophysical investigation further confirms the work of authors such as Dahlin & Zhou in 2006 where the authors stated that the use of multi-electrode system and multi-channel equipment makes the ERT method rapid as it covers large distances with good resolution as seen from the investigation above. Günther and Rücker in 2012 also confirmed that due to its unique nature in aquifer characterization, depth of investigation, refined interpretation techniques and lithology delineation, the ERT method has been widely used and this can also be confirmed from the investigation and interpretation shown above.

5.3 Determination of aquifer flow regime and boundary conditions

Understanding the complexity and heterogeneity of aquifer systems is important if one will have a proper interpretation of the system hence why derivative analysis is used to understand how groundwater flow to well has been affected. Results from objective 2 focussed on derivative analysis from the Langebaan Road Aquifer unit and amplification of the heterogeneity in the aquifer system. The description focusses on the difference between the traditional drawdown versus time curve and drawdown plus derivative versus time. The aim of this objective was to further confirm the aquifer type, flow regimes, boundary conditions and aquifer heterogeneity influencing groundwater flow to wells. Furthermore, it adds to the existing knowledge on complex aquifer heterogeneity influencing groundwater flow to wells within the selected borehole. This was imperative to ensure that pumping test data analysis was performed using the appropriate analytical models relevant for the hydrogeological conditions of the aquifer. To achieve this objective, secondary pumping test data from the Hopefield area was used to produce derivative plots for interpretation and discussion.

Pumping test has been traditionally used for characterization of aquifers, investigation or quantifying their hydraulic properties and determination of the efficiency and sustainable yield. The objective or purpose of the borehole determines the type and duration of the test that will be carried out on the well. Types of tests includes multiple discharge test, constant discharge, and recovery test. In the present study, constant discharge and recovery test were conducted for 72 hours mainly because the borehole was a production well. The constant discharge test conducted in this study was also to identify the different flow regimes in the cycle and show boundary conditions present. These are important to show and must be clearly seen and distinguished in the plot. The flow regimes and boundary condition are important because they influence the flow to well and decision around management of the well which is important for sustainability of the well.

There are different diagnostic plots used in showing the distinction that occurs during the pumping cycle. They include-

- the drawdown (s) versus time (t) in a log-log plot (log s vs. log t),
- the drawdown versus the logarithm of time (semi-log plot: s vs. log t),
- the drawdown versus the square root of time (s vs. t1/2),
- the drawdown versus the fourth root of time (s vs. t1/4), and
- the time derivative of the drawdown versus the time in a log-log.

In this study, 3 of the 5 stated plots above were chosen and shown for interpretation. They included the drawdown (s) versus time (t) in a log-log plot (log s vs. log t), the drawdown versus the logarithm of time (semi-log plot: s vs. log t), and the time derivative of the drawdown versus the time in a log-log. The reason for the choice of plots was because the signal segments of *s* and *ds/dlogt* is improved in terms of flow dimension when plotted on a semi-log and on a bi-log plot. This approach integrates the strength of both plots; the semi-log plot of *s* is less noisy, whereas the bi-log plot of *ds/dlogt* is sensitive to both pumping rates and changes in the flow regime (Figure 19).

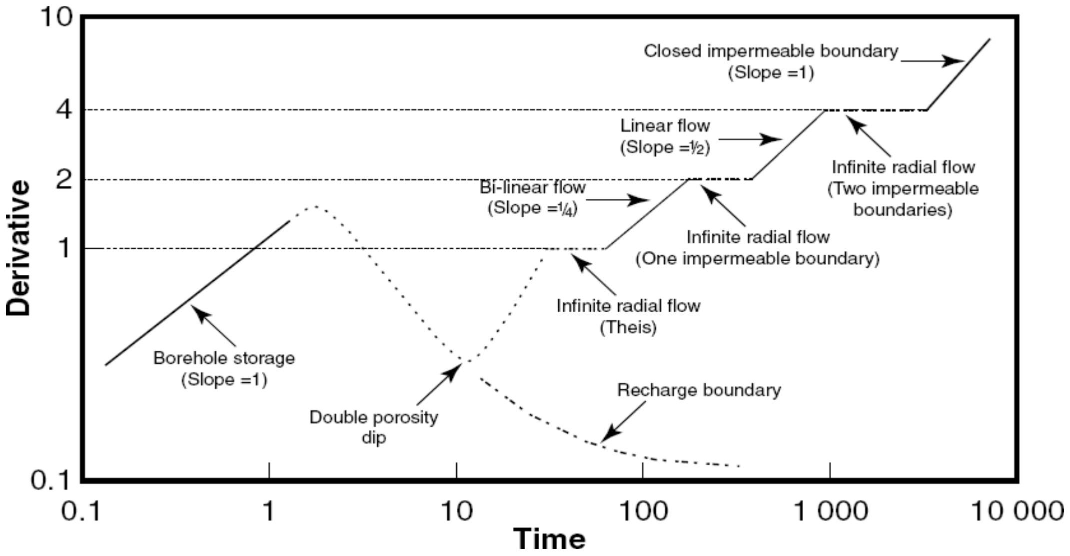


Figure 19-Graphs of the first logarithmic derivative of the drawdown in a borehole for a few types of geometries and boundaries (Van Tonder et al., 2001)

5.3.1 Identification of characteristic flow regimes (constant discharge test)

On 01 October 2018, borehole T2-1190 was pumped at a constant rate of 5 l/s for 4320 minutes (72 hours), followed by a recovery of 1320 minutes (22 hours) measurement. The data from the test was analysed with the flow characteristic (FC) Program (developed by the Institute for Groundwater Studies, University of the Free State) and the results are shown below. The static groundwater level before the test started and the total drawdown was 11.39 mbgl and 24.39 m, respectively. From the constant discharge test and drawdown plot, the system reached a steady state condition which was shown from the stabilization of the groundwater level.

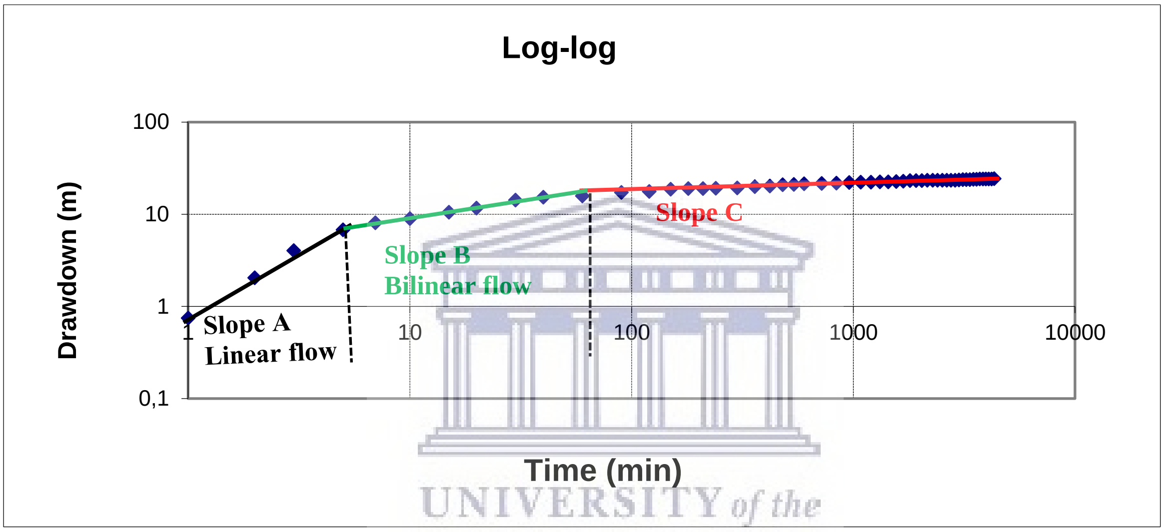


Figure 20- Log-log diagnostic plot of T2/1190

The behaviour of the drawdown in both plots (log-log and semi-log) are similar. The drawdown log-log plot of the T2/1190 shows 3 distinct groundwater flow characteristics. From the log-log plot, slope A showed a slope of 1/2 while slope B showed a of slope of 1/4 which is a linear and bilinear flow respectively. The T-value at the early stage is a representative of the early time response to pumping and it shows that the time drawdown plot has a unit linear slope on the log-log graph.

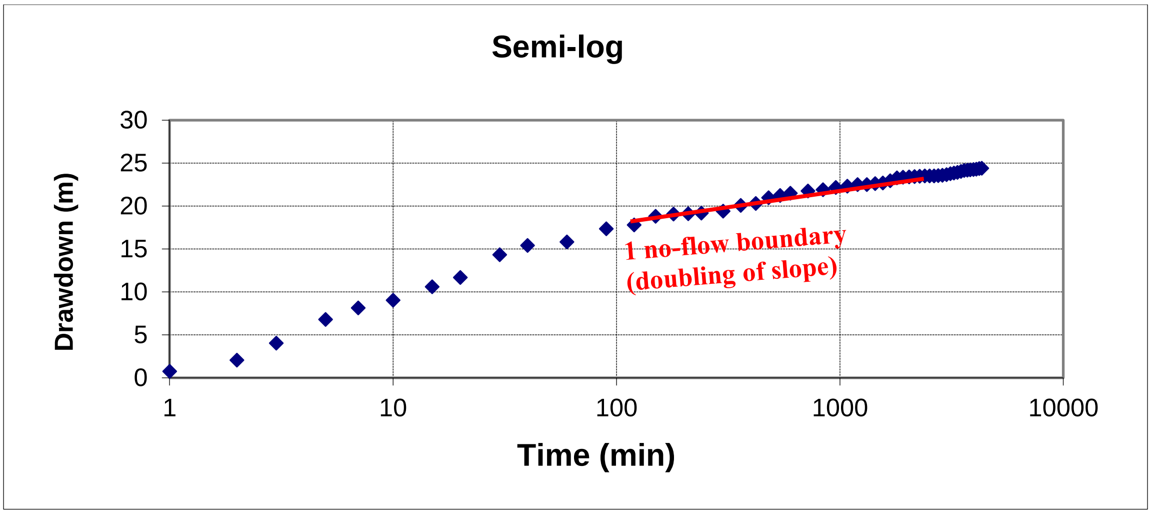


Figure 21- Semi-log diagnostic plot of T2/1190

A double porosity dip was encountered around the 150th to 420th minute which is an indication that the well was drilled in an unconfined aquifer. It is also an indication that a layer with less transmissivity have been encountered. There is a series of oscillations that occurred during the intermediate to late time and this might be an indication of heterogeneity. The nature of this heterogeneity is indicative of different aquifer or geological materials encountered during the pumping. Although there is a little period of stabilization that occurred, which is a characteristic feature of an Infinite-acting radial flow (IARF).

The stabilization shown on the plot indicates a flat circular disc starting at about 720th minute to 1080th minute. This means that there was a horizontal flow pathway converging in the well for about 6 hours and it may also be because of the medium grained sand that intercalated the grey fine grain sand in this well. The aquifer seems high yield and this can be attributed to the type of aquifer (unconfined), the geology of the area which determines the lithology and the fact that the well is in a coastal environment. Based on the derivative plot above, the standard derivative plot as proposed by Van Tonder et al., (2001) and the theoretical classification of derivative plots by Renard et al., (2009), it is concluded that well T2/1190 has been drilled in a double porosity aquifer which is also unconfined.

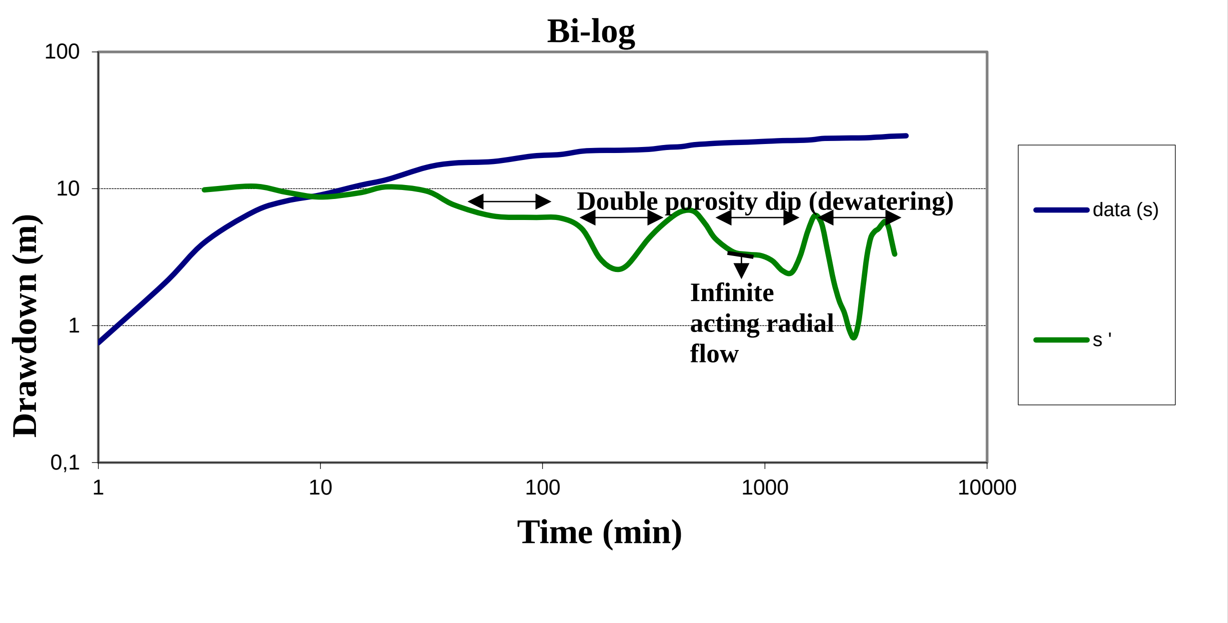


Figure 22- Derivative plot of T2/1190.

On 08 November 2018, T3W-1510 was pumped at a constant rate of 5 l/s for 4320 minutes (72 hours), followed by a recovery of 2040 minutes (34 hours) measurement. The data from the test were analysed with the FC-Program and the results are shown below. The static groundwater level before the test started and the total drawdown was 11.89 mbgl and 18.03 m, respectively. From the constant discharge test and drawdown plot, the system reached a steady state condition which was shown from the stabilization of the groundwater level.

The behaviour of the drawdown in both plots (log-log and semi-log) are similar, even the jump in the drawdown due to the change of the discharge rate between point 1 and 2, is clearly seen. The drawdown log-log plot of well T3W-1510 showed 3 distinct groundwater flow characteristics: From the log-log plot, slope A and B showed a slope of 1/2 and 1/4 which is a linear and bilinear flow respectively. Slope A is an early time of the water level drawdown that occurs during/aftereffects of borehole storage and skin effect have ceased to dominate the response. The T-value at this stage is a representative of the early time response to pumping and it showed that the time drawdown plot has a unit linear slope on the log-log graph.

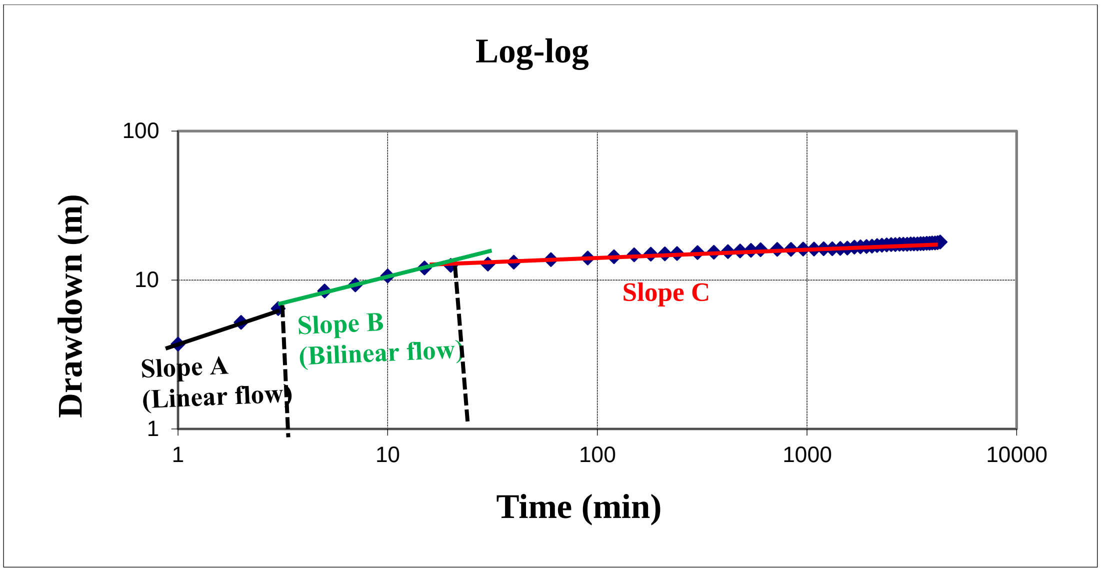


Figure 23- Log-log diagnostic plot of T3W-1510

This may also be an indication of a formation with a good transmissivity network (Kruseman and De Ridder, 2000). Slope B, which is the second slope, showed a flattened curve lying below the infinite acting radial flow (IARF) line (Theis) and this indicated that water may have come from all directions due to the porosity of the aquifer. This is due to the fact that T3W-1510 was drilled in a sand dominated zone.

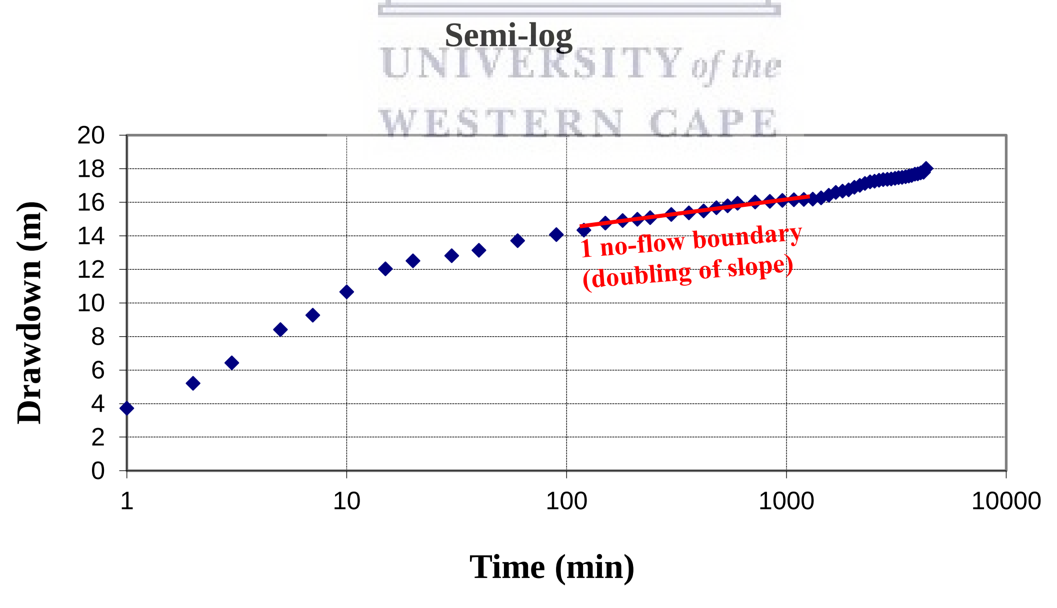


Figure 24- Semi-log diagnostic plot of T3W-1510

Multiple oscillations were seen along the derivative curve, and this indicated that the groundwater flow was variable as it encountered different geological materials during the cycle also an indication of aquifer heterogeneity. It is also an indication of layering in the aquifer which behaves on the same principle as a fracture dip.

A double porosity dip occurred as drawdown continues to increase thus indicating a decrease in transmissivity (Holland, 2011). This aquifer is regarded as a productive aquifer, and it indicates that the borehole is high yielding. From the geology of the Hopefield, the aquifer was seen to be in a coastal environment having a shallow water table with sand-gravel hydrogeologic units which are good for groundwater yield and abstractions. The dip of the double porosity showed a trough that can be described as a period of time in which the flow was coming from a higher permeability layer while the crest of the oscillation indicates lower permeability layers on the drawdown during the test.

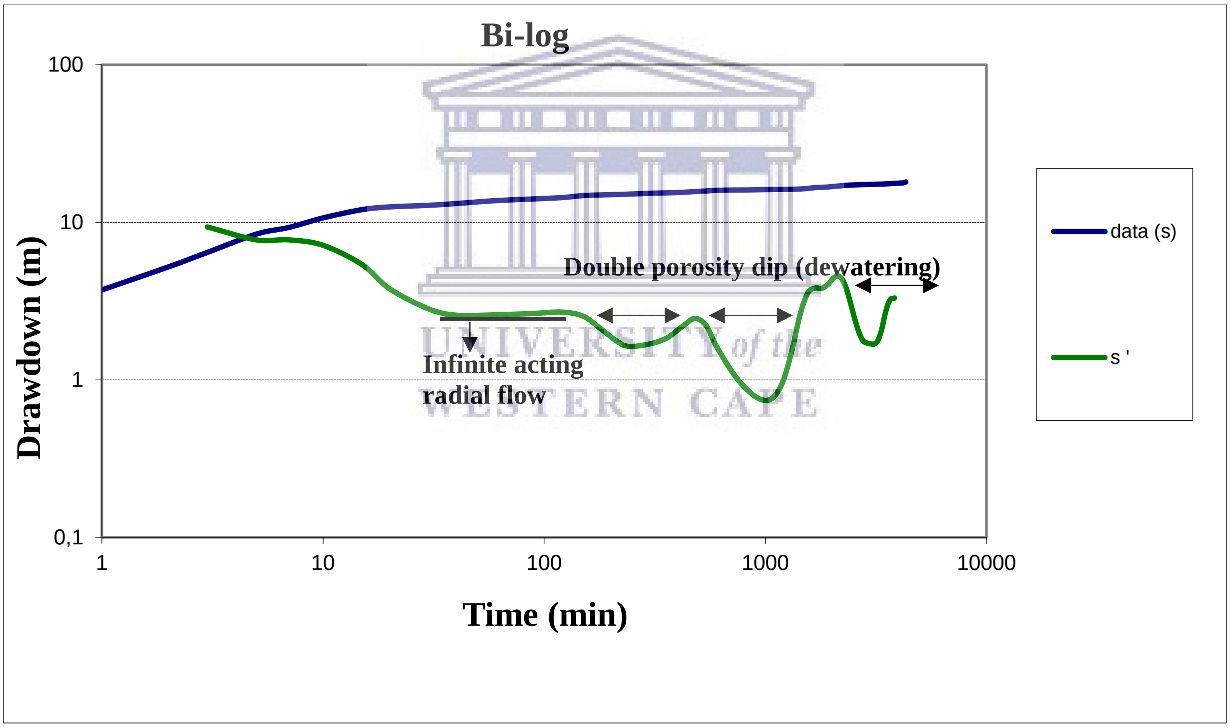


Figure 25- Derivative plot of T3W-1510

At late times on the derivative, a wiggling trend is seen, and this is caused mainly by the resolution of the data obtained from the pumping test investigation. The data points were too close which resulted in the data been calculated as a high speed and hence the rise in derivative as seen on the plot in figure 25. It was concluded that well T3W-1510 was drilled in a double porosity aquifer, based on the derivative plot and the theoretical classification of derivative plots by Renard et al., (2009). The above plots were compared to the standard derivative plot as proposed by Van Tonder, et al., (2001).

On 13 November 2018, T4/2240 was pumped at a constant rate of 10 l/s for 4320 minutes (72 hours), followed by a recovery of 2280 minutes (38 hours) measurement. The data from the test were analysed with the FC-Program and the results are shown below. The static groundwater level before the test started and the total drawdown were 11.36 mbgl and 16.38 m, respectively. From the constant discharge test and drawdown plot, the system reached a steady state condition which was shown from the stabilization of the groundwater level. The log-log plot showed 3 segments or slopes A, B and C. Slope A is a linear flow while B is a bilinear flow. Slope B showed several dewatering (double porosity dips) clearly showing on the bi-log plot in figure 28. On the log-log plot, it showed a slope of 1/4 indicating that water may have entered the well from all around its pores. This can be seen by its extended steepness, also because this is the deepest well (60m) within the study area. The derivative plots showed early, intermediate, and late times with about 4 porosity dips and multiple oscillations. The porosity dip around the 360th minute increases on average around the dip and maybe an indication of a boundary condition. In this case, hydrogeological boundary, or layering.

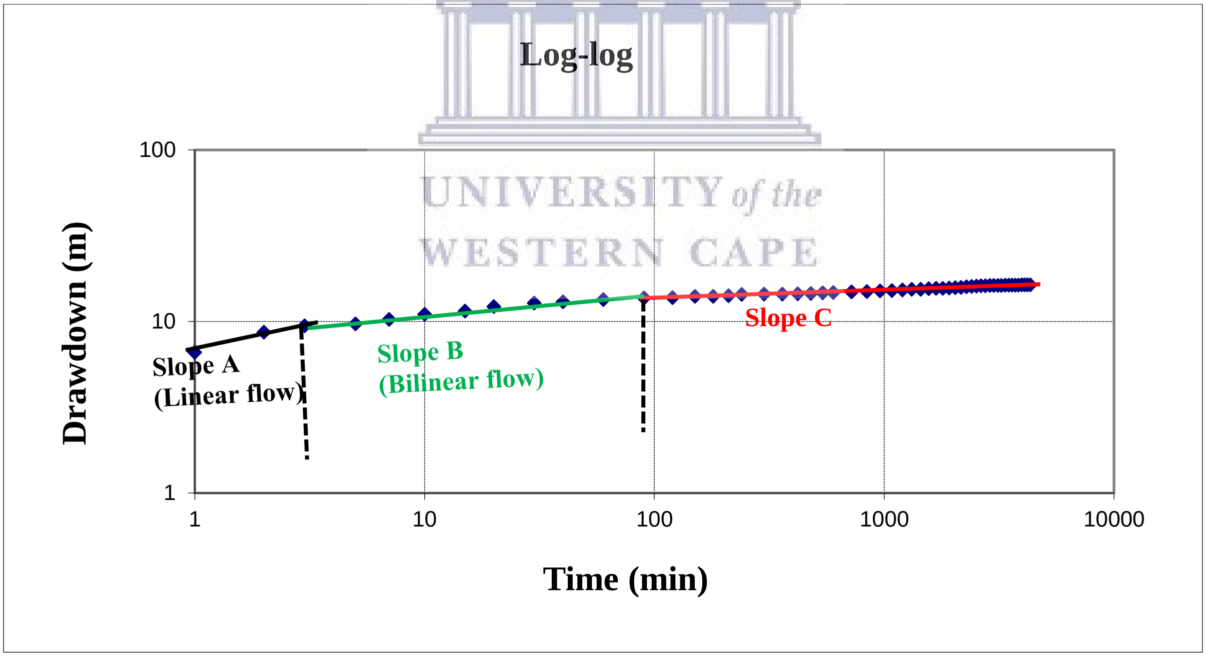


Figure 26- Log-log diagnostic plot of T4/2240

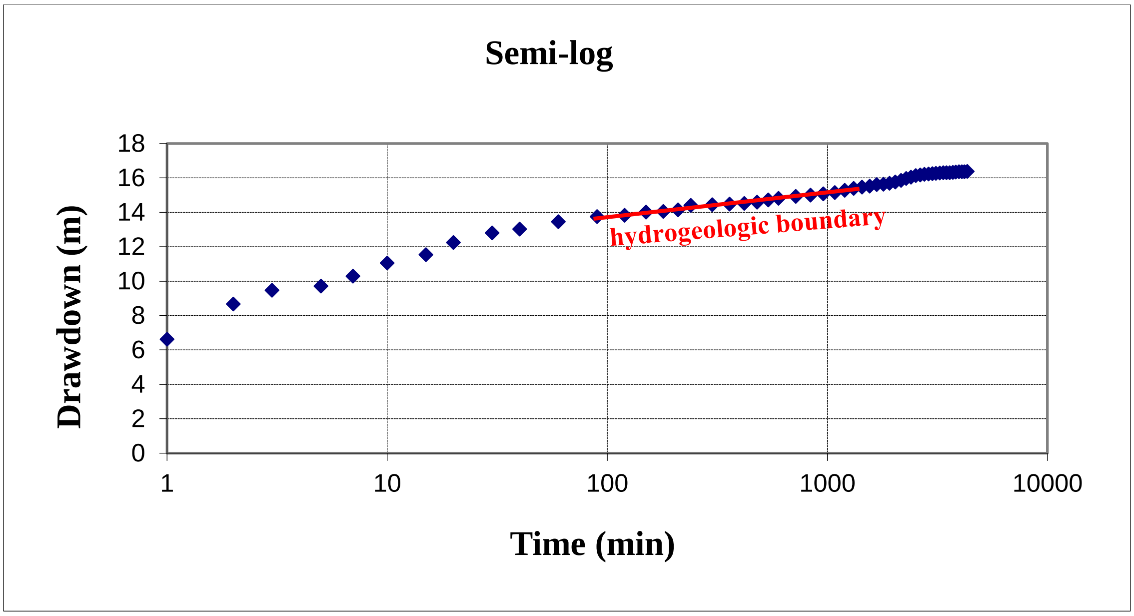


Figure 27- Semi-log diagnostic plot of T4/2240

Hydrological boundaries in this case does not necessarily need to be physical geological boundaries, they can be sand layers which has high permeability and then thins out on another end causing the grain sizes to get finer on one side. This is evident from the drilling logs obtained from this well where fine to coarse grained sand were seen with peat intercalations. The borehole T4-2240, has been drilled in a double porosity aquifer based on the derivative plot and the theoretical classification of derivative plots by Renard et al., (2009).

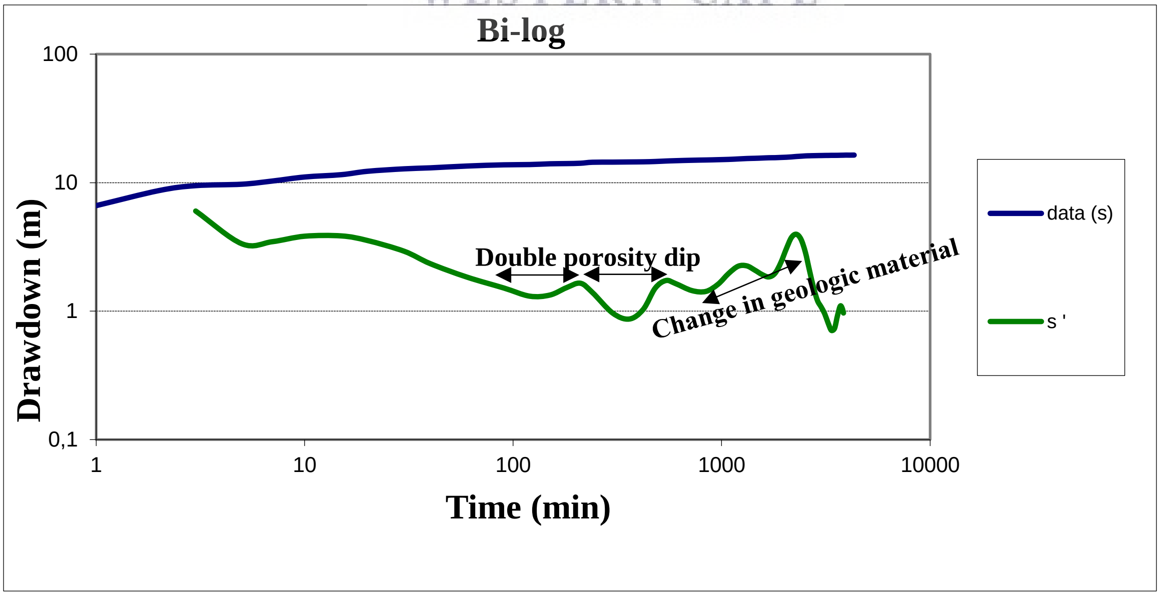


Figure 28- Derivative plot of T4/2240

On 18 November 2018, TA/1850 was pumped at a constant rate of 6 l/s for 4320 minutes (72 hours), followed by a recovery of 1320 minutes (22 hours) measurement. The data from the test were analysed using the FC-Program and the results are shown below. The static groundwater level before the test started and the total drawdown was 8.77 mbgl and 26.69 m, respectively. From the constant discharge test and drawdown plot, the system reached a steady state condition which was shown from the stabilization of the groundwater level. The log-log plot for well TA/1850 shown in figure 29 below portrays two distinct groundwater flow regimes, linear and bilinear flow during early time and intermediate time respectively. An infinite acting radial flow is indicated in the bi-log plot (figure 31) during intermediate time. The well showed an infinite confined aquifer that is approximately homogenous as seen through the oscillations on the derivative plots. The derivative curve did not follow the drawdown curve during early, thus suggesting that water was withdrawn from the well itself.

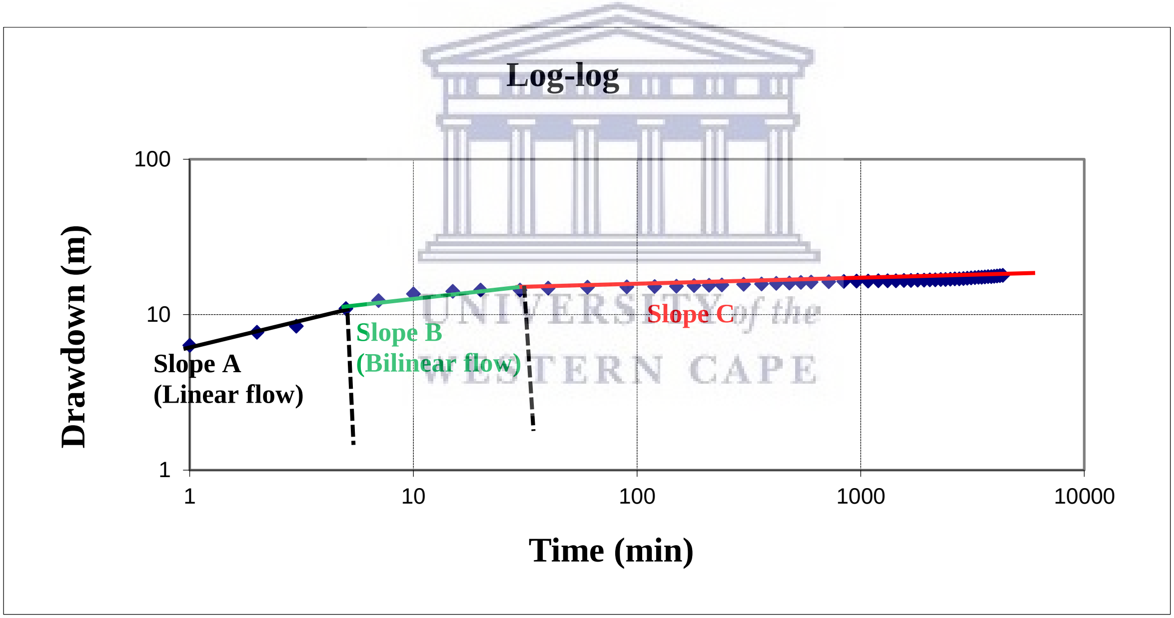


Figure 29- Log-log diagnostic plot of TA/1850

From the 10th minute, pumping pressure spreads rapidly thus resulting to a quick drawdown response as seen on the derivative and this may be the aquifer experiencing full stress from pumping and it may also indicate the presence of the clay intercalation that was avoided during the drilling as seen in the resistivity model (figure 14). There are 2 double porosity dips (dewatering) shown in the plot. The first one is seen between the 60th minute and 150th minute while the second porosity dip is seen between the 960th minute and 1440th minute. Infinite-acting radial flow (IARF) is seen to be occurring before the boundary. The slight stabilization shown on the plot indicates a flat circular disc starting at about 240th minute to 360th minute.

This means that there was a horizontal flow pathway converging in the well for about 2 hours and it may be because of the coarse-grained sand that intercalated the fine grain in this well. The steeping seen in the semi-log plot can be clearly seen in the derivative plot as a boundary condition. At the 1200th minute, a sharp increase in the derivative started and extends all the way towards the end of the test about 3240th minute. This means that this well experienced a boundary condition for more than 24 hours. The boundary in this case is a no flow boundary indicated by the doubling of slope (Figure 30).

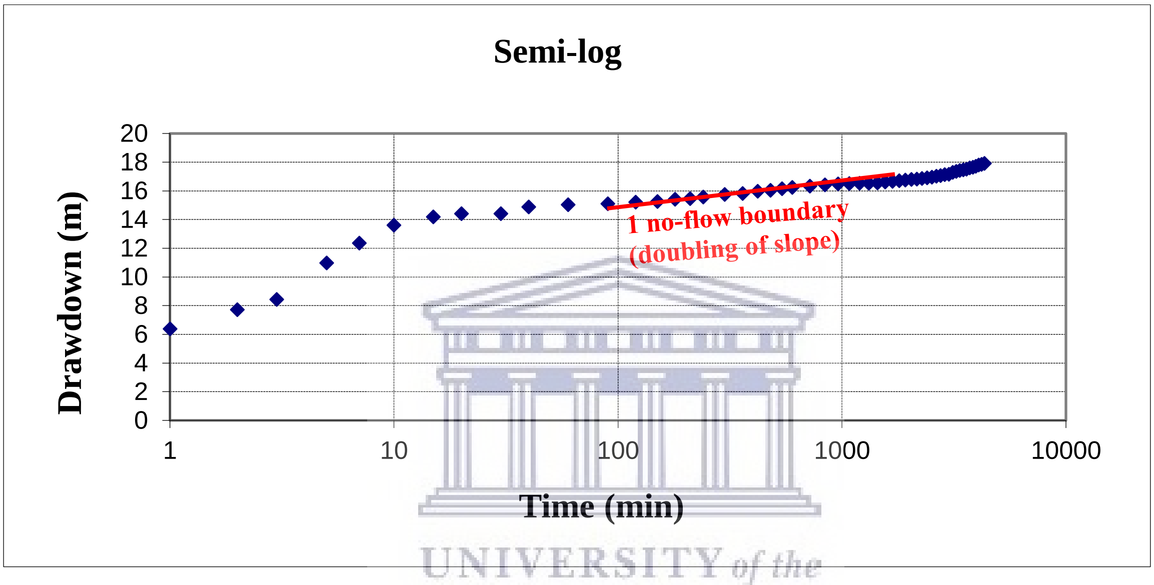


Figure 30- Semi-log diagnostic plot of TA/1850

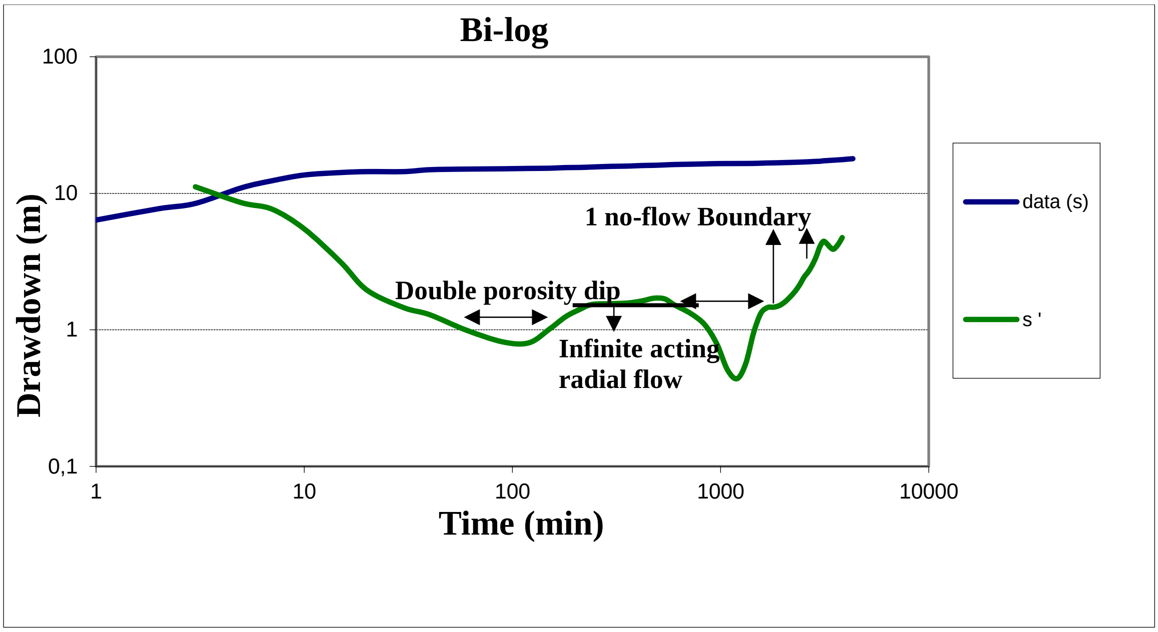


Figure 31-Derivative plot of TA/1850

Borehole TB/2150 was pumped at a constant rate of 3 l/s for 4320 minutes (72 hours), followed by a recovery of 480 minutes (8 hours) measurement. The investigation was conducted on 21 November 2018 and the data was analysed with the FC-Program and the results are shown below. The static groundwater level before the test started and the total drawdown was 15.48 mbgl and 18.24 m, respectively. From the constant discharge test and drawdown plot, the system reached a steady state condition which was shown from the stabilization of the groundwater level. The log-log and semi-log plots well TB/2150 shown in figures 32 and 33 below portrays three distinct groundwater flow regimes, linear flow during early time, a bilinear flow during intermediate time, including a double porosity dip and a boundary condition during the late time, indicative by a rise in derivative.

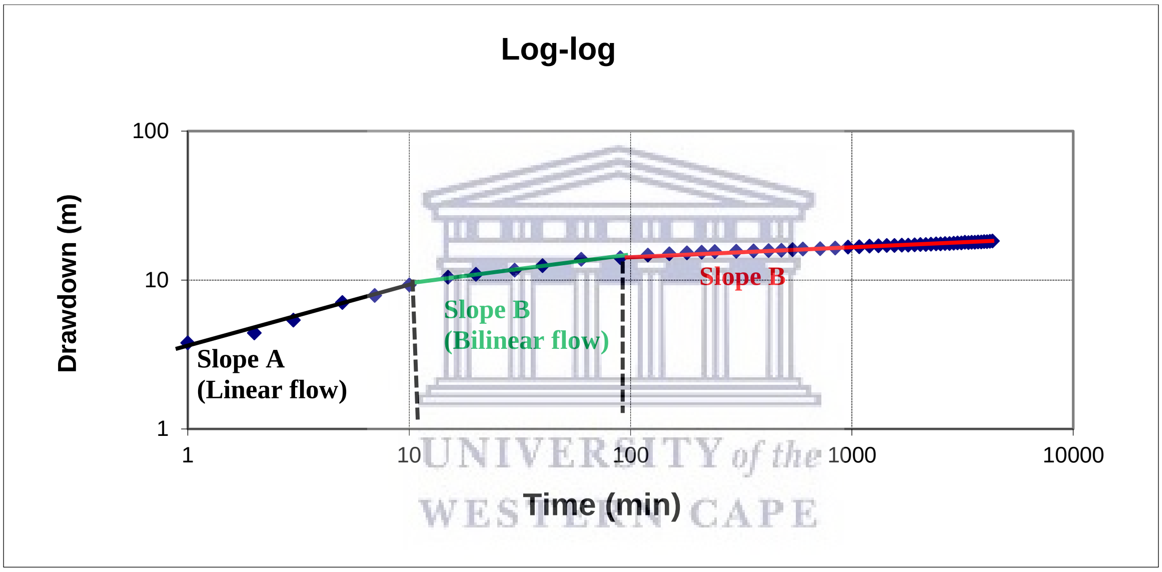


Figure 32- Log-log diagnostic plot of TB/2150

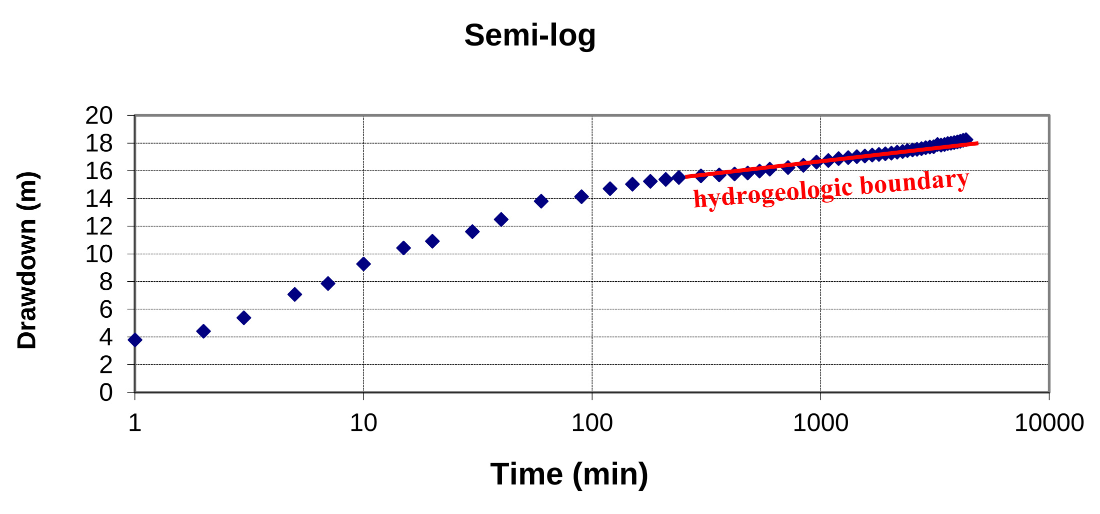


Figure 33- Semi-log diagnostic plot of TB/2150

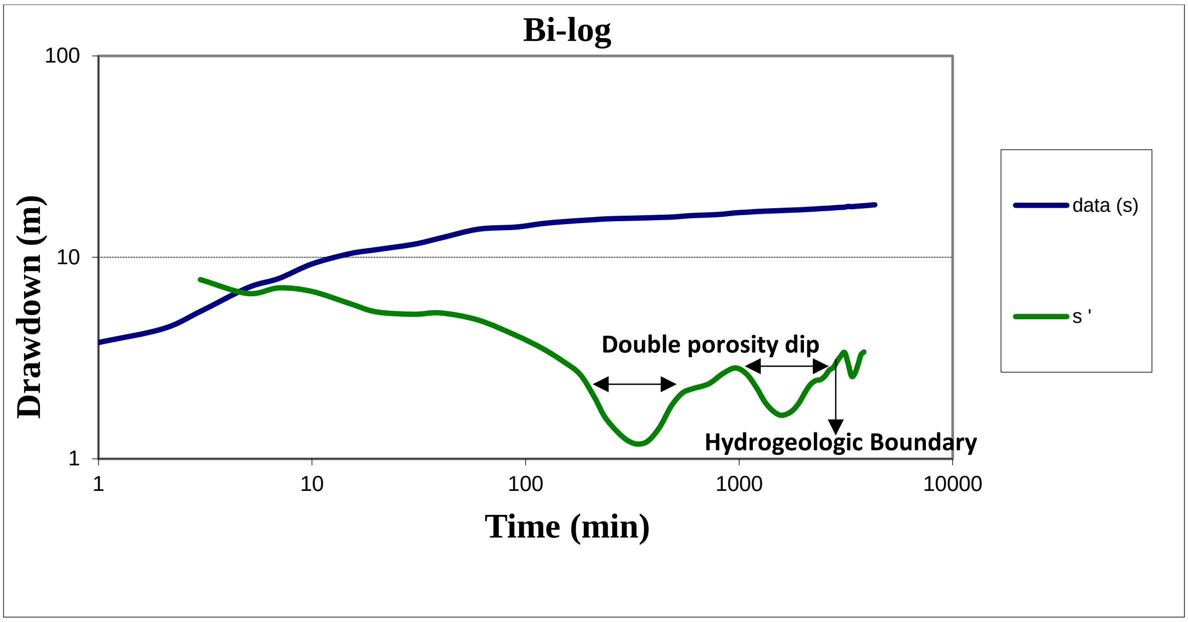


Figure 34- Derivative plot of TB/2150

From the 10th minute, a sharp decline in drawdown was seen causing a double porosity dip or dewatering of the aquifer. (Figure 34). Again, there are 2 double porosity dips in this well. The first one was seen between the 180th minute and 600th minute while the second porosity dip was seen between the 1080th minute and 2160th minute. The steep increase in the semi-log plot was clearly seen in the bi-log plot as a boundary condition. The first double porosity dip (before the 1000th minute) occurred about a few hours. The second double porosity dip is increasing for more than 24 hours (3600 – 1680 = 1920). 1920 is about 32 hours meaning that this well experienced a boundary condition for more than 24 hours and this indicated a boundary condition. This might be the effect of the well sorted fine to coarse grained sand that are brownish in colour intercalating with medium grained sand which thins out to fine sand again.

5.3.2 Comparative analysis of results

The results shown above represents derivative plots for the borehole drilled in the Hopefield area in the Saldanha Bay Municipality. Analysis of the flow regime and flow dimension were conducted using drawdown derivative plots as recommended by Van Tonder et. al, (2001) and Samani et. al, (2006). The FC method was used in the analysis to produce the derivative plots, derivative analysis was used to identify the typical drawdown behaviour in the study areas and to identify the various complexities that exist in the aquifer system. The observed data sets were compared to the standard derivative plot and a set of theoretical plots as proposed by Tonder, et al., 2001 and Renard et al., 2009, respectively. The reason for the comparism is to correctly identify aquifer flow regimes and the model that can be used to interpret the data better. Pacome (2010) used the FC method for the fracture characterisation of the Karoo aquifers. The derivative of the chosen well showed a dewatering of the fracture by a decrease in the derivative curve (double porosity). Transmissivity were estimated using the Cooper-Jacob and Theis recovery with values of 20 m^2/day and 20.2 m^2/day respectively while Holland (2011) conducted a hydrogeological characterization of crystalline basement aquifers using the Limpopo Province in South Africa as a case study. Aquifer characterization was conducted by pumping test and derivative analysis was employed in other to identify the appropriate model that fits the observed pumping test data. A double porosity response was gotten from 3 borehole in the study area and bore depths ranging between 40 and 50 meters. Similarly, a double porosity dip was gotten from all 5 wells in the Hopefield and almost similar depth ranging between 48 and 60 meters. A double porosity analytical solution was then identified as the most appropriate model to interpret the pumping test data, and this is because of the results obtained from the derivative analysis hence this shows that the analytical model selected is appropriate.

In another environment, groundwater yield reliability analysis and operating rules for data constrained rural areas in South Africa was conducted by Odiyo et al (2017). The hydrogeological information revealed that the study was conducted in a fractured rock aquifer comprised of sandstone, quartzite, and basalt. The output of the analysis showed plots indicating a double porosity aquifer characterised by fracture dewatering or different dips during late time while Paxton (2018) also used the FC method for the hydrological investigation of the Rietvlei Sandstone. Estimated average transmissivity and storativity was 23.32 m^2/day and $4.8x10^{-4}$. The results from the Hopefield also indicated a double porosity behaviour and the flow regimes identified from the analysis is an indication of the hydrogeological condition of the area. The geology of the study also confirms the hydrogeological conditions shown on the derivative plots and this also an indication that the analytical model selected for the pumping test analysis in the area is appropriate.

5.3.3 Implication of results for practice

The results above have shown the aquifer heterogeneity, boundary condition that existed and flow regimes of aquifers in the Hopefield and this demonstrating that derivative analysis is an easy and powerful tool to assess and better understand the complexity that exist in aquifer system. A better understanding of the complexity that exist and how it influences the flow of groundwater has been seen and the above method has also provided more information on the aquifer characteristics in the Hopefield and more importantly facilitating the selection of an appropriate analytical model to evaluate and understand the hydraulic parameters of the aquifer system. It is therefore recommended that derivative analysis should be considered as a mandatory tool for pumping test analysis among hydrogeologists to ensure that reliable results for information about the aquifer system as this informs decisions towards usage and management of the resource.

5.4 Estimation of aquifer parameters

Estimations of aquifer hydraulic parameters is important to evaluate the groundwater potential in the area and to assess the impact of pumpage on the groundwater flow regime, it also gives way to reliable information on the aquifer which in turn enables adequate and proper management practices. Estimation of aquifer hydraulic parameters is also important for prediction of future availability of groundwater hence this section discusses the results from the estimation of aquifer hydraulic parameters in the Hopefield area thus addressing objective 3 of the study. The aim of this objective was to study the borehole performance by identifying aquifer parameters through pumping test of the newly drilled boreholes, predict future water level trends and long-term operation of boreholes. To achieve objective 3 of this study, pumping test data from 5 boreholes were acquired through performing constant discharge rate test. Data collected included borehole depth, static water level. This was done to assess groundwater potential and to evaluate the effects of pumping on the groundwater system. Parameters estimated include Transmissivity (T), Storativity (S) and Sustainable yield (Sy). Pumping test data were analysed using applicable analytical solution based on their theoretical assumptions. The analysis was done using the Flow Characteristic (FC) Method.

Interpretation and description of key results on aquifer parameter estimation

5.4.1 Cooper-Jacob Time Drawdown (1965)

The constant discharge and recovery test results are presented in table 2 and 3 respectively. From the tables below, it is evident that variable T and S values were obtained from different well with variable geological features.

Table 2- Cooper-Jacob time drawdown results for constant discharge test

Borehole	**Formation**	**Analytical Model**	**Transmissivity (m^2/day)**	**Storativity**
T2/1190	Elandsfontein	Cooper-Jacob	19.0	1.68E-04
T3W-1510	Elandsfontein	Cooper-Jacob	37.0	1.54E-06
T4/2240	Elandsfontein	Cooper-Jacob	94.5	1.18E-07
TA/1850	Elandsfontein	Cooper-Jacob	50.4	1.47E-07
TB/2150	Elandsfontein	Cooper-Jacob	21.4	1.21E-06

The results shown in table 2 above shows T values which in agreement as they range not more than 100m^2/day. Borehole T2/1190 yielded T and S values of 20.0 m^2/day and 1.68E-04 respectively, borehole T3W-1510 yielded T and S values of 37.0 m^2/day and 1.54E-06 respectively, borehole T4/2240 yielded T and S values of 94.5 m^2/day and 1.18E-07 respectively, borehole TA/1850 yielded T and S values of 50.4 m^2/day and 1.47E respectively while the last borehole TB/2150 yielded T and S values of 21.4 m^2/day and 1.21E-06 respectively. All boreholes were drilled on the sand and gravel aquifer of the Elandsfontein Formation. The drawdown plots of the stated boreholes are presented below.

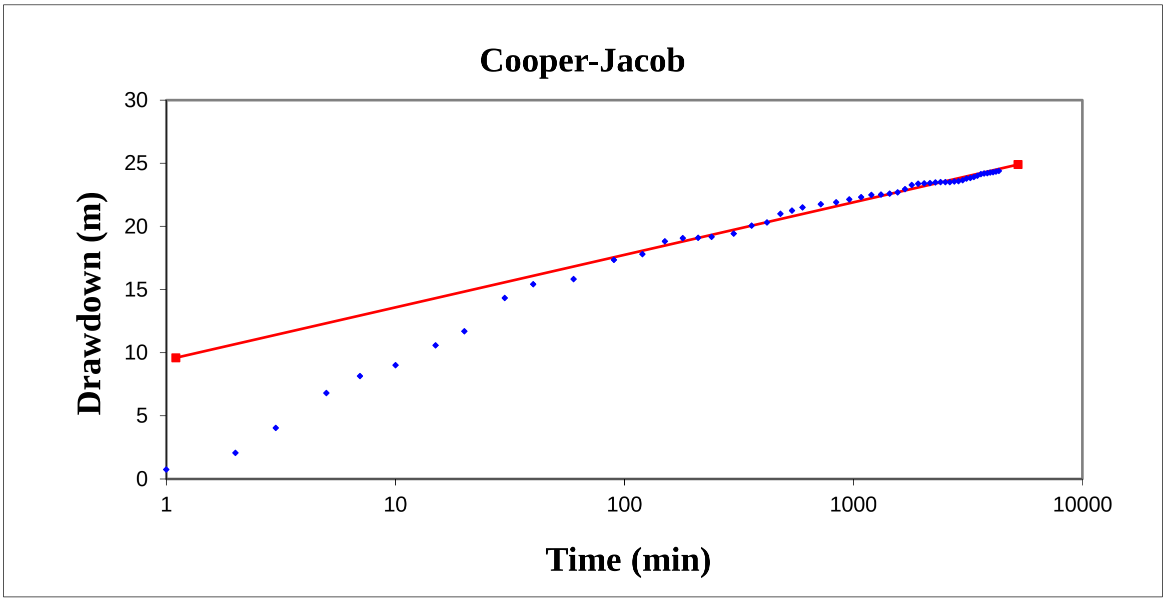


Figure 35- Borehole T2/1190 Cooper-Jacob plot showing line of best fit

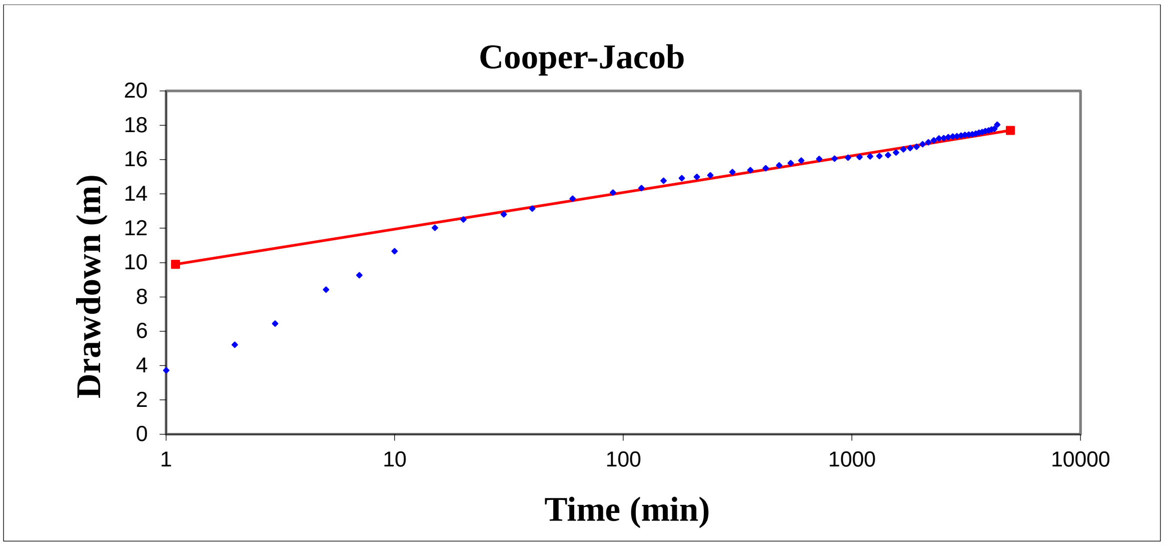


Figure 36-Borehole T3W-1510 Cooper-Jacob plot showing line of best fit

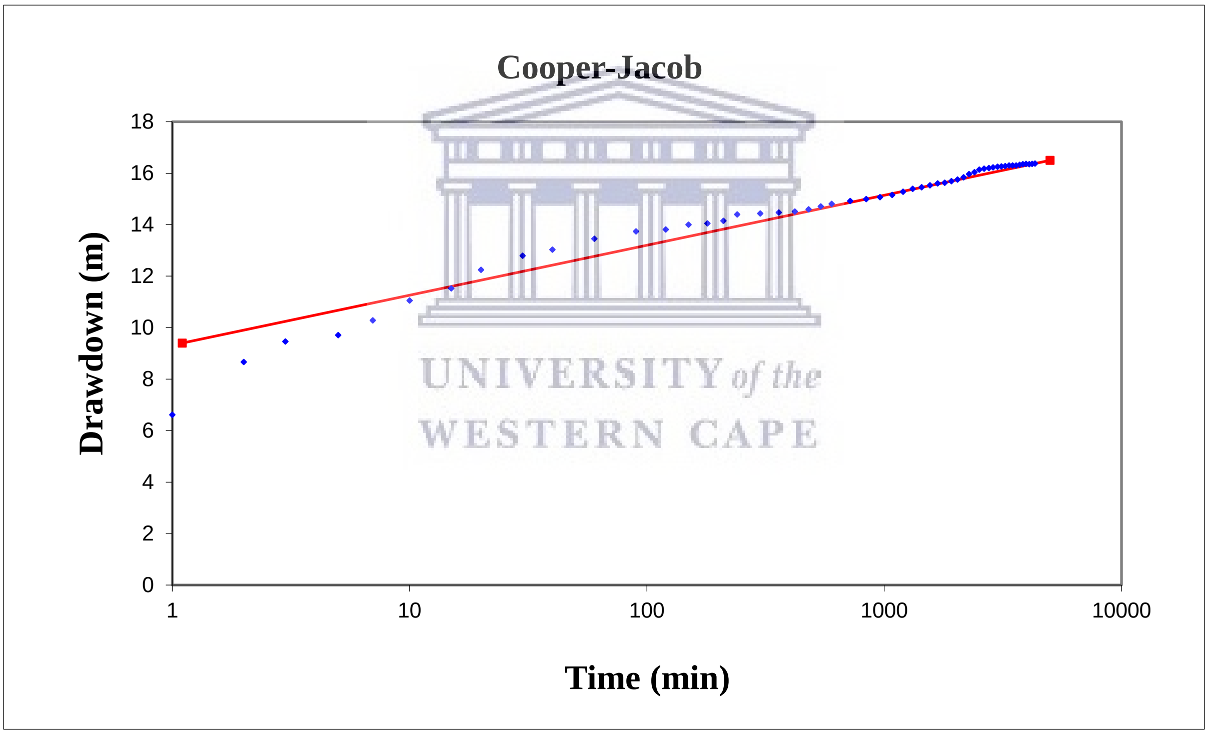


Figure 37-Borehole T4/2240 Cooper-Jacob plot showing line of best fit

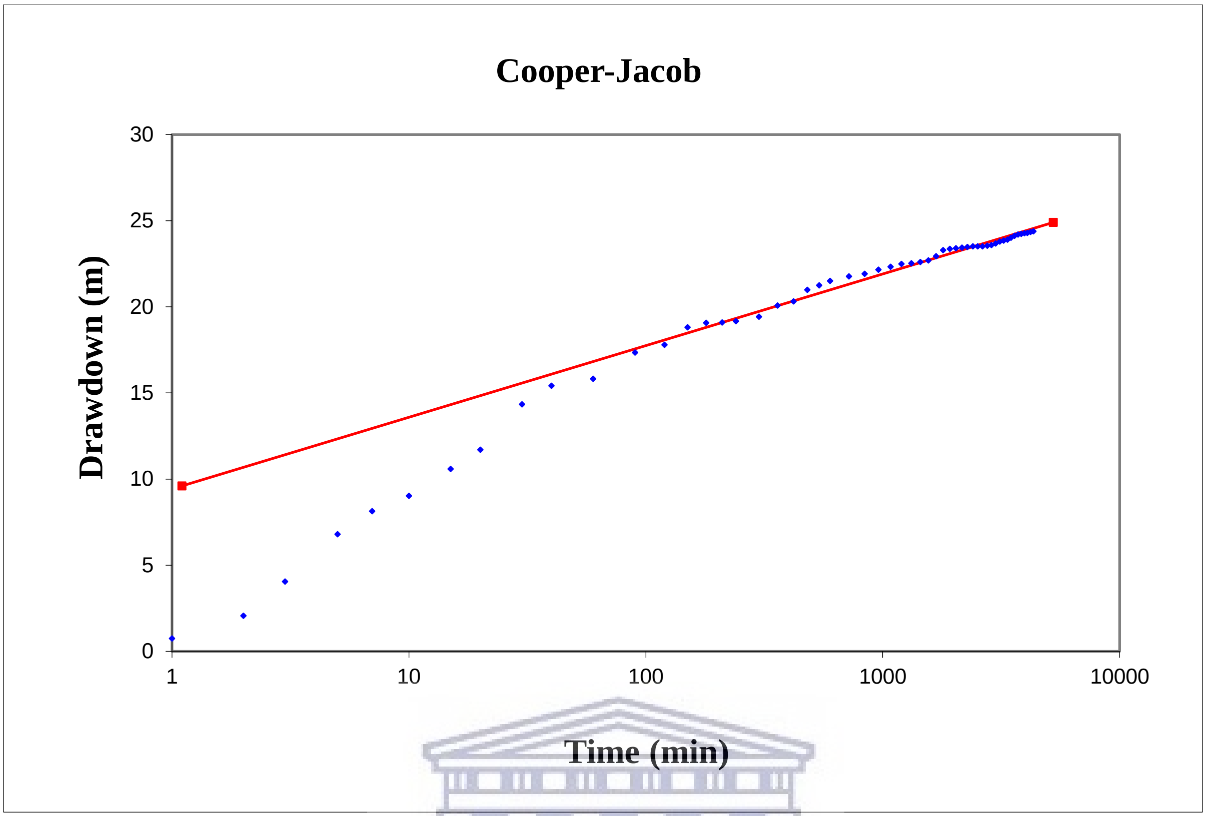


Figure 38- Borehole TA/1850 Cooper-Jacob plot showing line of best fit

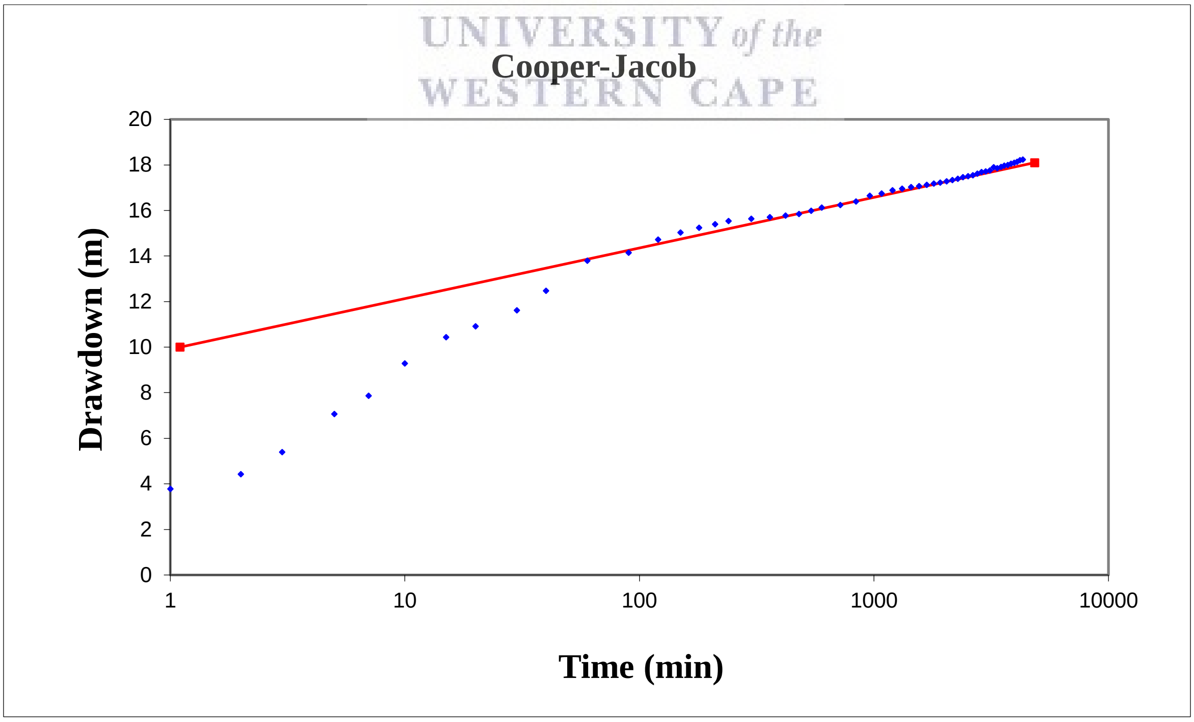


Figure 39- Borehole TB/2150 Cooper-Jacob plot showing line of best fit.

Cooper-Jacob was used for analysing the boreholes and hence used to estimate the aquifer parameters. Van Tonder (1997) stated that two types of distinctive slope exist within constant rate discharge drawdown curves: the fractures and matrix flow. Vivier and Van Tonder, (1997) also specified fractures have high T and low S while matrices have low T and high S but in the Hopefield area where the geology and pumping test results indicated a porous and unconfined aquifer, the T value here was greatly influence by the porous nature of the sand and gravel aquifer of the Elandsfontein Formation giving it its low (19.0 m^2/day) to moderate (94.5 m^2/day) values. Borehole T4/2240 had the highest T value which could be due to the dominate fine to medium grained sand that existed in this area, the sand here has a high porosity and hence a high transmissivity while borehole T2-1190 had the lowest T. This may have been caused by the fact that this well is dominated with fine grained sand making it to have low specific yield. The presence of the coarse-grained sand in well TA/1850 is also a determinant towards its high T value. The Transmissivity range of the Elandsfontein aquifer is between 10 m^2/day to 4000 m^2/day as stated by Timmerman, (1985b), therefore the acquired T values fall within the expected range, and they also correlate to the recovery T values hence the constant discharge test results can be considered as reliable.

5.4.2 Theis recovery (1935)

Table 3- Theis recovery transmissivity estimate for constant discharge test

Borehole	**Formation**	**Transmissivity (m^2/day)**
T2/1190	Elandsfontein	12.0
T3W-1510	Elandsfontein	23.0
T4/2240	Elandsfontein	66.6
TA/1850	Elandsfontein	35.0
TB/2150	Elandsfontein	14.1

The results shown in table 3 above shows recovery T values which in agreement with the constant rate pumping values. The recovery plots of the stated boreholes are presented below.

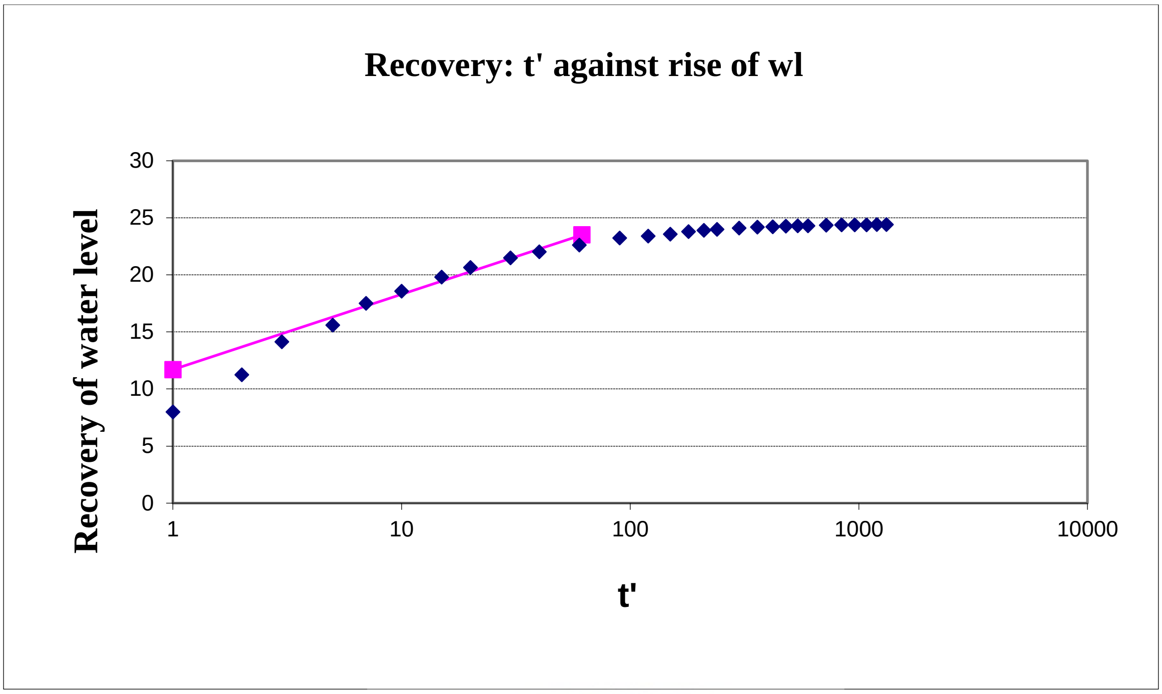


Figure 40- Recovery T plot for T2/1190

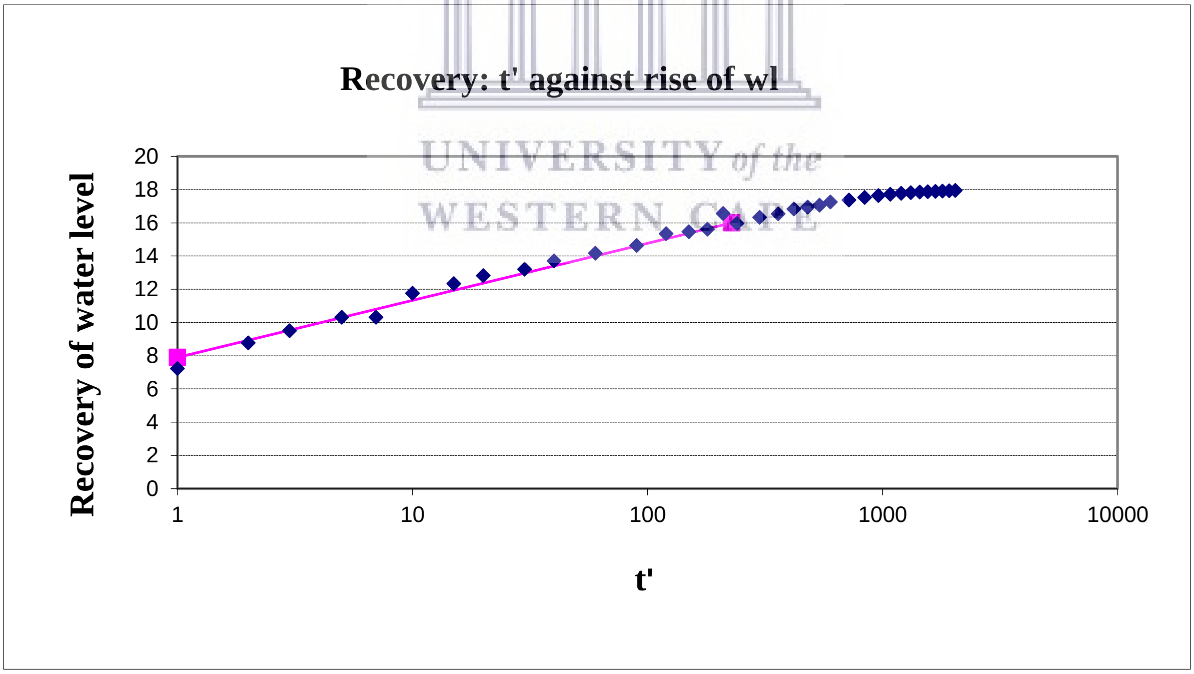


Figure 41- Recovery T plot for T3W-1510

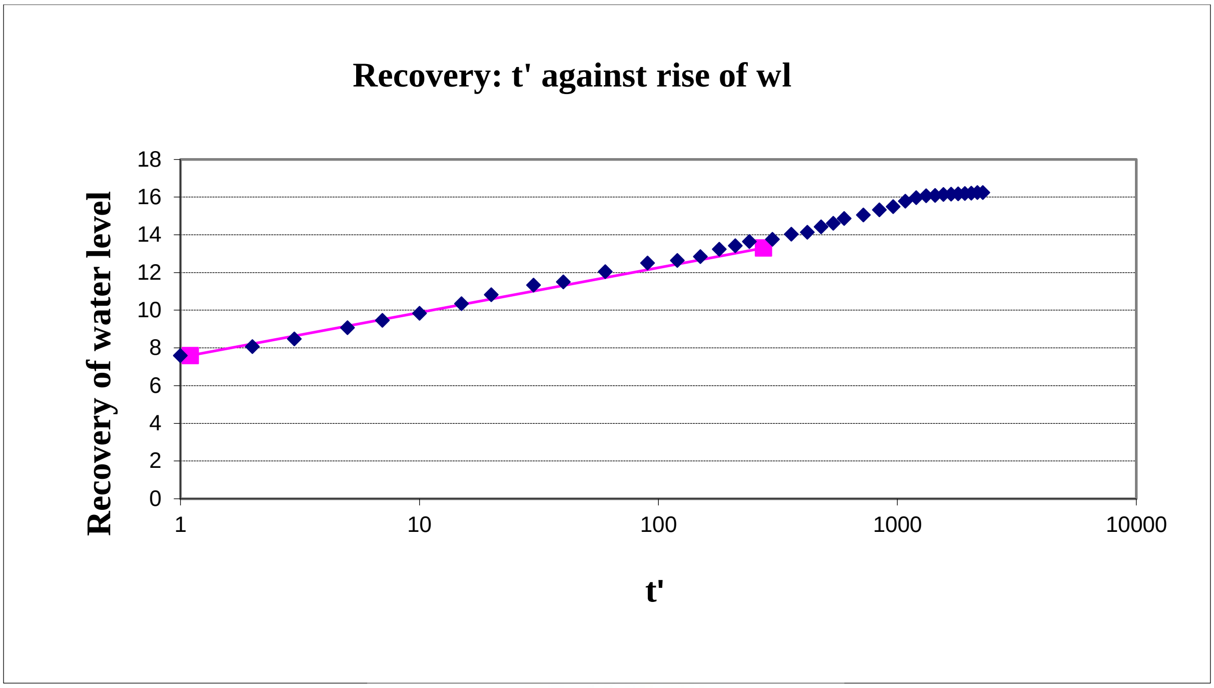


Figure 42- Recovery T plot for T4/2240

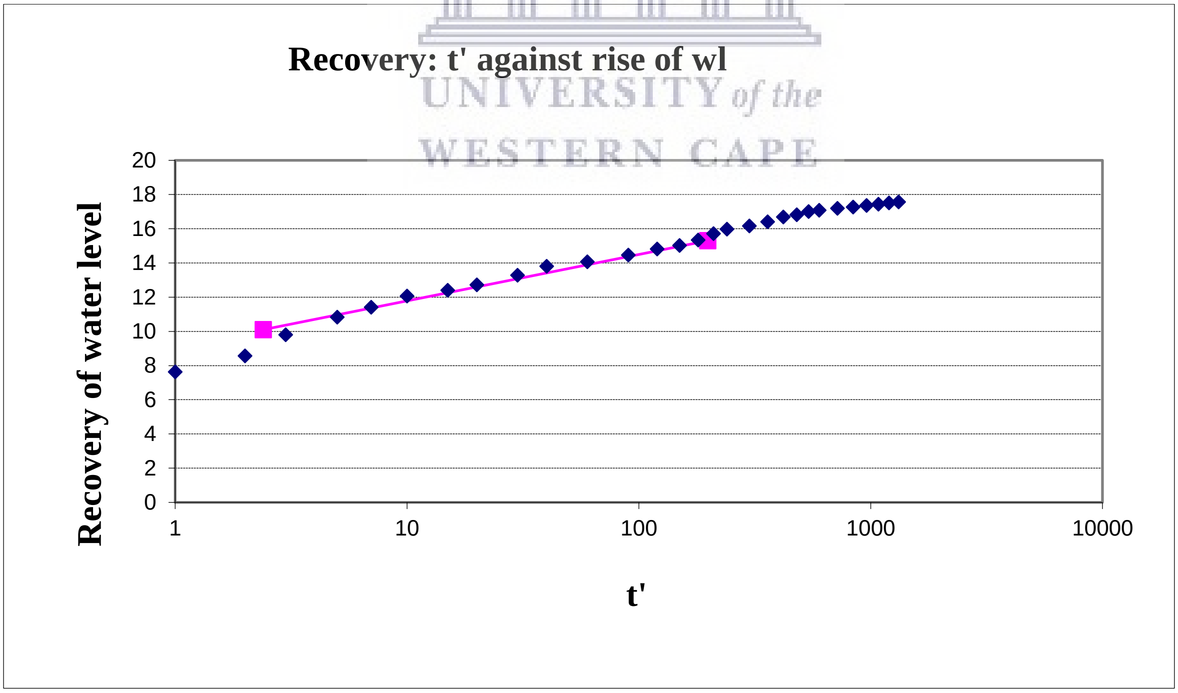


Figure 43- Recovery T plot for TA/1850

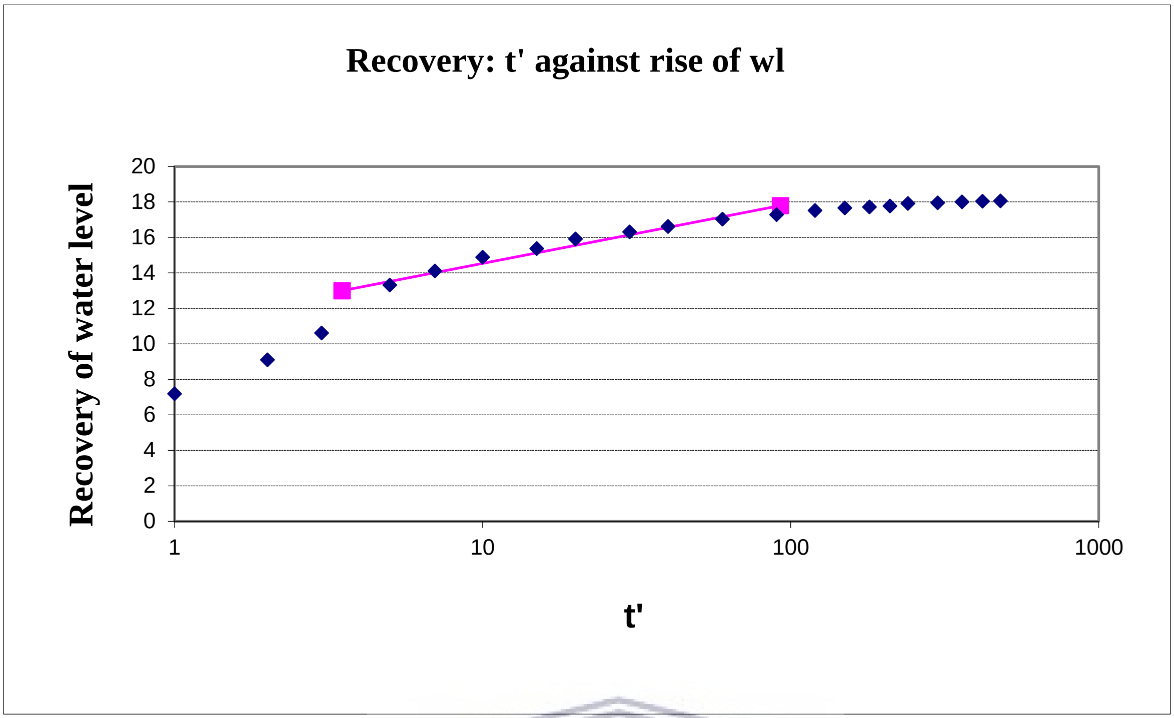


Figure 44- Recovery T plot for TB/2150

The Theis Recovery Method was applied because this method is a support method to evaluate the adequacy of the results obtained from the constant rate pumping test. It is also applied because at this point of recovery, the aquifer is not under any stress hence data from the natural flow of water that is not influenced by well bore storage or any eternal influence of flow rate can be obtained. The method indicated that the T value for T4/2240 was still high, like for the Cooper-Jacob. In other wells T values ranged between 12.0 m^2/day to 35.0 m^2/day.

Estimation of aquifer hydraulic parameters was done using constant discharge and recovery data using the Cooper-Jacob and Theis method respectively. Results from the estimation are shown in tables 2 and 3, respectively. The choice of the chosen analytical model was based on hydrogeological information, results from derivative analysis and model assumptions where strength and limitations were used as a major factor. Transmissivity and storativity were the parameters estimated with transmissivity being of particular interest as it determines the capacity of the aquifer to transmit water and this capacity depends on the yield of the aquifer (Chen, 2003). The T value obtained from the constant discharge and recovery test at borehole T2/1190 was 19 m^2/day and 12m^2/day, respectively. Comparing to Timmerman's (1985b) transmissivity range for the Elandsfontein formation, the estimated values fall within the recommended T range. Comparing the T value obtained from well T2/1190 with the classification of T magnitude by Krasny (1993), the well falls within class 3 with intermediate transmissivity magnitude, meaning that groundwater withdrawal is suitable for local water supply in areas such as small communities. The remaining 4 boreholes with T values ranging from 37.0 m^2/day to 94.5 m^2/day all fall under the intermediate transmissivity magnitude according to Krasny (1993) classification.

The volume of water that can be retained or released gives an indication of the storativity of that aquifer hence it varies depending on the type of aquifer which makes it a dimensionless quantity. Younger (2007) defined the storativity of an unconfined aquifer as the volume of water that an aquifer takes or releases from storage per unit surface area of aquifer, per unit decline in hydraulic head. Storativity values for unconfined aquifer and confined aquifer ranges between 0.01 and 0.40, and 0.00005 and 0.005 respectively (Freeze and Cherry 1979, Todd and Mays 2005). Since it gives an indication of the volume of water an aquifer can retain or release, a high storativity value gives an indication that the aquifer can takin or release high volumes of water while a low storativity value is an indication that the aquifer can take in and release low volume of water (Freeze and Cherry, 1979). The obtained storativity of the boreholes T2/1190, T3W-1510, T4/2240, TA/1850 and TB/2150 fall between 1.68E-04 and 1,18E-07 and it is within the range recommended by Timmerman (1985b) where he stated that the average storativity range of the Elandsfontein aquifer obtained from pumping test data is $3.1x10^{-3}$.

Table 4: Summary of Aquifer Parameters determined from Pumping Test Analysis.

Borehole ID	**Dominant flow regime**	**Transmissivity (m²/day) in FC program**		**Storativity**	**Comment on flow characteristics**
		Cooper-Jacob	**Theis-Recovery**		
T2/1190	Linear flow Bilinear Flow	19.0	12.0	1.68E-04	Linear & bilinear flow occurred during early and intermediate time respectively, a double porosity dip encountered around 150th to 420th min which is an indication of an unconfined aquifer. Series of oscillations indicate a change in aquifer material or presence of heterogeneity.
T3W-1510	Linear flow Bilinear Flow	37.0	23.0	1.54E-06	Linear & bilinear flow occurring, intermediate time show stabilization indicating IARF while multiple oscillations during the late time indicates variability of groundwater flow, also possibly due to different rock or aquifer type. 1-no flow boundary encountered.
T4/2240	Linear flow Bilinear Flow	94.5	66.6	1.18E-07	Multiple oscillations are clearly shown. At late time, a change in aquifer material caused a doubling in the derivative plot and this is an indication of a boundary, in this case, a hydrogeologic boundary.
TA/1850	Linear flow Bilinear Flow	50.4	35.0	1.47E-07	Clearly shows an infinite semi-confined -unconfined aquifer that is clearly heterogenous. Stabilization causing IARF around 240th – 360th min. A double porosity dip also occurs around 60th to 150th min. A sharp increase in derivative plot occurs after 1560 mins indicating a no-flow boundary.
TB/2150	Linear flow Bilinear Flow	21.4	14.1	1.21E-06	Double porosity dip is noticed with a dip around 180th-600th min and boundary condition are seen during the late time.

5.5 Determination of sustainable yield

Table 5 below summarises the borehole details, showing static water level, methods used in the determination of yield, the recommended yield and average Q. The sustainable yield was calculated using the FC Program while the recommended yield over 24-hour period was shown. The sustainable yield correlates directly with the transmissivities; higher sustainable yield was determined by high transmissivity. The average between methods would be recommended as an abstraction rate. If borehole T2/1190 is to be used for abstraction purposes for a period of two years, the average between the methods (Basic FC and Cooper-Jacob) which is 1.50 l/s would be the recommended sustainable abstraction rate for 24 hours per day. By this, the borehole may also be given time to recover and while recovering is done, monitoring and reporting should be done to also understand if a change in hydraulic behaviour is noticed as this will make sure that the sustainable yield is maintained.

Table 5- Recommended sustainable yield for boreholes in the study area

Borehole	**Static water level (mbgl**	**Method**	**Recommended sustainable yield (l/s) over 24-hour period**	**Average Q_sust (l/s)**
T2/1190	11.39	Basic FC	1.48	1.50
		Cooper-Jacob	1.51	
T3W-1510	11.89	Basic FC	1.70	1.77
		Cooper-Jacob	1.83	
T4/2240	11.36	Basic FC	6.31	5.20
		Cooper-Jacob	4.10	
TA/1850	8.77	Basic FC	1.88	2.07
		Cooper-Jacob	2.25	
TB/2150	15.48	Basic FC	1.15	1.11
		Cooper-Jacob	1.07	
TOTAL				**2.33**

5.6 Comparative analysis and implication of results for practice

The results on estimated aquifer parameters have been shown above thus addressing objective 3 of the study. The analysis and estimation were done using the Flow Characteristic (FC) method. The aim of this objective was to identify and predict if whether the boreholes are reliable enough and to improve knowledge on the estimated parameters in the Hopefield. Aquifer parameters estimated included Transmissivity (T), Storativity (S) and Sustainable yield (Sy). Pumping test data was analysed using applicable analytical solution based on geological information of the study area, derivative analysis results and the theoretical assumptions of analytical solution applied. The results revealed that the boreholes under study will perform long term because they have been drilled in a porous formation of the Elandsfontein sand and gravel aquifer with moderate transmissivity values. In addition, the study area is a zone where groundwater recharge occurs effectively due to the highly transmissive geologic materials of the Elandsfontein aquifer. With depths of up to 60m, tapping on the unconfined aquifer, groundwater from the Hopefield is suitable for local water supply in areas such as small communities and this is considered as reliable. These results were considered as reliable because studies on aquifer parameter estimation from the West Coast Aquifer System and beyond have been reviewed and were compared to the current study. It has been identified that the results from other scholars do agree with those of the current study, thus suggesting that the results are reliable. The results have contributed to the existing knowledge of aquifer hydrogeological characteristics of the Elandsfontein aquifer and the Hopefield. This will help inform decision around usage and management of the borehole and ensure sustainability. This will also prevent long term effects of abstraction from the aquifer which may impact on the storage fracture networks thus resulting to borehole failure and informing modelling for action.

5.7 Chapter summary

This chapter presented results on the understanding of the subsurface using the electrical resistivity tomography (ERT) which addressed objective 1 of the current study, flow regime identification using derivative analysis of pumping test data which addressed objective 2 of this study and the estimation of aquifer hydraulic parameters where transmissivity and storativity values were estimated using the Cooper-Jacob method embedded in the flow characteristic method. Sustainable yield of the boreholes under study were also computed using the Basic FC and Cooper-Jacob method. The main aim of the study was to improve understanding of the flow dynamics in the Hopefield area using hydrogeophysics and derivative analysis and confirming the reliability of the Flow Characteristic (FC) method in addressing aquifer complexities.

The argument in this chapter is that if the hydrogeological and hydrogeophysical conditions of an aquifer system are understood prior to selecting the analytical model of analysis, then reliable information on the type of aquifer, complexities that exist within the aquifer system and estimates of aquifer parameters to understand aquifer productivity will be obtained. Results obtained suggested that boreholes were drilled in porous sand and gravel aquifer of the Elandsfontein Formation in the West Coast Aquifer System. The derivative plots and drawdown behaviour portrayed a linear and bilinear flow regime, double porosity, and unconfined aquifer behaviour. A linear flow occurs in channelized aquifers, fractured or porous wells and horizontal well while a bilinear flow occurs also in fractured or porous wells. Channelized aquifer occurs mainly as a permeable body between two parallel no-flow boundaries, and this can be seen. In the Hopefield area, the porous nature of the sand and gravel aquifer gave rise to the channelized nature of the system as indicated in the log-log plot while a flow boundary occurring is also evident shown in the bi-log plots above.

Double porosity or unconfined aquifer behaviour was portrayed by the stabilization of drawdown during mid-time of pumping, suggesting that the matrix blocks feed the porous opening made by the gravels with water at an increasing rate. Gomo, (2011) stated that the dip in the drawdown derivative plot of a channelized system (sand and gravel) is caused by the rapid release of water hence it shows like a recharge boundary. Van Tonder 2001 also stated that the dip in the derivative plot after the wellbore storage is often because of the double porosity behaviour of the aquifer or possibly a recharge boundary. However, in the Hopefield, the decrease in the derivative plot is because of the quantitative groundwater supply from the sand and gravel aquifer system. The activity of wellbore storage cannot be seen in any of the boreholes in this study because of the high-transmissivity value of the sand and gravel aquifer. Although, the transmissivity of the wells used in this study were significantly influenced by the fracturing (dewatering) of the system hence its low to moderate values. These findings are supported by Gomo 2001, Van Tonder et. al, (2001), Renard et al (2009), Holland et al., (2011) and Ferroud et al., (2018).

CHAPTER 6: CONCLUSION AND RECOMMENDATION

This chapter provides the conclusion and recommendations based on the findings. The research question was to checkmate the advantages of using hydrogeophysics data and derivative analysis for aquifer hydrogeological characterization and the results from this study has answered the research question. The results have been summarised objective by objective.

The first objective was to establish the aquifer units in the Hopefield using geological information and hydrogeophysics data. The electrical resistivity tomography was used as the chosen method to achieve this stated objective and it is concluded that the study area is underlined by the sand and gravel aquifer of the Elandsfontein aquifer. This was seen from the geophysics resistivity model, historical geological and geophysical information and borehole logs obtained from the drilling. It is evident that the high voltages on the image represented low resistivities which indicated the presence of water i.e., aquifer while the low voltages represented high resistivities represented other geological materials like clay and shale. This is true water has a high conductivity which means that it allows current to flow, so inversely, it will have a low resistivity. The total of 2 distinctive layers were noticed in the resistivity model-fine to coarse grained sand layer and clay intercalated with sand layer. The results have shown the usefulness of the resistivity method alongside geological information in characterizing subsurface.

The second objective was to determine aquifer flow regime and boundary conditions present in the Hopefield using the derivative analysis of pumping test data. The Flow Characteristic method was used in this objective, and it was successful in delineating the different flow regimes and boundary that existed in the Hopefield area. From the derivative plots shown in figures 22, 25, 28, 31 and 34, the dominant flow regime was linear and bilinear flow which occurred during early and intermediate time respectively. Boundary conditions occurred during the late time and in this case, a no flow boundary was seen, due to the doubling of slope in the semi-log plot. The series of oscillations shown in the bi-log plot indicated a change in aquifer material or presence of heterogeneity. This also showed that there is variability in the flow of groundwater as it moves from one geologic material (different rock or aquifer type) to the other.

The third objective was to estimate aquifer hydraulic parameters in order to assess the impact of pumpage on the groundwater flow regime. It also gives way to reliable information on the aquifer which in turn enables proper management practices. The Flow Characteristic Method was used for the estimation while data were analysed using applicable analytical solution based on their theoretical assumptions. Parameters estimated include Transmissivity (T), Storativity (S) and Sustainable yield (Sy). Transmissivity and storativity values for study area are within the T and S range suggested for the Elandsfontein formation. Furthermore, the results revealed that the low to moderate transmissivity values obtained from the study area were assumed to be due to the low porous nature of clay and the quarzitic geological materials that intercalates the fine to medium sand and gravel aquifer.

Another reason is that when a fracture is dewatered, a change of aquifer system has occurred from confined (or semi-confined) to unconfined due to the dewatering and this results in a decrease in the T-value (the slope in the diagnostic plots before and after reaching the fracture position is normally not the same). However due to the porous nature of the Elandsfontein aquifer, it has been proven to have a bulk water supply for various uses within the West Coast Aquifer System. Moderate storativity values were obtained from the Hopefield area and this was assumed to be due to the presence of clayey and fine-grained sandy materials within the Elandsfontein aquifer. Transmissivity values for the study area have an intermediate range and this means that the groundwater withdrawal is suitable for local water supply in areas such as small communities.

Borehole T4/2240 and TA/1850 has unique Transmisivity (T) value of 94.5 m^2/day and 50.4 m^2/day respectively with depths of 60m and 50m respectively. This indicates that these boreholes were likely drilled in the paleochannels of the Elandsfontein sand and gravel. Since this paleochannel runs along the coastline and releases into the Atlantic Ocean, it signifies that groundwater in the study area flows along the axis of the paleochannels in a Southwest direction and controlled mainly by the bedrock topography. Results from the models must inform intervention, must provide information to solve problem and must be solution based. Before such models are developed, input data must be complete. Leaving out data from geophysics survey and derivative analysis in modelling will results in choosing groundwater models that will produce results for academic knowledge only but may not provide information to solve practical problem hence we advocate for solution-based modelling.

Recommendations for future research

- The flow characteristic method has proven to be successful in the identification of important flow regimes encountered during the pumping test, highlighting heterogeneity in the aquifer system or detection of aquifer boundaries and detection of the no flow boundary condition in the study area hence the method is universal and should be used further in the study area to describe the extent of the no-flow boundary and how it affects groundwater movement.
- Since no sufficient information relating to the hydraulic nature and extensiveness of this no flow boundary which divides the LRAU and the EAU exist, it is recommended that more research is conducted using the magnetic and electrical geophysical methods to delineate the missing information.

References

Adagunodo, T. A., Akinloye, M. K., Sunmonu, L. A., Aizebeokhai, A. P., Oyeyemi, K. D., & Abodunrin, F. O. (2018). Groundwater exploration in Aaba residential area of Akure, Nigeria. *Frontiers in Earth Science*, *6*, 66.

Adelana, S. M. A. (2008). Groundwater research issues in Africa. Applied groundwater studies in Africa. SMA Adelana and AM MacDonald.

Al Farajat, M. (2009). Characterization of a coastal aquifer basin using gravity and resistivity methods: a case study from Aqaba in Jordan. *Acta Geophysica*, *57*(2), 454-475.

Aladejana, J. A., Kalin, R. M., Sentenac, P., & Hassan, I. (2020). Hydrostratigraphic Characterisation of Shallow Coastal Aquifers of Eastern Dahomey Basin, S/W Nigeria, Using Integrated Hydrogeophysical Approach; Implication for Saltwater Intrusion. *Geosciences*, *10*(2), 65.

Alexander, M., Berg, S. J., & Illman, W. A. (2011). Field study of hydrogeologic characterization methods in a heterogeneous aquifer. *Groundwater*, *49*(3), 365-382.

Al-Fares, W. (2011). Contribution of the geophysical methods in characterizing the water leakage in Afamia B dam, Syria. *Journal of Applied Geophysics*, *75*(3), 464-471.

Al-Khafaji, W. M. S. (1999). *A geophysical study to evaluate the groundwater reserve and structural situation of south Sinjar anticline region–NW Iraq* (Doctoral dissertation, University of Baghdad).

Andersen, M. S., & Acworth, R. I. (2009). Stream-aquifer interactions in the Maules creek catchment, Namoi valley, New South Wales, Australia. *Hydrogeology Journal*, *17*(8), 2005-2021.

Andersen, T. R., Poulsen, S. E., Christensen, S., & Jørgensen, F. (2013). A synthetic study of geophysics-based modelling of groundwater flow in catchments with a buried valley. *Hydrogeology Journal*, *21*(2), 491-503.

Andersen, T. R., Poulsen, S. E., Thomsen, P., & Havas, K. (2018). Geological characterization in urban areas based on geophysical mapping: a case study from Horsens, Denmark. *Journal of Applied Geophysics*, *150*, 338-349.

Anderson, E. I., & Bakker, M. (2008). Groundwater flow through anisotropic fault zones in multiaquifer systems. *Water Resources Research*, *44*(11).

Anderson, M. P., & Woessner, W. W. (1992). Applied groundwater modeling: Simulation of flow and Advection transport Academic Press. *San Diego, New York Boston*.

Asfahani, J. (2012). Quaternary aquifer transmissivity derived from vertical electrical sounding measurements in the semi-arid Khanasser Valley Region, Syria. *Acta Geophysica*, *60*(4), 1143-1158.

Attandoh, N., Yidana, S. M., Abdul-Samed, A., Sakyi, P. A., Banoeng-Yakubo, B., & Nude, P. M. (2013). Conceptualization of the hydrogeological system of some sedimentary aquifers in Savelugu–Nanton and surrounding areas, Northern Ghana. *Hydrological Processes*, *27*(11), 1664-1676.

Attwa, M., & Ali, H. (2018). Resistivity Characterization of Aquifer in Coastal Semiarid Areas: An Approach for Hydrogeological Evaluation. In *Groundwater in the Nile Delta* (pp. 213-233). Springer, Cham.

Ayolabi, E. A., Folorunso, A. F., Odukoya, A. M., & Adeniran, A. E. (2013). Mapping saline water intrusion into the coastal aquifer with geophysical and geochemical techniques: the University of Lagos campus case (Nigeria). *SpringerPlus*, *2*(1), 1-14.

Babu, S. D., Hindi, E., Da Rosa Filho, E., & Bittencourt, A. (2002). Characteristics of Valadares Island aquifer, Paranagua coastal plain, Brazil. *Environmental Geology*, *41*(8), 954-959.

Balia, R., Gavaudo, E., Ardau, F., & Ghiglieri, G. (2003). Geophysical approach to the environmental study of a coastal plain. *Geophysics*, *68*(5), 1446-1459.

Beauheim, R. L., & Pickens, J. F. (1986, May). Applicability of pressure derivative to hydraulic test analysis. In *poster session at the Annual Meeting of America Geophysical Union, Baltimore, Maryland*.

Beauheim, RL, Roberts, RM, & Avis, JD (2004). Well testing in fractured media: flow dimensions and diagnostic plots. *Journal of Hydraulic Research* , *42* (S1), 69-76.

Berrios, R., & Lucca, N. (2006). Qualitative methodology in counseling research: Recent contributions and challenges for a new century. *Journal of Counseling & Development*, *84*(2), 174-186.

Betancur, T, Carlos, T., and John M. (2012) Conceptual models in hydrogeology, methodology and results." hydrogeology - A global perspective.

Boucher, M., Favreau, G., Descloitres, M., Vouillamoz, J. M., Massuel, S., Nazoumou, Y., ... & Legchenko, A. (2009). Contribution of geophysical surveys to groundwater modelling of a porous aquifer in semiarid Niger: An overview. *Comptes Rendus Geoscience*, *341*(10-11), 800-809.

Bourdet, D. (2002). *Well test analysis: The use of advanced interpretation models*. Elsevier.

Bourdet, D., Ayoub, J. A., & Pirard, Y. M. (1989). Use of pressure derivative in well test interpretation. *SPE Formation Evaluation*, *4*(02), 293-302.

Bourdet, D., Ayoub, J. A., Kniazeff, V., Pirard, Y. M., & Whittle, T. M. (1983b). Interpreting well tests in fractured reservoirs. *World Oil;(United States)*, *197*(5).

Bourdet, D., Whittle, T. M., Douglas, A. A., & Pirard, Y. M. (1983a). A new set of type curves simplifies well test analysis. *World oil*, *196*(6), 95-106.

Bruckshaw, J. M. (1967). Principles of Direct Current Resistivity Prospecting Geza Kunetz (Gebriider Borntraeger, Berlin, 1966, pp. 103+ xvi).

Bruntland, G. (1987). Our common future. *The World Commission on Environment 1 and Development*, 45-65.

Busari, O., & Mutamba, J. (2014). Groundwater development for localized water supply in South Africa. *Journal of Medical and Bioengineering, 3*(4).

Calvache, M. L., Duque, C., Fontalva, J. G., & Crespo, F. (2011). Processes affecting groundwater temperature patterns in a coastal aquifer. *International Journal of Environmental Science & Technology, 8*(2), 223-236.

Casas, A., Himi, M., Diaz, Y., Pinto, V., Font, X., & Tapias, J. C. (2008). Assessing aquifer vulnerability to pollutants by electrical resistivity tomography (ERT) at a nitrate vulnerable zone in NE Spain. *Environmental Geology, 54*(3), 515-520.

Chabaane, A., Redhaounia, B., Gabtni, H., & Amiri, A. (2018). Contribution of geophysics to geometric characterization of freshwater–saltwater interface in the Maâmoura region (NE Tunisia). *Euro-Mediterranean Journal for Environmental Integration, 3*(1), 1-8

Chachadi, A. G., & Gawas, P. (2012). Correlation study between geoelectrical and aquifer parameters in West coast laterites.

Chalikakis, K. (2006). *Application of geophysical methods for the recognition and protection of water resources in karst environments* (Doctoral dissertation, Université Pierre et Marie Curie-Paris VI).

Chandra, P. C. (2019). *Groundwater geophysics in hard rock*. CRC Press.

Chapuis, RP., Belanger, C., Chenaf, D., 2006. Pumping test in a confined aquifer under tidal influence. Groundwater 44(2), pp. 300–305.

Choudhury, K., Saha, D. K., & Chakraborty, P. (2001). Geophysical study for saline water intrusion in a coastal alluvial terrain. *Journal of applied geophysics, 46*(3), 189-200.

Chow, V. T. (1952). On the determination of transmissibility and storage coefficients from pumping test data. *Eos, Transactions American Geophysical Union, 33*(3), 397-404.

Clark, I. D., & Fritz, P. (1997). Environmental Isotopes in Hydrology Lewis Publishers. *Boca Raton, New York.*

Cole, D. I., & Roberts, D. L. (1996). Lignite from the western coastal plain of South Africa. *Journal of African Earth Sciences*, *23*(1), 95-117.

Conrad, J., Nel, J., & Wentzel, J. (2004). The challenges and implications of assessing groundwater recharge: A case study northern Sandveld, Western Cape, South Africa. *Water SA*, *30*(5), 75-81.

Conrad, J., Smit, L., Murray, K., van Gend-Muller, J., & Seyler, H. (2019). The Malmesbury Group-an aquifer of surprising significance. *South African Journal of Geology 2019*, *122*(3), 331-342.

Cooper Jr, H. H., & Jacob, C. E. (1946). A generalized graphical method for evaluating formation constants and summarizing well-field history. *Eos, Transactions American Geophysical Union*, *27*(4), 526-534.

Copty, N. K., Trinchero, P., & Sanchez-Vila, X. (2011). Inferring spatial distribution of the radially integrated transmissivity from pumping tests in heterogeneous confined aquifers. *Water Resources Research*, *47*(5).

Creswell, J. W., & Clark, V. L. P. (2017). *Designing and conducting mixed methods research*. Sage publications.

Dahlin, T., & Zhou, B. (2006). Multiple-gradient array measurements for multichannel 2D resistivity imaging. *Near Surface Geophysics*, *4*(2), 113-123.

De La Cruz, M. A. (1978). Marine Geophysical and Geological Investigations in Saldanha Bay. Joint Geological Survey, University of Cape Town, Marine Geoscience Group. *Bulletin, 9*.

Department of Water Affairs and Forestry, South Africa. (2008) The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related

Models: Groundwater Model Report Volume 6 – Langebaan Road and Elandsfontein Aquifer System Model.

Diamantopoulou, P., & Voudouris, K. (2008). Optimization of water resources management using SWOT analysis: the case of Zakynthos Island, Ionian Sea, Greece. *Environmental geology*, *54*(1), 197-211.

Dickson, N. E., Comte, J. C., Renard, P., Straubhaar, J. A., McKinley, J. M., & Ofterdinger, U. (2015). Integrating aerial geophysical data in multiple-point statistics simulations to assist groundwater flow models. *Hydrogeology Journal*, *23*(5), 883-900.

Dippenaar, M. A. (2008). *Characterisation of some fractured-rock aquifers in Limpopo province, South Africa: review and case study* (Doctoral dissertation, University of Pretoria).

Djebbar, T., & Anil, K. (1980). Application of the p'D Function to Interference Analysis. *Journal of Petroleum Technology*, *32*(08), 1465-1470.

Du Plessis, J. A. (2009). Managing the unseen: Langebaan Road aquifer system. *Water SA*, *35*(2).

Duque, C., Calvache, M. L., Pedrera, A., Martín-Rosales, W., & López-Chicano, M. (2008). Combined time domain electromagnetic soundings and gravimetry to determine marine intrusion in a detrital coastal aquifer (Southern Spain). *Journal of Hydrology*, *349*(3-4), 536-547.

Ehlig-Economides, C. (1988). Use of the pressure derivative for diagnosing pressure-transient behavior. *Journal of Petroleum Technology*, *40*(10), 1280-1282.

Ehlig-Economides, C. A. (1994, August). Applications for multiphase compartmentalized material balance. In *University of Tulsa Centennial Petroleum Engineering Symposium*. OnePetro..

Ehlig-Economides, C. A., Hegeman, P., & Vik, S. (1994). Well testing-1: Guidalines simplify well test interpretation. *Oil & gas journal*, *92*(29), 33-40.

Engdahl, N. B., Weissmann, G. S., & Bonal, N. D. (2010). An integrated approach to shallow aquifer characterization: combining geophysics and geostatistics. *Computational Geosciences*, *14*(2), 217-229.

Escobar, F. H., Rojas, M. M., & Bonilla, L. F. (2012). Transient-rate analysis for long homogeneous and naturally fractured reservoir by the TDS technique. *Journal of Engineering and Applied Sciences*, *7*(3), 353-370.

Esu, E. O., Okereke, C. S., & Edet, A. E. (1999). A regional hydrostratigraphic study of Akwa Ibom State, southeastern Nigeria. *Global Journal of Pure and Applied Sciences*, *5*, 89-96.

Falgàs, E., Ledo, J., Benjumea, B., Queralt, P., Marcuello, A., Teixidó, T., & Martí, A. (2011). Integrating hydrogeological and geophysical methods for the characterization of a deltaic aquifer system. *Surveys in Geophysics*, *32*(6), 857-873.

Fernandez-Garcia, D., Trinchero, P., and Sanchez-Vila, X. (2010). Conditional stochastic mapping of transport connectivity, Water Resources. Res., 46, formation of a research strategy. WRC report, 158(1), pp. 9-18.

Ferroud, A., Chesnaux, R., & Rafini, S. (2015, September). Pumping test diagnostic plots for the investigation of flow patterns in complex aquifers: numerical results. In *42nd IAH international congress BHydrogeology: Back to the Future* (pp. 13-18).

Ferroud, A., Chesnaux, R., & Rafini, S. (2016, September). Numerical investigations of the spherical flow regimes induced by constant-rate pumping tests. In *43rd IAH Congress, September* (pp. 25-29).

Ferroud, A., Chesnaux, R., & Rafini, S. (2018). Insights on pumping well interpretation from flow dimension analysis: The learnings of a multi-context field database. *Journal of hydrology*, *556*, 449-474.

Ferroud, A., Rafini, S., & Chesnaux, R. (2019). Using flow dimension sequences to interpret non-uniform aquifers with constant-rate pumping-tests: a review. *Journal of Hydrology X*, *2*, 100003.

Fourie, F. D., Huber, M. S., & Kovaleva, E. (2019). Geophysical characterization of the Daskop granophyre dyke and surrounding host rocks, Vredefort impact structure, South Africa. *Meteoritics & Planetary Science*, *54*(7), 1579-1593.

Francés, A. P., Ramalho, E. C., Fernandes, J., Groen, M., Hugman, R., Khalil, M. A., ... & Santos, F. A. M. (2015). Contributions of hydrogeophysics to the hydrogeological conceptual model of the Albufeira-Ribeira de Quarteira coastal aquifer in Algarve, Portugal. *Hydrogeology Journal*, *23*(7), 1553-1572.

Frohlich, K., Frohlich, W., & Wittenberg, H. (1994). Determination of groundwater recharge by baseflow separation: regional analysis in northeast China. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences*, *221*, 69-76.

Galazoulas, E. C., Mertzanides, Y. C., Petalas, C. P., & Kargiotis, E. K. (2015). Large scale electrical resistivity tomography survey correlated to hydrogeological data for mapping groundwater salinization: a case study from a multilayered coastal aquifer in Rhodope, Northeastern Greece. *Environmental processes*, *2*(1), 19-35.

Gao, Q., Shang, Y., Hasan, M., Jin, W., & Yang, P. (2018). Evaluation of a weathered rock aquifer using ERT method in South Guangdong, China. *Water*, *10*(3), 293.

Garin, T., Arfib, B., Dewandel, B., Ladouche, B., & Goncalves, J. (2019, June). Improving pumping tests interpretation in carbonate aquifers with diagnostic plot method. In *27th International Karstological School" Classical Karst"*.

GEOSS, (2010). Geohydrological Prospecting scoping report for a phosphate prospecting permit application, Elandsfontein No 349, Malmesbury Magisterial District, West Coast. GEOSS project no 2010/07-623

Goldman, M., & Neubauer, F. M. (1994). Groundwater exploration using integrated geophysical techniques. *Surveys in geophysics*, *15*(3), 331-361.

Gomo, M. (2011). A groundwater-surface water interaction study of an alluvial channel aquifer (Doctoral dissertation, University of the Free State).

Gomo, M., Van Tonder, G. J., & Steyl, G. (2013). Investigation of the hydrogeochemical processes in an alluvial channel aquifer located in a typical Karoo Basin of Southern Africa. *Environmental earth sciences*, *70*(1), 227-238.

Goode, D. J. (1997). Composite recovery type curves in normalized time from Theis' exact solution. *Groundwater*, *35*(4), 672-677.

Government of South Africa. (2016) "Water and Sanitation." Water and Sanitation Reports.

Gringarten, A. C. (2008). From straight lines to deconvolution: The evolution of the state of the art in well test analysis. *SPE Reservoir Evaluation & Engineering*, *11*(01), 41-62.

Günther, T., & Rücker, C. (2012). Electrical Resistivity Tomography (ERT) in geophysical applications-state of the art and future challenges. In *Schlumberger Symposium--100 years of electrical imaging, Paris,(January)*.

Hamill, L., & Bell, F. G. (2013). *Groundwater resource development*. Elsevier.

Hammond, P. A., & Field, M. S. (2014). A reinterpretation of historic aquifer tests of two hydraulically fractured wells by application of inverse analysis, derivative analysis, and diagnostic plots. *Journal of Water Resource and Protection*, *2014*.

Hantush, M. S. (1960). Modification of the theory of leaky aquifers. *Journal of Geophysical Research*, *65*(11), 3713-3725.

Hauck, C., & Kneisel, C. (2008). *Applied geophysics in periglacial environments*. Cambridge University Press.

Hay, ER, K Riemann, G Van Zyl, and I Thompson. (2012) Ensuring water supply for all towns and villages in the Eastern Cape and Western Cape Provinces of South Africa. *Water SA* 38, no. 3.

Hendey, O. B. (1981). Palaeoecology of the late Tertiary fossil occurrences in" E" Quarry, Langebaanweg, South Africa, and a reinterpretation of their geological context.

Hendey, Q. B. (1974). Faunal dating of the late Cenozoic of Southern Africa, with special reference to the Carnivora. *Quaternary Research*, *4*(2), 149-161.

Hendey, Q. B. (1974). The late Cenozoic Carnivora of the south-western Cape Province. Annals. S. *Afr. Mus*, *63*.

Hendey, Q. B. (1981). Geological succession at Langebaanweg, Cape Province, and global events of the late Tertiary. *South African Journal of Science*, *77*(1), 33-38.

Hernández-Espriú, A., Castro-Herrera, I., Zapata-Norberto, B., Arias-Paz, A., Luna-Izazaga, G., Salinas-Calleros, G., ... & Villegas-Díaz, A. (2016). Channel-Aquifer width estimation from pumping test data: a simple approach using oil reservoir techniques.

Himi, M., Tapias, J., Benabdelouahab, S., Salhi, A., Rivero, L., Elgettafi, M., ... & Casas, A. (2017). Geophysical characterization of saltwater intrusion in a coastal aquifer: The case of Martil-Alila plain (North Morocco). *Journal of African Earth Sciences*, *126*, 136-147.

Hodlur, G., Prakash, R. M., Deshmukh, S., & Singh, V. (2002). Role of some salient geophysical, geochemical, and hydrogeological parameters in the exploration of fresh groundwater in a brackish terrain. *Environmental Geology*, *41*(7), 861-866.

Holland, M. (2011). *Hydrogeological characterisation of crystalline basement aquifers within the Limpopo Province, South Africa* (Doctoral dissertation, University of Pretoria).

Ibraheem, I. M., El-Qady, G. M., & ElGalladi, A. (2016). Hydrogeophysical and structural investigation using VES and TDEM data: a case study at El-Nubariya–Wadi El-Natrun area, west Nile Delta, Egypt. *NRIAG Journal of Astronomy and Geophysics*, *5*(1), 198-215.

Indelman, P., 2003. Transient pumping well flow in weakly heterogeneous formations, Water Resources Journal, 39(10), pp. 1287

Jovanovic, N., Bugan, R. D., Tredoux, G., Israel, S., Bishop, R., & Marinus, V. (2017). Hydrogeological modelling of the Atlantis aquifer for management support to the Atlantis Water Supply Scheme. *Water SA*, *43*(1), 122-138.

Kafri, U., & Goldman, M. (2005). The use of the time domain electromagnetic method to delineate saline groundwater in granular and carbonate aquifers and to evaluate their porosity. *Journal of Applied Geophysics*, *57*(3), 167-178.

Karasaki, K., Long, J. C. S., & Witherspoon, P. A. (1988). Analytical models of slug tests. *Water Resources Research*, *24*(1), 115-126.

Keller, G. V., & Frischknecht, F. C. (1966). Electrical methods in geophysical prospecting.

Kelly, W. E. (1977). Geoelectric sounding for estimating aquifer hydraulic conductivity. *Groundwater*, *15*(6), 420-425.

Kemna, A., Binley, A., Day-Lewis, F., Englert, A., Tezkan, B., Vanderborght, J., ... & Winship, P. (2006). Solute transport processes. In *Applied Hydrogeophysics* (pp. 117-159). Springer, Dordrecht.

Kemna, A., Vanderborght, J., Kulessa, B., & Vereecken, H. (2002). Imaging and characterisation of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models. *Journal of hydrology*, *267*(3-4), 125-146.

Keskinocak, P., & Tayur, S. (2001). Quantitative analysis for internet-enabled supply chains. *Interfaces*, *31*(2), 70-89.

Klee, P. (2013) Greater water security with groundwater. Groundwater mapping and sustainable groundwater management. The Rethink Water network and Danish Water Forum, Copenhagen.

Koefoed, O. (1979). Geosounding principles, 1, Methods in Geochemistry and Geophysics, 14 A.

Kotze, J. C. (2002). *Hydrogeology of the Table Mountain Sandstone aquifer–Klein Karoo. Unpub* (Doctoral dissertation, PhD Thesis).

Kpegli, K. A. R., Alassane, A., van der Zee, S. E., Boukari, M., & Mama, D. (2018). Development of a conceptual groundwater flow model using a combined hydrogeological, hydrochemical and isotopic approach: A case study from southern Benin. *Journal of Hydrology: Regional Studies*, *18*, 50-67.

Krásný, J. (1993). Classification of transmissivity magnitude and variation. *Groundwater*, *31*(2), 230-236.

Krivochieva, S., & Chouteau, M. (2003). Integrating TDEM and MT methods for characterization and delineation of the Santa Catarina aquifer (Chalco Sub-Basin, Mexico). *Journal of Applied Geophysics*, *52*(1), 23-43.

Kruseman, G. P., De Ridder, N. A., & Verweij, J. M. (1970). *Analysis and evaluation of pumping test data* (Vol. 11, p. 200). The Netherlands: International institute for land reclamation and improvement.

Lasher, C. (2011). *Application of fluid electrical conductivity logging for fractured rock aquifer characterisation at the University of the Western Cape's Franschhoek and Rawsonville research sites* (Doctoral dissertation, University of the Western Cape).

Lee, BS., Song, S.H., Kim, J.S., Um, J.Y., Nam, K., 2014. Availability of coastal groundwater discharge as an alternative water resource in a large-scale reclaimed land, Korea. Environ Earth Sci 71(4), pp. 1521–1532

Logan, J. (1964). Estimating transmissibility from routine production tests of water wells. *Groundwater*, *2*(1), 35-37.

Loke, M. H., Acworth, I., & Dahlin, T. (2001). A comparison of smooth and blocky inversion methods in 2-D electrical imaging surveys. *ASEG Extended Abstracts*, *2001*(1), 1-4.

Ma, J., Zhou, Z., Guo, Q., Zhu, S., Dai, Y., & Shen, Q. (2019). Spatial characterization of seawater intrusion in a coastal aquifer of Northeast Liaodong Bay, China. *Sustainability*, *11*(24), 7013.

Maillet, R. (1947). The fundamental equations of electrical prospecting. *Geophysics*, *12*(4), 529-556.

Maliva, R. G. (2016). *Aquifer characterization techniques*. Berlin: Springer.

Marescot, L., Rigobert, S., Lopes, S. P., Lagabrielle, R., & Chapellier, D. (2006). A general approach for DC apparent resistivity evaluation on arbitrarily shaped 3D structures. *Journal of Applied Geophysics*, *60*(1), 55-67.

Martorana, R., Lombardo, L., Messina, N., & Luzio, D. (2014). Integrated geophysical survey for 3D modelling of a coastal aquifer polluted by seawater. *Near Surface Geophysics*, *12*(1), 45-59.

Masciopinto, C., Liso, I. S., Caputo, M. C., & De Carlo, L. (2017). An integrated approach based on numerical modelling and geophysical survey to map groundwater salinity in fractured coastal aquifers. *Water*, *9*(11), 875.

Massoud, U., Santos, F., Khalil, M. A., Taha, A., & Abbas, A. M. (2010). Estimation of aquifer hydraulic parameters from surface geophysical measurements: a case study of the Upper Cretaceous aquifer, central Sinai, Egypt. *Hydrogeology Journal*, *18*(3), 699-710.

Meier, P. M., Carrera, J., & Sánchez-Vila, X. (1998). An evaluation of Jacob's method for the interpretation of pumping tests in heterogeneous formations. *Water Resources Research, 34*(5), 1011-1025.

Meier, P., Kalscheuer, T., Podgorski, J. E., Kgotlhang, L., Green, A. G., Greenhalgh, S., ... & Ntibinyane, O. (2014). Hydrogeophysical investigations in the western and north-central Okavango Delta (Botswana) based on helicopter and ground-based transient electromagnetic data and electrical resistance tomography. *Geophysics*, *79*(5), B201-B211.

Meju, M. A., Gallardo, L. A., & Mohamed, A. K. (2003). Evidence for correlation of electrical resistivity and seismic velocity in heterogeneous near-surface materials. *Geophysical Research Letters*, *30*(7).

Merriam, S. B. (1998). *Qualitative Research and Case Study Applications in Education. Revised and Expanded from" Case Study Research in Education."*. Jossey-Bass Publishers, 350 Sansome St, San Francisco, CA 94104.

Metwaly, M., El-Qady, G., Massoud, U., El-Kenawy, A., Matsushima, J., & Al-Arifi, N. (2010). Integrated geoelectrical survey for groundwater and shallow subsurface evaluation: case study at Siliyin spring, El-Fayoum, Egypt. *International Journal of Earth Sciences, 99*(6), 1427-1436.

Mogaji, K. A., San Lim, H., & Abdullah, K. (2015). Modeling of groundwater recharge using a multiple linear regression (MLR) recharge model developed from geophysical parameters: a case of groundwater resources management. *Environmental Earth Sciences*, *73*(3), 1217-1230.

Mokgatle, T., and F. D. Fourie. (2017) Groundwater Exploration in The Tsineng area Using Airborne and Ground Geophysical Methods.

Mota, R., & dos Santos, F. M. (2006). 2D sections of porosity and water saturation percent from combined resistivity and seismic surveys for hydrogeologic studies. *The Leading Edge*, *25*(6), 735-737.

Muchingami, I., Mkali, A., Vinqi, L., Pietersen, K., Xu, Y., Whitehead, R., ... & Kanyerere, T. (2021). Integration of hydrogeophysical and geological investigations in enhancing groundwater potential assessment in Houtriver gneiss crystalline basement formation of South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, *123,* 103009.

Mukhwathi, U., & Fourie, F. (2020). The influence of angled survey lines on 2D ERT surveys using the Wenner (α) array with implications for groundwater exploration in Karoo rocks. *Journal of African Earth Sciences*, *168*, 103875.

Naafs, A., (1999). Evaluation of yield assessment methods for Karoo aquifers within the context of the Rural Water Supply Decision Support System. M.Sc. thesis, *Free Univ. of Amsterdam,* The Netherlands

Ndubuisi, I. G., Alex, N. N., Austin, O. C., & Sunday, A. A. (2014). Evaluation of Aquifer Hydraulics using Electrical Resistivity Method: A case of Nsugbe sandstone, Anambra State, Southeastern Nigeria. *International Research Journal of Geology and Mining*, *4*(3), 64-75.

Nema, S., Awasthi, M. K., & Nema, R. K. (2019). Conceptual groundwater modelling in an alluvial aquifer of upper Narmada basin. *Journal of Soil and Water Conservation*, *18*(2), 179-187.

Nguyen, F., Kemna, A., Antonsson, A., Engesgaard, P., Kuras, O., Ogilvy, R., ... & Pulido-Bosch, A. (2009). Characterization of seawater intrusion using 2D electrical imaging. *Near surface geophysics*, *7*(5-6), 377-390.

Nunan, D. (1999). *Second Language Teaching & Learning*. Heinle & Heinle Publishers, 7625 Empire Dr., Florence, KY 41042-2978.

Nwankwoala, H. O., & Udom, G. J. (2008). Hydrogeophysics: an overview of general concepts, applications and future perspectives. *Scientia Africana*, *7*(2), 54-63.

Okereke, C. S., Esu, E. O., & Edet, A. E. (1998). Determination of potential groundwater sites using geological and geophysical techniques in the Cross River State, southeastern Nigeria. *Journal of African Earth Sciences*, *27*(1), 149-163.

Orellana E, Mooney HM (1966). Master tables and curves for vertical electrical sounding over layered structures. Interscience, Madrid

Pacome, A. D. (2010). *Fracture characterisation of Karoo aquifers* (Doctoral dissertation, University of the Free State).

Paillet, F. L., & Reese, R. S. (2000). Integrating borehole logs and aquifer tests in aquifer characterization. *Groundwater*, *38*(5), 713-725.

Paxton, N. (2018). *Hydrogeological investigation of the Rietvlei sandstone, Robertson, South Africa* (Doctoral dissertation, University of the Free State).

Peach, D. (2000). Delleur, JW, editor, the handbook of groundwater engineering. Progress in Environmental Science, 2(4), 360-360.

Pedersen, L. B., Bastani, M., & Dynesius, L. (2005). Groundwater exploration using combined controlled-source and radiomagnetotelluric techniques. *Geophysics*, *70*(1), G8-G15.

Pienaar, H., Xu, Y., Braune, E., Cao, J., Dzikiti, S., & Jovanovic, N. Z. (2021). Implementation of groundwater protection measures, particularly resource-directed measures in South Africa: a review paper. *Water Policy*.

Podgorski, J. E., Green, A. G., Kalscheuer, T., Kinzelbach, W. K., Horstmeyer, H., Maurer, H., ... & Laletsang, K. (2015). Integrated interpretation of helicopter and ground-based geophysical data recorded within the Okavango Delta, Botswana. *Journal of applied geophysics*, *114*, 52-67.

Renard, P. (2005). The future of hydraulic tests. *Hydrogeology Journal*, *13*(1), 259-262.

Renard, P., Glenz, D., & Mejias, M. (2009). Understanding diagnostic plots for well-test interpretation. *Hydrogeology Journal*, *17*(3), 589-600.

Roberts, Dave & Berger, L. R. (1997). Last interglacial (c. 117 kyr) human footprints from South Africa. *South African Journal of Science*, *93*(8), 349-350.

Rogers, J. (1980). First report on the Cenozoic sediments between Cape Town and Elands Bay. *Geological Survey of South Africa Open File, 136*.

Rogers, J. (1982). Lithostratigraphy of Cenozoic sediments between Cape Town and Eland's Bay.

Rubin, Y., & Hubbard, S. (2005). Stochastic forward and inverse modeling: the "hydrogeophysical" challenge. In *Hydrogeophysics* (pp. 487-511). Springer, Dordrecht.

Rudestam, K., & Langridge, R. (2014). Sustainable yield in theory and practice: bridging scientific and mainstream vernacular. *Groundwater*, *52*(S1), 90-99.

Saayman, I. C., Scott, D. F., Prinsloo, F. W., Moses, G., Weaver, J. M. C., & Talma, S. (2003). Evaluation of the application of natural isotopes in the identification of the dominant streamflow generation mechanisms in TMG catchments. *Pretoria: Water Research Commission*.

Saayman, I., Colvin, C., Weaver, J., Fraser, L., Zhang, J., Hughes, S., ... & Israel, S. (2004). Interactions Between Groundwater and Surface Water: Assessment of The Langebaan Lagoon As A Study Area. *Division of Water, Environment and Forestry Technology*.

Samani, N., Gohari-Moghadam, M., & Safavi, A. A. (2007). A simple neural network model for the determination of aquifer parameters. *Journal of Hydrology*, *340*(1-2), 1-11.

Samie, K and E.C. Murray, (1998). Guidelines for the evaluation of Water Resources for Rural Development with an emphasis on Groundwater. *WRC Report* No. 677/1/98.

Samuel, A., Blin, N., Muñoz, J. F., & Suárez, F. (2020). An unsaturated/saturated coupled hydrogeological model for the Llamara salt flat, Chile, to investigate Prosopis tamarugo survival. *Geosciences*, *10*(1), 1.

Sánchez‐Vila, X., Meier, P. M., & Carrera, J. (1999). Pumping tests in heterogeneous aquifers: An analytical study of what can be obtained from their interpretation using Jacob's method. *Water Resources Research*, *35*(4), 943-952.

Scapozza, C., & Laigre, L. (2014). The contribution of Electrical Resistivity Tomography (ERT) in Alpine dynamics geomorphology: case studies from the Swiss Alps. *Géomorphologie: relief, processus, environnement*, *20*(1), 27-42.

Schwinn, W., & Tezkan, B. (1997, August). 1D joint inversion of radiomagnetotellluric (RMT) and transient-electromagnetic (TEM) data: an application for groundwater prospection in Grundfør, Denmark. In *3rd EEGS Meeting* (pp. cp-95). European Association of Geoscientists & Engineers.

Seidu, J., Ewusi, A., & Kuma, J. S. Y. (2019). Combined Electrical Resistivity Imaging and Electromagnetic Survey for Groundwater Studies in the Tarkwa Mining Area, Ghana. *Ghana Mining Journal*, *19*(1), 29-41.

Senthilkumar, S., Vinodh, K., Babu, G. J., Gowtham, B., & Arulprakasam, V. (2019). Integrated seawater intrusion study of coastal region of Thiruvallur district, Tamil Nadu, South India. *Applied Water Science*, *9*(5), 1-20.

Seyler, H., & Hay, E. R. (2013). Using numerical modelling to cope with uncertainty in the real world: Examples from various models in the Western Cape. *Assessing and Managing Groundwater in Different Environments*, 95.

Seyler, H., Witthüser, K., & Holland, M. (2016). The Capture Principle Approach to Sustainable Groundwater Use Incorporating Sustainability Indicators and Decision Framework for Sustainable Groundwater Use. *Water Research Commission: Pretoria, South Africa*.

Shaver, R. B., & Pusc, S. W. (1992). Hydraulic barriers in Pleistocene buried-valley aquifers. *Groundwater*, *30*(1), 21-28.

Shishaye, H. A., & Abdi, S. (2016). Groundwater exploration for water well site locations using geophysical survey methods. *Hydrol Current Res*, *7*(226), 2.

Singer, R., & Wymer, J. (1968). Archaeological investigations at the Saldanha skull site in South Africa. *The South African Archaeological Bulletin*, *23*(91), 63-74.

Smith, C. P. (1982). *Saldanha Project: Preliminary Results of the Electrical Resistivity Survey*. Technical Report GH3224, Division Geohydrology, Department of Water Affairs, Cape Town.

Soltau, L. E., & Anderson, N. L. (2006). An integrated geophysical survey of groundwater resources, Mamre Area, western Cape Province. *South African Journal of Geology*, *109*(4), 433-438.

Sonkamble, S., Chandra, S., Somvanshi, V. K., & Ahmed, S. (2016). Hydro-geophysical techniques for safe exploitation of the fresh groundwater resources in coastal area. *Environmental Earth Sciences*, *75*(4), 279.

Sørense, K. I., & Auken, E. (2004). SkyTEM? A new high-resolution helicopter transient electromagnetic system. *Exploration Geophysics*, *35*(3), 194-202.

Soupios, P. M., Kalisperi, D., Kanta, A., Kouli, M., Barsukov, P., & Vallianatos, F. (2010). Coastal aquifer assessment based on geological and geophysical survey, northwestern Crete, Greece. *Environmental Earth Sciences*, *61*(1), 63-77.

Spane Jr, F. A. (1993). *Selected hydraulic test analysis techniques for constant-rate discharge tests* (No. PNL--8539). Pacific Northwest Lab.

Spane Jr, F. A., & Wurstner, S. K. (1993). DERIV: A computer program for calculating pressure derivatives for use in hydraulic test analysis. *Groundwater*, *31*(5), 814-822.

SRK Consulting (2018). Proposed Kalbaskraal Landfill Site and Surrounds: Technical Report on Geology, Structure, Groundwater Occurrence and Aquifer Classification. Report no 479224. Cape Town.

SRK Consulting, (2008). Hydrogeological investigation to augment Struisbaai's municipal water supply from groundwater resources. Report No. 380120/Task42A

Stroebel, K., Lochner, P., Conrad, J., & Naicker, P. (2019). Geohydrological input into a Strategic Environmental Assessment for the Greater Saldanha Area, Western Cape.

Tassy, A., Maxwell, M., Borgomano, J., Arfib, B., Fournier, F., Gilli, E., & Guglielmi, Y. (2014). Electrical resistivity tomography (ERT) of a coastal carbonate aquifer (Port-Miou, SE France). *Environmental earth sciences*, *71*(2), 601-608.

Tessema, A., Mengistu, H., Chirenje, E., Abiye, T. A., & Demlie, M. B. (2012). The relationship between lineaments and borehole yield in North West Province, South Africa: results from geophysical studies. *Hydrogeology Journal*, *20*(2), 351-368.

Theis, C. V. (1935). The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground‐water storage. *Eos, Transactions American Geophysical Union*, *16*(2), 519-524.

Tiab, D., & Kumar, A. (1980). *Application of the pD'Function to Interference Analysis. JPT 32 (8): 1465–1470*. SPE-6053-PA. DOI: 10.2118/6053-PA.

Timmerman, L. R. A. (1985). Preliminary Report on the Cenozoic sediments of Part of the Coastal Plain Between the Berg River and Eland's Bay." *Report GH* 3370.

Timmerman, L. R. A. (1986). Sandveld Region: Possibilities for the Development of a Groundwater Supply Scheme from a Primary Aquifer Northwest of Graafwater." *Rep. GH3471. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa*.

Timmerman, L. R. A. (1988). Regional Hydrogeological Study of the Lower Berg River area Cape Province-South Afica." PhD diss., Ghent University.

Timmerman, L.R.A. (1985a). Preliminary report on the geohydrology of the Grootwater Primary Aquifer Unit between Yzerfontein and the Modder River, Geotechnical Report GH3372, Directorate: Geohydrology, Department of Water Affairs, Cape Town.

Timmerman, L.R.A. (1985b). Preliminary report on the geohydrology of the Langebaan Road and Elandsfontyn Aquifer Units in the Lower Berg River Region, Geotechnical Report GH3373, Directorate: Geohydrology, Department of Water Affairs, Cape Town.

Timmerman, L.R.A. (1985c). Possibilities for the development of groundwater from the Cenozoic sediments in the Lower Berg River Region, Geotechnical Report GH3374, Directorate: Geohydrology, Department of Water Affairs, Cape Town.

Tooley, J., & Erickson, D. (1996). *Nooksack watershed surficial aquifer characterization*. Washington State Department of Ecology.

Tóth, J. (2009). *Gravitational systems of groundwater flow: theory, evaluation, utilization*. Cambridge University Press.

Tredoux, G., & Engelbrecht, J. F. P. (2009). Langebaan Road Aquifer Artificial Recharge Study: Pilot Phase Recharge: Final Report; Prepared for the Department of Water and Environmental Affairs. *Natural Resources and the Environment, Document No CSIR/NRE/WR/ER/2009/0099/B*.

Tredoux, G., & Talma, A. S. (2009). Langebaan Road Aquifer: Environmental isotope and hydrochemical sampling, analysis, and interpretation of samples collected in 2008. *Report to West Coast District Municipality, Moorreesburg*.

Tredoux, G., Cavé, L., & Engelbrecht, P. (2004). Groundwater pollution: Are we monitoring appropriate parameters?. *Water SA*, *30*(5), 114-119.

Tredoux, G., Van Der Merwe, B., & Peters, I. (2009). Artificial recharge of the Windhoek aquifer, Namibia: Water quality considerations. *Boletín geológico y minero*, *120*(2), 269-278.

Trinchero, P., Sánchez-Vila, X., & Fernàndez-Garcia, D. (2008). Point-to-point connectivity, an abstract concept or a key issue for risk assessment studies?. *Advances in water resources*, *31*(12), 1742-1753.

Umvoto (2009) Deep artesian groundwater for Oudtshoorn Municipal Supply (DAGEOS): monitoring report. 2008–2009 Update. 603/E.7.4-5/2009, Umvoto, Cape Town, South Africa.

Umvoto (2018) Grensplaas 964 groundwater assessment and borehole siting.

Van Tonder G.J., H. Kunstmann, Y. Xu, (1998). Estimation of the Sustainable Yield of a Borehole Including Boundary Information, Drawdown Derivatives, and Uncertainty Propagation, Technical Report, University of the Orange Free State, Institute for Groundwater Studies, Bloemfontein, S.A.

Van Tonder, G. J., Botha, J. F., Chiang, W. H., Kunstmann, H., & Xu, Y. (2001). Estimation of the sustainable yields of boreholes in fractured rock formations. *Journal of Hydrology*, *241*(1-2), 70-90.

Van Tonder, G., & Xu, Y. (1999). A guide for the interpretation of pumping tests and estimation of sustainable yields of boreholes in fractured rock aquifers. *Department of Water Affairs and Forestry, Pretoria*.

Van Tonder, G., Hughes, D. and Usher, B.H. (2007). Groundwater/surface water interaction. A new perspective. Paper presented at the Groundwater Conference in Bloemfontein from 8 -10 October 2007.

Van Tonder, G., I. Bardenhagen, K. Riemann, J. Van Bosch, P. Dzanga, and Y. Xu. (2002). Manual on pumping test analysis in fractured-rock aquifers. *Water Research Commission (WRC) of South Africa, Report* 1116/1.

Van Tonder, G., Kunstmann, H., Xu, Y., & Fourie, F. R. A. N. C. O. I. S. (2000). Estimation of the sustainable yield of a borehole including boundary information, drawdown derivatives and uncertainty propagation. *IAHS PUBLICATION*, 367-376.

Verbovšek, T., 2009. influences of aquifer properties on flow dimensions in dolomites. Ground Water, 47 pp. 660–668.

Vereecken, H., Kemna, A., Münch, H. M., Tillmann, A., & Verweerd, A. (2006). Aquifer characterization by geophysical methods. *Encyclopedia of hydrological sciences*.

Vouillamoz, J. M., Chatenoux, B., Mathieu, F., Baltassat, J. M., & Legchenko, A. (2007). Efficiency of joint use of MRS and VES to characterize coastal aquifer in Myanmar. *Journal of Applied Geophysics*, *61*(2), 142-154.

Vouillamoz, J. M., Favreau, G., Massuel, S., Boucher, M., Nazoumou, Y., & Legchenko, A. (2008). Contribution of magnetic resonance sounding to aquifer characterization and recharge estimate in semiarid Niger. *Journal of Applied Geophysics*, *64*(3-4), 99-108.

Vouillamoz, J. M., Hoareau, J., Grammare, M., Caron, D., Nandagiri, L., & Legchenko, A. (2012). Quantifying aquifer properties and freshwater resource in coastal barriers: a hydrogeophysical approach applied at Sasihithlu (Karnataka state, India). *Hydrology and Earth System Sciences*, *16*(11), 4387-4400.

Water Research Commission. (2017). Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa.

Wenninger, J., Uhlenbrook, S., Lorentz, S., & Leibundgut, C. (2008). Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa/Identification des processus de formation du débit en combinat la méthodes hydrométrique, traceur et géophysiques dans un bassin versant sud-africain. *Hydrological Sciences Journal*, *53*(1), 65-80.

Werner, A. D. (2010). A review of seawater intrusion and its management in Australia. *Hydrogeology journal*, *18*(1), 281-285.

Werner, A. D. (2010). A review of seawater intrusion and its management in Australia. *Hydrogeology journal*, *18*(1), 281-285.

Werner, A. D., Bakker, M., Post, V. E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., ... & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: recent advances and future challenges. *Advances in water resources*, *51*, 3-26.

Werner, A. D., Bakker, M., Post, V. E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., ... & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: recent advances and future challenges. *Advances in water resources*, *51*, 3-26.

Woodford, A. C. (2001). Assessment of the performance of the Langebaan Road Wellfield and Geohydrological Monitoring Network, Toens & Partners.

Woodford, A. C. (2005). Assessment of the Response of the Langebaan Road Aquifer System to a 3 month Shutdown of the Municipal Wellfield. *SRK Consulting Engineers and Scientist. Report*, (335975).

Woodford, A. C., and M. Fortuin. (2003). Engineers and Scientists Completed for: Assessment of the development potential of groundwater resources for the West Coast District Municipality, specialist geohydrological report for Kwezi-V3 Consulting Engineers." *Pre-Feasibility Study of Potential Water Sources for the Area Served by the West Coast District Municipality*.

Wu, C.M., Yeh, T.C.J., Zhu, J., Lee, T.H., Hsu, N.S., Chen, C.H., Sancho, A.F., 2005. Traditional analysis of aquifer tests: Comparing apples to oranges? Water Resources. Res.,10, pp. 1029/2004.

Yeboah-Forson, A., & Whitman, D. (2014). Electrical resistivity characterization of anisotropy in the Biscayne Aquifer. *Groundwater, 52*(5), 728-736.

Yevalla, G. M. S., Blaise, B. B. M. E., Seth, R. E., Beka, É. T., & Tabod, T. C. (2020). Constructing a 3D geological model from geophysical data for groundwater modelling and management in the Kribi-Campo sedimentary sub-basin, Cameroon. *Water Practice and Technology*, *15*(1), 105-119.

Younger, P., 2007. Groundwater in the Environment: An Introduction 1 ed., New Castle: Blackwell publishing.

Zarroca, M., Bach, J., Linares, R., & Pellicer, X. M. (2011). Electrical methods (VES and ERT) for identifying, mapping and monitoring different saline domains in a coastal plain region (Alt Empordà, Northern Spain). *Journal of Hydrology*, *409*(1-2), 407-422.

Zhang, H., Xu, Y., & Kanyerere, T. (2019). A modelling approach to improving water security in a drought-prone area, West Coast, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C, 114*, 102797.