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HYDROGEOPHYSICAL CHARACTERISATION OF SHALLOW COASTAL AQUIFERS IN THE WESTERN CAPE, SOUTH AFRICA

by

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A thesis submitted in fulfillment of the requirements for the degree of Magister Scientiae (MSc) in Environmental and Water Science, Department of Earth Science, Faculty of Natural Science, University of the Western Cape, South Africa

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ABSTRACT

Coastal aquifers present a key groundwater resource for freshwater supply in many coastal zones of Africa, and its availability is largely driven by the physical hydrogeological properties. An understanding of the aquifer properties in coastal areas is fundamental in that these aquifers present unique resource largely controlled to a very large extent by its geological and hydrological features and process. This study thus analysed information of resistivity variation of formations, drilling samples, water levels and slug test data, in an attempt to characterise aquifers in the coastal region of the Heuningnes Catchment, Western Cape. This was in an effort to address the issue of limited knowledge on key hydrogeological properties of aquifers in coastal regions. Resistivity survey results indicated that the shallow aquifers in the study area were limited in extent, had a poor potential, with resistant layers occurring below shallow, high conductive formations. The long profile of the wellpoints revealed that the area is underlain by various layers of material of consolidated to unconsolidated form. The hard rocks formations are overlain by sandy materials of fluvial origin, and clay material with marine deposits (mollusc shells). This findings were in agreement with the results of the resistivity models. In addition, the findings indicated that the saturation thickness of the aquifers was also small. The findings of the study on aquifer properties indicated that, hydraulic conductivity (K), transmissivity (T) and borehole yields were generally poor and small. Estimates of K and T ranged from 0.0030 to 0.2856 m/day and from 0.0008 to10.993 m^2/day accordingly, while average borehole yields were at 0.55 l/s, with productivity of the aquifers classified as low to moderate. These were indicative of a low permeability environment, with low yielding formations. An updated conceptual groundwater flow model developed in this study, revealed a rather compacted groundwater flow systems, in which local and intermediate flows were dominant. These findings in this study support the view that aquifers in coastal regions were predominantly characterised by shallow depth, patchy distribution and low potential.

DECLARATION

I declare that *Hydrogeophysical characterisation of shallow coastal aquifers in the Western Cape, South Africa* is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Kinsley Mahlatse Manyama

November 2017

Signed: . . . .

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Every cloud has a silver lining!

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Study synopsis

This study investigates the hydrogeologic properties of shallow aquifers in coastal areas. It seeks to understand the key hydrogeological characteristics of the aquifers, such as hydraulic parameters, groundwater units and depths, and flow rates including flow directions. The study contributes to a deeper understanding on the aquifer properties in coastal areas, of which can be useful in providing a detailed description of the different aquifer units. In addition, this study illustrates the importance of implementing an integrated approach in characterising coastal aquifers, carrying out geophysical resistivity surveys, drilling, and slug tests as ideal methods for characterisation. Furthermore, the study shows the need for the systematic application of such methods as an integrated approach for characterizing aquifers.

1.2 Background

Coastal aquifers are of significance to human needs, and provide an essential source of freshwater supply in the often densely populated coastal areas (Vouillamoz et al., 2012). These aquifers can be composed of a variety of rock types including karstified limestone, fractured rock and unconsolidated sands. Their thickness varies from a few meters to over a kilometre and, at the surface, conditions of land use, topography and climate can be highly variable (Post, 2005). Consequently, coastal aquifers can be highly heterogeneous in complex environments. As a result, spatial knowledge of their hydrogeological properties and development of a groundwater model are essential for achieving a sustainable management of the resource.

Globally, some of the challenges currently faced, with regards to coastal aquifers concern conceptual understanding of coastal hydrogeological systems, the development of mathematical models and characterisation of subsurface hydrogeological and geochemical properties (Werner et al., 2010). In some coastal regions of Africa, and particularly in South Africa which is boarded by two oceans namely the Atlantic and Indian oceans, the lack of knowledge of hydrogeological properties with regards to coastal aquifers is a critical issue (Busari and Mutamba, 2014; Adelana, 2008). In this region, existing knowledge provides largely regional estimates which generally do not reflect the variable conditions that exist. This include in situ knowledge of the hydrogeological properties of the aquifers such as hydraulic parameters, groundwater units and depth, including groundwater flow rates and flow directions, important in understanding groundwater flow systems in these regions.

Regardless of coastal aquifers being an important source of freshwater supply in coastal regions. The lack thereof of spatial knowledge and understanding of their hydrogeological properties, has resulted in some aquifers not being fully explored (Adelana, 2008). The characterisation of these aquifers is thus essential to address this issue. Werner et al. (2012) suggest the use of hydrogeological methods and complementary geophysical surveys as ideal methods for characterising aquifers in coastal regions, while Falga`s et al. (2011) used an integration of hydrogeological and geophysical methods to characterise aquifers in coastal area. Such an integrated approach is necessary to provide complementing data on aquifer properties.

This study is based on the analysis of geophysical resistivity models, examination of borehole drilling data, the analysis of slug tests, the determination of groundwater flow directions, and the description of the groundwater flow system in the Heuningnes Catchment. The study uses an integrated approach in characterizing shallow coastal aquifers in the study area. It is driven by the needs to; 1) accurately describe aquifer properties in coastal areas; 2) assess the availability of groundwater for human needs such as in agriculture; and 3) to understand groundwater flow systems in coastal aquifers.

1.3 Problem statement

In coastal areas/regions, knowledge of the hydrogeological properties of shallow aquifers is limited. Often, aquifer properties such as hydraulic conductivity, transmissivity, aquifer productivity, borehole yields, groundwater units, depth and flow systems, are poorly described, and characteristics are regionalised. This has resulted in a patchy and fragmented understanding of the different aquifer units in these regions. This situation is evident in South Africa, where knowledge of the hydrogeological system of coastal aquifers is lacking, particularly in the Eastern Overberg region, Western Cape. This is despite the progress made in various hydrogeological studies such as Toens et al. (1998) and Toens (1996, 2001) in the region.

Up to date, the hydrogeological systems of coastal aquifers have been assessed on ad hoc basis. As a result, assessing groundwater availability in this coastal areas is challenging, without spatial knowledge of in situ hydraulic parameters, groundwater units, flow directions and rates. This has implications on the potential to use groundwater for water supply in these regions, particularly in agriculture which is the dominant activity. Subsequent to that, this study employed standard hydrogeological methods and a geophysical technique to characterise aquifer in the study area.

1.4 Research question

- Is regionalisation of hydrogeological properties in coastal aquifers an appropriate representation of the aquifer characteristics, given limited knowledge? In this study, regionalisation refers to, the delineation of the aquifer hydrogeology into sections of significantly, similar characteristics or properties.
- This study holds the view that, coastal aquifers displayed a highly variable hydrogeological environment. Thus, knowledge of the in situ aquifer properties is essential in building appropriate understanding of the aquifer hydrogeology in these regions.

1.5 Aim and study objectives

1.5.1 Aim of study

The aim of this study is to improve an understanding of hydrogeological properties in coastal aquifers, through characterisation of the aquifers using an integration of geophysical surveys, drilling, and hydraulic tests, in order to inform groundwater development and management options. These include understanding key properties of the aquifers, key aquifer parameters and groundwater units, including flow directions.

1.5.2 Objectives

The objectives of this study are to:

1. Establish groundwater units using surface geophysical resistivity method, for determining groundwater zones, and drilling points for piezometers.
2. Evaluate aquifer hydrogeological properties using hydraulic tests, for characterizing the aquifer permeability.
3. Determine groundwater flow directions at local and regional scale, in order to characterise the groundwater flow system.
4. Develop a conceptual model describing the hydrogeological properties and groundwater flow system, in order to provide a unified characterisation of the aquifers.

1.6 Scope and nature of the study

1.6.1 Scope of study

The study focuses on characterisation of hydrogeological properties of aquifers in coastal regions. Aquifer characterisation can involve establishing geological units and, their physical and hydraulic properties such as porosity and transmissivity, faults, fractures, groundwater recharge, flow paths, aquifer thickness, water table elevations, and flow directions, including the type of rocks (Attandoh et al., 2013; Vereecken et al., 2005; Tooley and Erickson, 1996). The study is thus, largely concerned with understanding the variations in aquifer properties as a way forward into deepening understanding and knowledge of aquifers properties in coastal regions. In addition, the study is mainly concerned with shallow aquifers, as these often are the sole sources of freshwater supply in coastal regions. Furthermore, this study is interested in determining the potential or productivity of the aquifers, of which such knowledge is critical for sound groundwater development and management planning. This requires knowledge of the aquifer hydraulic conductivity, transmissivity, borehole yields and flow directions. Groundwater recharge, which is also an important component in aquifer characterisation (Attandoh et al., 2013), is however not discussed in this study. This subject would warrant a comprehensive study on its own to detail all the mechanism and processes involved with regards to aquifer recharge in coastal regions of which is beyond the capacity of this study.

1.6.2 Nature of the study

This study uses a case study approach in assessing the hydrogeological system of coastal aquifers. The selected case study area in this study is Heuningnes Catchment area, located in coastal plains of the Eastern Overberg region in the Western Cape Province, South Africa. This coastal catchment is characterised by various numerous wetlands, rivers, springs and groundwater resources. Aquifer resources include both primary and secondary aquifers of variable extent, potential and groundwater quality.

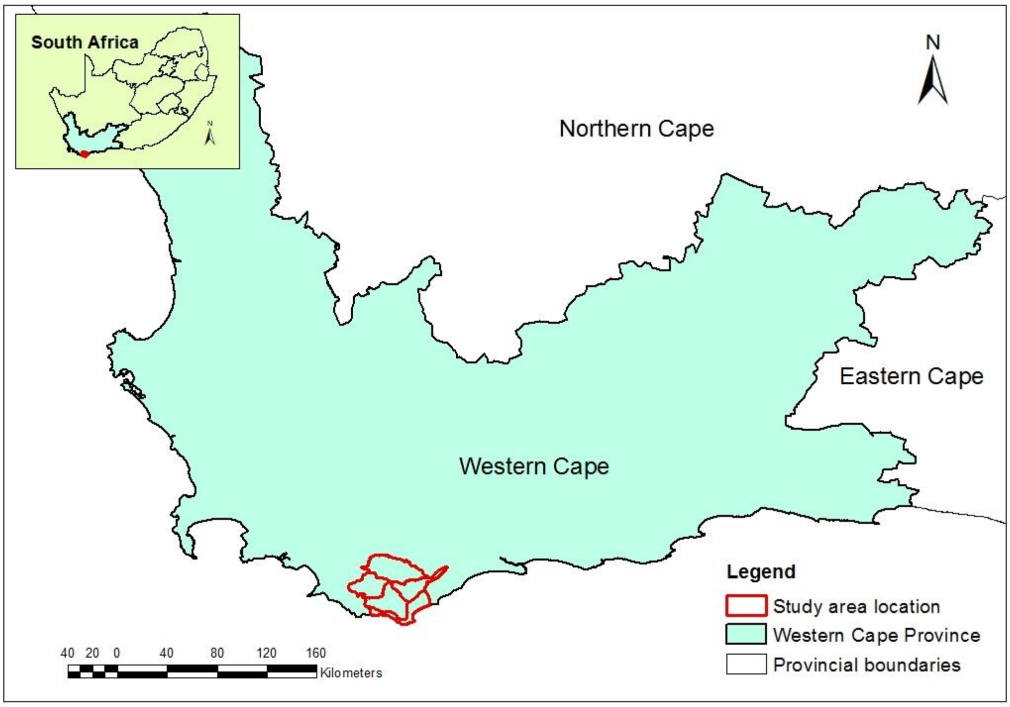


Figure 1: Case study area location map

The case study area is selected on the basis that, research on the hydrogeological system of the aquifers in this part of the coastal region in South Africa has been limited. This is despite that surface water resources are limited and the area often experience water shortages. In this case, groundwater can act as a strategic resource. However, its optimal use would require proper understanding of its availability and thus the hydrogeological properties of the aquifers.

1.7 Significance of study

This study is essential, as it is focused on improving understanding regarding the characteristics of the aquifer hydrogeological properties in coastal regions, crucial in water resource planning. In addition, the study provides certain level of information on the hydrogeological properties of coastal aquifers in the case study area, of which can be used to make inferences about the general expected formations, important in groundwater resource management and development cases, planning and investigation. Further, by producing information on groundwater flow directions and hydraulic properties which are essential for groundwater quantity and quality evaluations, this study thus contribute to a base for such future studies on the development and management of the aquifer resources in coastal regions.

Some of the outcomes of the study include a conceptual model of the subsurface of the target area within the catchment, useful in the development of a catchment numerical model. As the aim of the study is focused around the characterisation of aquifers at the selected target areas with the catchment, the study contribute significantly towards improved understanding and knowledge of the groundwater resource within the Heuningnes Catchment. Information and knowledge resulting from this study can be useful in planning and making decisions about well siting for uses such in agriculture, which is the dominant activity within the catchment.

1.8 Study framework

A study framework also referred to as a research framework, works as a guideline and foundation of the study, and bind it to its objective. It is an important component of a study and necessary to give research a structure in a chronological way. In this study, the study framework is centred on the need to provide an appropriate description of the hydrogeological properties of shallow aquifers in coastal regions. The framework presents the relations in the study objective, research question, including the problem statement in this study, of which all is focused towards achieving a certain level of aquifer characterisation. This include, gaining knowledge on the variations in permeabilities, depth and transmissivity of the aquifers in the case study area. The figure below provides a research framework for this study.

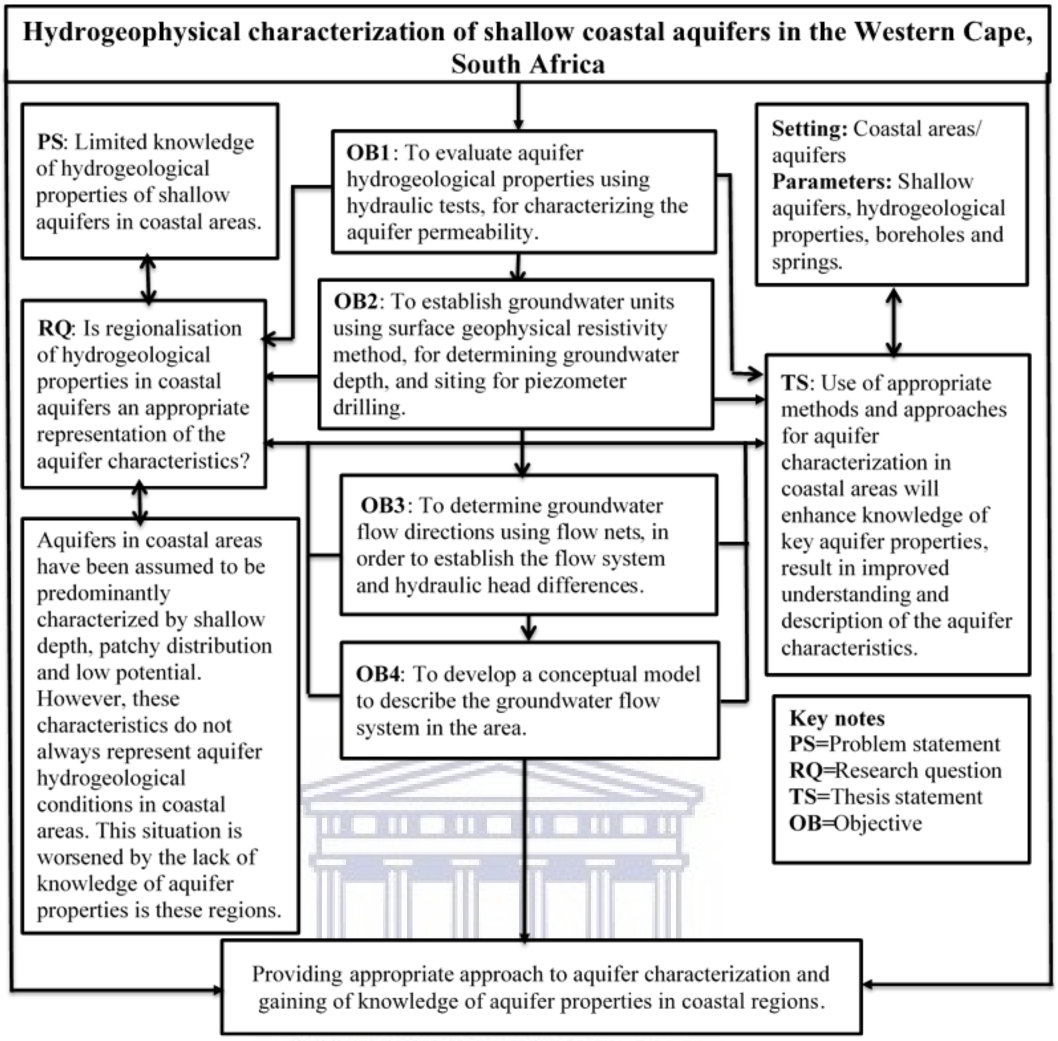


Figure 2: Research framework applied in this study

1.9 Outline of the thesis

The thesis outline of this study is a follows: Chapter 1: This provides a background on coastal aquifers and the need for aquifer characterisation in such regions. Chapter 2: This chapter is aimed a revealing some gaps in the literature concerning groundwater investigations on aquifer characterisation in coastal regions. It is also presents a review of previous studies on aquifer characterisation within the study area, including an analysis of appropriate methods for characterisation. Chapter 3: Provides a description of the study research design, methodology and limitations in the study, indicating how the study was conducted. Chapter 4: This chapter is based on the results on subsurface mapping, which are part of objective one of the study. Chapter 5: Is based on wellpoint drilling and sampling. Chapter 6: The chapter is based on estimation aquifers parameter. Chapter 7: This chapter is on the groundwater flow dynamics and lastly Chapter 8: Is based on conceptual description of groundwater flow systems in the study area. Chapter 9: This presents the conclusion and recommendations of the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides a perspective to the aim of the study which is based towards improving understanding of hydrogeological properties in coastal aquifers. The chapter presents a review of the literature on the subject of aquifer characterisation in an attempt to address the problem of lack of appropriate knowledge and understanding of aquifer properties in coastal regions. This include a review on some applicable methods for characterising hydrogeological systems of coastal aquifers. Lastly, the chapter presents the conceptual and theoretical framework applied in this study.

2.2 Review of previous studies

In coastal regions, aquifers are assumed to be predominantly characterised by shallow depth, patchy distribution and low potential (Falga`s et al., 2011). Addressing groundwater issue in this region is often challenging, as it requires knowledge of key aquifer properties essential in understanding the hydrogeology of the region. Without an understanding of key characteristics of the aquifers, groundwater development and management planning in coastal areas can be a futile exercise.

Globally, various studies (e.g. Post and Abarca, 2010; Werner, 2010; Silliman et al., 2010; Shao et al., 2013) on coastal aquifers are fairly documented in the literature. These studies have focused mostly on issues such as the problem of seawater intrusion and numerical simulation of the complex flow system for contamination and solute transport models. However, the emphasis on establishing the aquifer hydrogeological properties is limited and not given the much needed attention. This is despite the facts that a thorough knowledge of such is essential in aquifer resource management.

The lack of studies on assessing aquifer hydrogeological properties in coastal areas is also common in South Africa. This is particularly true to areas like the Cape Flats (Adelana et al., 2010) and in the coastal catchments of the Eastern Overberg region, Western Cape. Despite the progress made in various hydrogeological investigations (e.g. Toens et al., 1998; Toens, 1996, 2001) in the Eastern Overberg region catchments. Little is understood about the aquifer hydrogeological properties in the catchments.

Though, very little is understood about the aquifer hydrogeological properties in Eastern Overberg region, the unpublished literatures in the form of government and consultant reports with most notably Toens et al. (1998) and Toens (1996, 2001), does provide a basis for such studies. Toens (1996) focused on wetland systems and hydrology, while Toens (2001) gives an overview of the Eastern Overberg catchment management status, which the Heuningnes Catchment is part of.

The studies by Toens et al. (1998) and Toens (1998) provides some ideas about the groundwater resource that occurs within the catchment. Toens (2001) on the other hand provides some important information (expected aquifers and geology) about the groundwater resource in the catchment of which can be helpful during site selection in this study. However, all the above studies mostly provide only regional estimates which generally do not reflect conditions in all the areas and are based on ad hoc objectives in response to problems. There is therefore a need for specific studies focused on the understanding of the aquifer hydrogeological properties in coastal areas. This study therefore attempts to fill this gap in knowledge in addressing the problem of study.

2.3 Aquifer characterisation

In assessing aquifer hydrogeological properties, various approaches have been applied for coastal aquifer resources. These include among others aquifer characterisation; numerical and analytical simulation; and application of tracers and isotope hydrology (Falga`s et al., 2011; Post and Abarca, 2010; Werner, 2010; Silliman et al., 2010; Shao et al., 2013). Most investigations seem to employ new technologies and multidisciplinary approaches. However, Falga`s et al. (2011) indicated that applying an integrated use of hydrogeological and hydrogeophysical information allows for more insight to be gained about the groundwater system compared to using individual approaches.

For many aquifers with poor information on hydraulic and physical properties, their characterisation is crucial for proper management of the groundwater resource (Paillet and Reese, 2000). It provides a hydrogeological framework to develop knowledge and understanding about aquifer hydrogeology and properties using various traditional and unconventional methods. In short, aquifer characterisation afford prospect for description and conceptualisation of the aquifer hydrogeological environment and subsurface, which is often hid from view. Without understanding the characteristics of the aquifer resources, groundwater development and management planning can be a futile exercise; hence this concept is important in hydrogeological studies.

Often, aquifer characterisation involves determining the physical and hydraulic properties of the aquifer under study. These may include determining hydraulic conductivities and transmissivities of the stratigraphic units, rates of groundwater flows, flow paths and directions, thickness of the confining units including saturated zones. Tooley and Erickson (1996) states that aquifer characterisation involves mapping of lateral boundaries and spatial definition of lithology, thickness, water table elevations, and flow direction of groundwater. It comprises also establishing geological units and their hydraulic properties such as porosity and transmissivity, faults, fractures, groundwater flow paths and the geometry of the aquifers including the type of rocks (Vereecken et al., 2005). Thus, aquifer characterisation afford prospect for description and conceptualisation of the aquifer hydrogeological environment and subsurface.

On the other hand, Attandoh et al. (2013) states that aquifer characterisation often involves water budgets analysis; recharge estimation and groundwater resource potential or availability assessment, while Peach (2000) observed that aquifer characterisation can be either preliminary or more advanced incorporating basic information on the geology with hydraulic properties depending on the needs of the investigations. 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). It can therefore be argued that the focus on aquifer characterisation should primarily be on the hydraulic and physical properties including groundwater flows of which result general understanding of the aquifer resource.

On the elements that constitute characterisation process, Dippenaar (2008) and Lasher (2011) states that this depends on the type of aquifers being investigated. For example, in fractured rock aquifers, faults and fractures sizes are established during characterisation (Dippenaar, 2008; Lasher, 2011), while primary porosities are important for intergranular aquifers. In studies such Paillet and Reese (2000), the objective of the study dictated the properties which were investigated. However, in all case of aquifer characterisation, adequate level of aquifer characterisation is required for gaining appropriate knowledge on aquifers properties (Falga`s et al., 2011).

2.3.1 Methods for characterisation

When characterising aquifers, various approaches have been applied for coastal areas. These include among others, hydrogeological, numerical and analytical modelling; and application of tracers and isotope hydrology (Falga`s et al., 2011; Post and Abarca, 2010; Werner, 2010; Silliman et al. 2010; Shao et al. 2013). However, applying an integrated use of hydrogeological and hydrogeophysical information allows more insight to be gained about the aquifer properties (Falga`s et al., 2011).

In most case, various traditional and unconventional methods have been widely applied in characterizing aquifers. The commonly applied methods in characterizing aquifers are geological mapping, cross-section, drilling, core or well logging, surface and borehole geophysics, pumping tests and remote sensing including groundwater models (Paillet and Reese, 2000; Lasher, 2011). Unconventional methods like Fluid Electrical Conductivity logging are also applied to characterise fractures in aquifers (Tsang and Doughty, 2003). However, the use of a single method does not allow full characterisation of the aquifer resource. Hence, an integrated approach which involves the use of hydraulic test, lithologs and geophysical logs proves to be useful for effective characterisation as stated by Paillet and Reese (2000). Lasher (2011) suggested use of complementary methods that give both quantitative and qualitative data about the aquifers.

The application of standard methods in characterizing aquifers of various geologies and settings has been recorded in the literature. Vouillamoz et al. (2006)

characterised a non-consolidated coastal aquifer using a combination of borehole drillings, pumping tests and geophysical methods, focusing on the quantity aspect by determining aquifer physical and hydraulic properties such transmissivity. The same approach was applied in Paillet and Reese (2000), using an integration of lithologic logs, geophysical logs and hydraulic tests to characterise a heterogeneous aquifer. Dippenaar (2008) on the other hand characterised some fractured rock aquifers using pumping tests to determine aquifer parameters namely transmissivity and the sustainable yield. Thus, standard methods such as pumping test tend to have a wider application for different environment, though some of their condition may not be met.

With standard methods for characterisation, Hubbard and Rubin (2000) states that almost all traditional aquifer characterisation methods are inherently time consuming, costly and labour intensive. However, pumping tests (Botha et al. 2000), drilling (Vouillamoz et al., 2012) and geophysical techniques are mostly used and preferred methods for various cases despite the limitations. This also calls for integration of methods in characterisation of aquifer to complement limitation of some methods.

2.4 Hydrogeological setting

The availability of groundwater resources is mostly viewed as determined by the prevailing geology, topography and climate within the area. In addition, the occurrence of groundwater in varying quantities has been associated with different hydrogeological characteristics of the underlying aquifers (Holland, 2012). However, in coastal aquifers, resource availability is influenced by unique characteristics such as proximity to the sea and variable quality, and the view that the aquifers are discharge zones of regional groundwater systems (Falga`s et al., 2011). Thus, understanding the large variability of the hydrogeological conditions under which groundwater flow is important for determining the groundwater resource for various uses and protection.

In understanding the nature of groundwater resource, mainly availability/potential and flow directions, knowledge of the hydrogeological setting is essential for such needs. This includes gaining information on the physical and hydraulic parameters of the aquifer that can act as indicators from which inferences about the nature of the groundwater resources can be made (Paillet and Reese, 2000). The physical properties of interest include among others geological units, groundwater zones, stratigraphy, rock type, dykes, faults and fractures (Falga`s et al., 2011), while hydraulic properties include hydraulic conductivity, transmissivities, storativity and borehole yields (Price, 2013). These properties of the aquifer are useful when explaining the occurrence, movement and discharge of groundwater in the subsurface. As a result, methods have been developed to characterise the hydrogeological setting of aquifers.

In determining aquifer physical and hydraulic properties, conventional and nonconventional methods have been employed in many groundwater investigations. Vouillamoz et al. (2007) employed traditional technique of pumping tests and a nonconventional method (using magnetic resonance soundings (MRS) and vertical electrical soundings (VES) geophysical methods) based on conversion equations to determine hydraulic conductivity and transmissivity estimates for non-consolidated coastal aquifer. On the other hand, Leketa (2011) used pumping tests (both step and constant discharge methods for determining borehole efficiently and aquifer transmissivity) and slug tests for determining aquifer parameters of an unconfined aquifer. Though, these methods have their benefits and limitations in terms of spatial representation, data quality and quantity, cost of application and technicality, the use of standard methods in aquifer characterisation is essential as these methods are widely used as an acceptable practice and standard. The application of hydrogeological and geophysical methods in investigating aquifer properties is a standard practice.

2.4.1 Physical properties of the aquifer

Lacking knowledge of the hydrogeological setting can present difficulties in groundwater resources assessments. This can be an issue arising from inadequate characterisation of the hydrogeological framework in which groundwater occurs (Taylor and Greene, 2008). Inadequate characterisation can includes having limited knowledge about the aquifer units and their properties including groundwater potential. Limited knowledge of these characteristics often leads to misleading decisions with regards to management of groundwater, resulting in improper knowledge and measures about pollution, overexploitation and seawater intrusion in coastal aquifers.

Methods for determining aquifer physical properties

Vouillamoz et al. (2007) states that borehole drilling is the commonly used method in determining aquifer physical properties, such fracture, water strike and aquifer units and boundaries. Botha et al. (2000) employed pumping tests to determine some of the physical properties namely aquifer boundaries for fractured rock aquifers. On the other hand, Lasher (2011) used multiple methods such as the Fluid Electrical Conductivity (FEC), geological mapping, drilling and surface geophysical method including pumping tests for characterizing fractures of a fracture rock aquifer. Though, drilling is can be an expensive method to use, it seems to be the most basic way to accurately determine aquifer physical properties, and is a standard practice.

Drilling and sampling

Borehole drilling is one of the most ancient traditional methods applied in groundwater studies for establishing characteristics of the aquifer materials. The method has been used for centuries even before the advent of geophysical methods, and such is still a relevant method and the most practical means for accurately establishing subsurface materials and physical properties (Price, 2013). In addition, the method provides the only means from which groundwater can be directly measured in the ground surface (Botha et al., 2000). However, Vouillamoz et al. (2012) states that drilling is costly and does not provides for effective characterisation. Another limitation is that the method gives point measurements and does not provides spatial heterogeneities of the subsurface materials (Paillet and Reese, 2000; Price, 2013).

Despite this limitation, drilling remains a useful method for establishing aquifer hydrogeological properties in areas were existing well are limited. This method commonly involve making a vertical hole into the ground surface and taking samples of the aquifer materials at determined intervals (may be a meter interval) to establish aquifer properties such as rock type, fracturing, faulting, texture and composition. Heavy machinery is used, with a drilling bit mounted on the drilling rod which is stationed on a truck. Drilling methods include Percussion drilling for more hard surface rock and Mud-Rotary for drilling in soft, sandy and alluvial formations, and Hydraulic jetting (Botha et al., 2000; Price, 2013).

Mud-Rotary drilling method involves the use of mud water pressured through a drilling bit, and works well in alluvial aquifers, weathered and in sandy formations with clay materials (Sundaram et al., 2009). On the other hand, Air Percussion drilling uses percussion drill bit with air forced down the hole inside the drill, removing cuttings from the hole. In addition, percussion drilling allows for successful drilling through hard rock formations. Hydraulic jetting on the other hand involves the use of high pressure water through a jetting steel rod. This method is cheap to use and allows for drilling in unconsolidated and alluvial formations, and in sandy formations. Mud-Rotary drilling however may fail to penetrate through hard rock formations, and this can be challenging where such prevails.

Geophysical methods

Core logs description and hydraulic tests are approaches commonly applied for investigating aquifer characteristics (Vouillamoz et al., 2012). However, a gap exist between qualitative description of an aquifer given by logs and cores, and quantitative estimates of hydraulic properties derived from the traditional hydraulic tests (Paillet and Reese, 2000). Hence, it is difficult to correlate the results of hydraulic tests and core log data.

Surface geophysical methods afford the capability to carry out informative characterisation of subsurface or aquifer resource. Vouillamoz et al. (2012) report that surface geophysical methods address the issue of scale in core logs and resolution of pumping tests as they provide an analysis of the vertical and spatial distribution of the aquifer properties. They offer the capability to derive basic characteristics, key variables, and properties of geological formations (Vereecken et al., 2005). In addition, they provide a closer link between geophysical parameters to the presence of water (Vouillamoz et al., 2012), from which groundwater units and confining layers can be mapped. Moreover, surface geophysical methods allow mapping of the stratigraphic units of the subsurface, faults, weathered zones including depth of ground layers (Falgàs et al., 2011).

The commonly applied surface geophysical methods in mapping of the subsurface include Electrical Resistivity, Seismic and Electromagnetic methods (Vereecken et al., 2005). However, Electrical Resistivity is the preferred method for assessing groundwater potential zones for exploration purposes (Binley et al., 2010), due to its capability to distinguish layers of different resistivities due to water saturation. The method is capable of providing rapid, dense and low cost data coverage, and can be useful in proving effective characterisation of the aquifer material and properties (Vouillamoz et al., 2012). Given such advantages, Electrical Resistivity method thus present a useful method for bridging the gap between core log data from drilling and quantitative data from hydraulic tests.

2.4.2 Aquifer hydraulic properties

Hydraulic properties are key parameters used to assess and describe aquifer resource (Attandoh et al., 2013; Brown et al., 2003). They are used to explain the ability of geological formations to store, and transmit groundwater, important for groundwater assessment studies. According to Paillet and Reese (2000) information of aquifer hydraulic properties were essential, in order to provide adequate prediction of groundwater quantity and quality. Vouillamoz et al. (2012) state that knowledge of the aquifer hydraulic properties is required for achieving a sustainable management of the resource. The properties are essential in assessing the groundwater resource (Brown et al., 2003).

Hydraulic properties of interest are often, transmissivity and storage coefficient, hydraulic conductivity and specific yield, borehole yield and specific capacity (Tse and Amadi, 2008; Xu et al., 2009; Price, 2013; Heath, 1983; Freeze and Cherry, 1979). These properties determine the flow of groundwater readily to boreholes (Price, 2013), and thus important attribute of hydrogeological setting of a particular region. As a result, an assessment of the hydrogeological setting aimed at understanding aquifer properties should thus pay attention to various hydraulic properties of the aquifer resource.

Methods for determining aquifer hydraulic properties

Hydraulic tests are methods commonly used for determining hydraulic properties. These include pumping tests, recovery tests, slug tests and bailer test (Freeze and

Cherry, 1979). However, both slug and bailer tests offer point measurements or less spatial coverage of hydraulic properties of the aquifer, and thus fail to account for both heterogeneity and anisotropy. Pumping tests, however does offer a representation of a larger area, and in some cases does address issues of heterogeneity (Price, 2013). Streamflow analysis and non-invasive geophysical methods are some of the methods that allow assessment of the aquifer properties (Ballochestani, 2008). These methods, more like pumping tests allow investigation of aquifer properties at large scales.

Pumping tests

Pumping tests are seen as the simplest approach to study the physical behaviour of aquifers, with the main purposes as to identify aquifer properties (Botha et al., 2000). They involve the action of applying stress to the aquifer through pumping of groundwater and observing the response of the aquifer in monitoring wells. Pumping tests can be both constant rate and multi-rate discharge tests in which the pumping rates are controlled (Tse and Amadi, 2008). Constant rate tests are employed for determining hydraulic properties, while multi-rate discharge tests are used for establishing pumping rates at which to pump the borehole (Botha et al., 2000). In order to use pumping test methods to determine hydraulic conductivity, it requires the existence of a pumping or production borehole and at least one observation borehole or piezometer in the capture zone. The well is then pumped at a constant rate and drawdown in the piezometer is measured as a function of time. However, the installation of wells and piezometers is costly and may not be justified in some cases.

Slug tests

Slug tests are another type of hydraulic tests used in low yielding wells and in situations where groundwater is contaminated or the tests are taking place in protected areas. The method for determining the hydraulic conductivity provides point measurements and works as a single well test. There are two types of a slug test, a falling head test and rising head test (MacDonald et al., 2008). The rising head test is conducted by instantaneously causing a change in the head by removing water from the piezometer, while a falling head is conducted by causing a change in the head by adding water to the piezometer and monitoring the recovery of the water level to its initial head.

The rising head test is, in many cases, more reliable than the falling head or constant head test (Power and Herridge, 2007). This is because, in falling head test, the exposed portion of the aquifer may be affected by resistance to flow when injecting water. On the other hand, the fines or sediments are more readily pushed into the hole and resistance to flow is much less in rising head test. As a result, rising head test tends to give significantly higher estimates of hydraulic conductivity than falling head test (Power and Herridge, 2007).

When estimating the hydraulic conductivity, two solutions which are the Bouwer and Rice (1967) and the Hvroslev (1951) analytical solutions are commonly used. The solutions assume full or partial penetration of the well, and work for unconfined and confined conditions (Duffield, 2007).

Permeameter tests

Laboratory Permeameter tests are some of the methods of which hydraulic properties can be estimated. Price (2013) indicates that permeameter tests can be generally instruments for holding core samples, designed in such a way that fluid can pass through the sample and hydraulic conductivity can be calculated following Darcy’s law. Darcy’s law governs fluid flow through a porous media and is given by the following equation (Heath, 1983):

Equation 1: Darcy's law of fluid flow

$$Q = -KA\left(\frac{dh}{dl}\right)$$

Where Q is the quantity of water per unit time; K is the hydraulic conductivity; A is the cross-sectional area measured at right angle to the flow direction and dh/dhl is the hydraulic gradient, sometimes given by the letter (I). However, permeameter tests provide point measurements of hydraulic conductivity, thus fail to represent spatial heterogeneities in the hydraulic conductivity (Kalbus et al., 2006). Also, scale is an issue associated with use of permeameter tests, and often difficult to give representative data, of which generalisation can be misleading at times.

Permeameter tests can be designed as constant-head test in which a constant-head potential is set up and a steady discharge flows through the system or as falling-head test in which the time needed for the hydraulic head to fall between two points is recorded (Kalbus et al., 2006). Hydraulic conductivity is then calculated from the head difference, the time, and the tube and sample geometry (Hvorslev, 1951; Freeze and Cherry, 1979; Todd and Mays, 2005). Depending on the direction of flow through the sediment sample in the experiment, directional hydraulic conductivity may be obtained (Price, 2013). It is however, difficult to take and transport samples from streambed sediments without disturbing the packing and orientation of the sediment grains, which may influence measurement results. Because of such challenges, the present study does not conduct Laboratory permeameter tests.

2.4.3 Determining aquifer productivity

Other parameters that are a function of the hydraulic parameters are also important properties of the hydrogeological setting. These include specific capacity, well efficiency (Peach, 2000) and groundwater productivity which is based on the use of some hydraulic parameters as indicators variables. However, well efficiency and groundwater potential estimations are often ignored in many characterisation studies.

Aquifer productivity is a function of both the physical and hydraulic properties of an aquifer, and can be used as an indicator of aquifer potential and groundwater availability. This property of an aquifer is important in the siting of new boreholes, which often is a wildcard drilling exercise with limited geophysical support (Botha et al. 2000). Aquifer productivity can be determined from geological information and hydraulic tests (Tadesse et al., 2010; MacDonald et al., 2012). In many catchment settings, information on this property is often not provided, and classification of aquifers productivities to inform groundwater resource developments cannot be carried out. Through understanding of aquifer productivity and properties, groundwater availability for use in agriculture and domestic supply can be determined. Proper understanding of the hydrogeological system is thus developed, and informed decisions on management and utilisation of the resource can be taken.

Methods for determining aquifer productivity

Various methods for determining aquifer productivity have been recorded in some literature. However, the main parameter used to assess productivity of aquifers is transmissivity data. Chowdhury et al. (2003) determined the aquifer productivity of some aquifer using transmissivity and hydraulic conductivity estimates, and concluding that due to high value of the parameters the aquifer productivity was generally very good. On the other hand, MacDonald et al. (2004) determined the aquifer productivity using borehole yields. Banks et al. (2005) used the same approach as MacDonald et al. (2004). However, no one preferred parameters is used to determine the productivity of an aquifer.

In search of a better approach to establish aquifer productivity, significant progress has been made, on the choice of the hydraulic variable from which inference can be made. A study by Graham et al. (2009) focused on the suitability of transmissivity, specific capacity and borehole yield data as a measure of aquifer productivity in Scotland using statistical analyses. In his study, Graham et al. (2009) found a strong correlation ($r^2 = 0.8$) between specific capacity and transmissivity and a significant correlation ($r^2 = 0.57$) between transmissivity and borehole yield data. Graham et al. (2009) concluded that preferably specific capacity may be used as a reliable indicator of aquifer productivity where no transmissivity data are available, though under certain circumstance borehole yield can apply as well.

In another study, MacDonald et al. (2012) determined aquifer productivity classifications based on judgements of the typical long-term abstraction rate, in litres per second (l/s). In his study MacDonald et al. (2004) determined aquifer productivity classes as ranging from very low productivity, of igneous and metamorphic rocks, which are generally suitable only for boreholes supplying less than 0.1 l/s to single or small groups of houses, to very high productivity (>20 l/s), of sandstones, potentially exploitable for public supplies and industry (see table 1 below).

Table 1: Aquifer productivity classes (after MacDonald, 2004)

Aquifer productivity classes (l/s)	**Productivity Class**	**Associated aquifer material**
>20	Very High	Karstic and fractured rock aquifers
5-20	High	Unconsolidated to poorly consolidated sedimentary rocks
1-5	Moderate	
0.5-1	Low-moderate	Crystalline basement rocks
0.1-0.5	Low	
<0.1	Very low	

On the other hand, Tadesse et al. (2010) indicated aquifer productivity as good or poor based on high or low transmissivity value. As a result, no general concession or restriction about the form of indices to represent the variation in the productivity of aquifer is provided. However, distinction should be developed between aquifers with varying yields. This is important for the purpose of groundwater exploitation to meet various needs such in agriculture using meaningful indices.

2.5 Groundwater flow systems and dynamics

In characterising aquifers, assessing groundwater flow systems and dynamics is essential in coastal regions, where groundwater flow can affect water quality. This is due to that, they form part of the aquifer hydrogeological system, indicating the interplay of the aquifer physical and hydraulic properties. Roets et al. (2008) indicated that groundwater flows are important for understanding linkages between surface water bodies and groundwater systems. Thus, identification of permeable and impermeable horizons and of geological structure that control flow of groundwater could facilitate targeting of boreholes at economic depth (Abiye and Haile, 2008).

2.5.1 Groundwater flows concept

Groundwater flows obey Darcy's law of fluid flow in porous medium (Price, 2013; Heath, 1983). The nature of groundwater flow can vary significantly from area to area. In fractured rock aquifers affected by secondary porosity, fractures and caverns in limestone serve as conduits and main storage of groundwater (Botha et al., 2000). This is more unlike in alluvial aquifers affected by primary porosity, in which flow occurs between the pore matrixes of the rock or soil materials (Heath, 1983). The secondary porosity forms one of the key controlling properties of groundwater occurrence, storage, flow and discharge in fractured rock aquifers (Price, 2013; Heath, 1983; Freeze and Cherry, 1979). This is of one of the main reasons characterisation of fractured rock aquifers tend to be focused of fracture identification (Lasher, 2011). However, fracture connectivity which determines if a fracture can allow groundwater flow is often difficult to determine. The figure below depicts the nature of groundwater flow in primary and secondary aquifers.

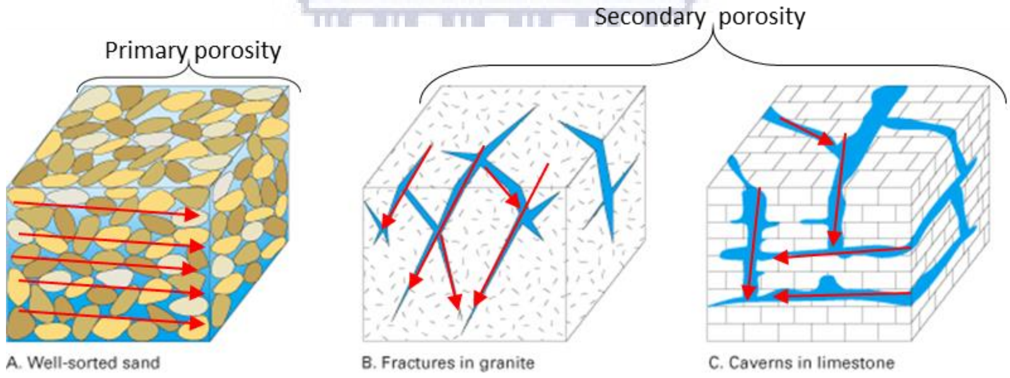


Figure 3: Flow of groundwater in primary and secondary aquifer mediums (Barlow, 2003)

2.5.2 Systems of groundwater flow

Groundwater flow systems occurs hierarchically at local, intermediate (subregional) and regional scale (figure 4). Topography, geology and climate are major factors that determine the development of these systems of gravity driven flow in a homogeneous and isotropic groundwater basin (Zhou and Li, 2011). The link of aquifer basin to rivers and wetland bodies, can also contribute to such structures of groundwater flow.

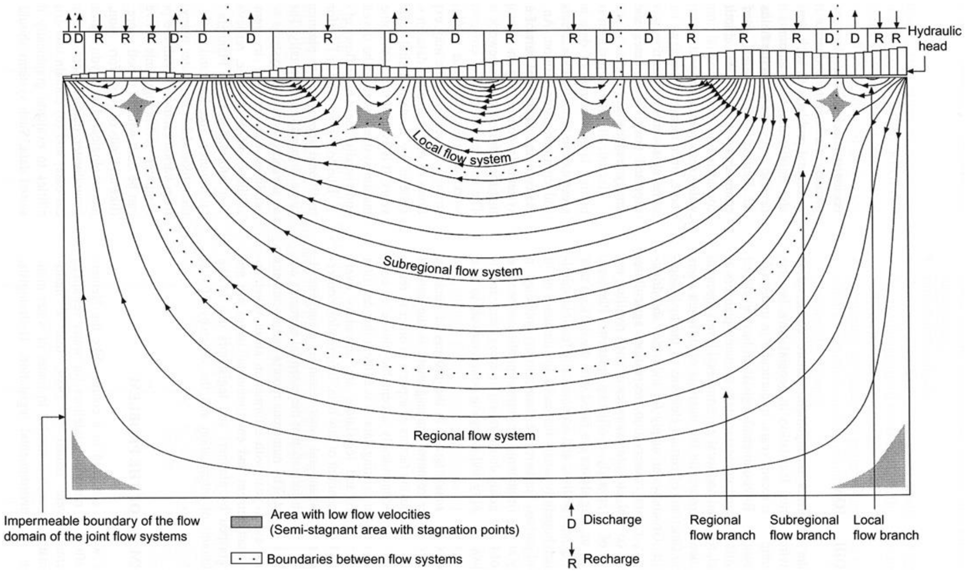


Figure 4: Hierarchically nested groundwater flow systems (Zhou and Li, 2011)

The three groundwater flow basins are delineated based on the assumption that high laying areas are recharge zones, while lower laying areas are discharge zones (Zhou and Li, 2011). Understanding of the dominant flow system of the groundwater basin is essential for assessing groundwater resources as part of the aquifer characterisation process in coastal regions. In cases where data is lacking, regional groundwater flows can be assumed to illustrate the postulated regional groundwater flow directions using schematic sections (Xu et al., 2009). However, local groundwater flows can be an important dynamic feature of the area hydrogeology. In the current study, local, intermediate and regional groundwater flow system is assumed.

2.5.3 Methods for determining groundwater flow direction

Various methods are available for establishing groundwater flow in aquifer systems. These can be grouped into methods depending on Darcy' Law of fluid flow through porous media and tracer tests. The former include triangulation method and flow nets (Heath, 1983) and Cross-sectional methods. On the other hand, natural tracer tests such as Cl and artificial tracers such as (dye) can be used. In the absent of hydraulic head data, topography, geology and water feature such rivers can be used to determine general groundwater flows, following principles of hydrogeology. However, such can be misleading in fractured rock aquifer setting, in which groundwater flow through fractures which may generally be in any direction.

Head measurements from monitoring well or piezometers are important for establishing hydraulic gradient, which drive the groundwater flow (Roets et al., 2008; Price, 2013). In some catchment monitoring well are limited or unavailable, thus impedes on the objective of obtaining information on flow directions. In this regard, piezometer installation offers an opportunity to gather such information cheaply.

2.5.4 Hydrogeological models

In hydrogeology field, models are commonly used tools to represent the system under study. These are referred to as hydrogeological models and, allows hydrogeologists to study and understand groundwater and related processes. A hydrogeological model can be simply a detailed representation of groundwater processes and features such groundwater flows and sources, physical and hydraulic properties of a particular geological formation. This can be conceptual, physical, analytical or numeric in nature, and are important tools for understanding the behaviour and nature of a groundwater systems.

The most basic model useful to the hydrogeologists is the conceptual hydrogeological model, which is defined as a visual representation of how water moves over and through the earth surface, and often combine geological and groundwater features (Price, 2013). According to Betancur et al. (2012), conceptual models are commonly used to illustrate the occurrence of groundwater resource. These can be either in a block diagram or cross-section. Apart from representation of hydraulic heads and water table, Parsons (2009) states that a conceptual model should take into account both the topographical and geohydrological conditions prevalent, for it to be useful in understanding a groundwater system. However, availability of data and information is often the limiting factor in the development of these models, and often present initial understanding of the system.

In addition to conceptual models is numerical modelling. These are most widely used tools for groundwater evaluation (Liling et al., 2011), and offer better capability for hydrogeologists to elucidate groundwater systems and processes. On the other hand, Yilanda et al. (2013) states that conventional practice for investigating hydrogeological conditions of aquifers involves the use of all data obtained from remote sensing techniques together with field based data and borehole information to develop conceptual model, which is then converted into a numerical model to predict the hydrogeological conditions of the aquifer. However, demand of mass data limits their application and hence simpler approaches are needed that utilise less data, and so far conceptual modelling provides such option.

Developing a conceptual model

The main objective of aquifer characterisation has always been to create sound understanding of the groundwater system, by evaluating properties of concern as per the situation of the catchment. This has evolved now, to involve the application of conceptual and numeric models to best understand the environment through which groundwater stores and reside, flows and discharges (Zhou, 2009). As a result, the outcome is a detailed representation of the groundwater system which can be used in decision making and planning about water resources. Spatial knowledge of the aquifer properties and creation of a groundwater models are required for achieving a sustainable management of the resource (Vouillamoz et al., 2012). The basic form of models useful to hydrogeologists is the conceptual hydrogeological model. Field data collection has always been the most costly component of groundwater exploration. However, models have shown to provide an alternative cost effective approach for understanding and making predictions of behaviour of complex hydrogeological systems (Nyende et al., 2013). The contributions of this study include the construction of hydrogeological frameworks (conceptual models) to provide an understanding of groundwater flow systems.

2.6 Theoretical framework

The theoretical framework applied in this study is that aquifer characterisation results in knowledge, and building understanding of the aquifer hydrogeological properties. In addition, this study regards aquifers occurring in the coastal areas or regions, particularly in South Africa as poorly characterised to uncharacterised. In order to provide an analysis of the aquifer hydrogeological properties, this study applies theory of aquifer characterisation as involving gaining insight or knowledge about the aquifer resource. This may involve use of various methods applicable in coastal regions in order to establish the aquifer hydrogeological properties.

The theory on coastal aquifers which are interpreted to present unique, complex conditions and under hydrological pressure, is used to justify the crucial need for assessing aquifer properties thereof. Another important theory used in this study is the theory of gravity-driven basin-scale flow of groundwater also known as regional groundwater flow theory by Toth (2009). This theory explains the formation of groundwater flow systems in a hierarchical order, from local, subregion to regional flow in large basins. In Toth's theory, regional flow systems of groundwater commensurate with the dimensions of the natural topographic relief, with the geology as the main actor. Hydrogeophysical principles are also applied, which relate geophysical parameters to hydraulic properties from which aquifer resources can be mapped.

2.7 Chapter summary

This chapter was based on the review of the literature in relation to the aim of the study which is centred on improving understanding of hydrogeological properties in coastal aquifers. The review covered aquifer characterisation concept, with focus on mapping of the subsurface, estimation of aquifer hydraulic properties, establishing groundwater flow systems, and developing a groundwater conceptual model, as reflected in the objectives of the study. The main issues arising from the literature review included the problem of lack of characterisation studies in coastal regions. Most studies focused on seawater intrusion, contamination and simulation of complex groundwater flow systems. This was despite the fact that a thorough knowledge of the aquifer properties is essential for such studies. In terms of aquifer characterisation, the literature supports mapping of lateral boundaries and spatial definition of lithology, thickness, water table elevations, and flow direction of groundwater. In addition, should comprises also establishing geological units and their hydraulic properties such as porosity and transmissivity, faults, fractures, groundwater flow paths and the geometry of the aquifers including the type of rocks (Vereecken et al., 2005). However, the commonly used methods for aquifer such as hydraulic tests and borehole drilling left a gap between qualitative description of an aquifer given by logs and cores, and quantitative estimates of hydraulic properties derived from the traditional hydraulic tests (Paillet and Reese, 2000). Surface geophysical methods, such resistivity surveys have been stated to afford the capability to bridge this gap between data. The position of this study is to apply an integration of the hydrogeological methods, such as hydraulic tests and drilling with geophysical methods, and developing a conceptual model, to characterise aquifer in coastal regions. The approach of using an integrated approach, including complimenting methods in aquifer characterisation is also suggested in several studies, such Paillet and Reese (2000) and Lasher (2011).

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

This chapter presents the study research design which includes description of the study area and its physiographic factors, criteria for site selection including methods applied in data collection and analysis. Steps taken to ensure data quality control, limitations of this study and ethics of the research are also presented accordingly. This is to address the problem of lack of knowledge of the aquifer properties distribution in coastal regions.

3.2 Research design

3.2.1 Study design

This study established some preliminary ideas about the properties of aquifers within the study area to improve understanding on aquifer hydrogeology in coastal regions. The approach used in this study provided a systematic characterisation of the aquifer resource, with four stages (i) by mapping of the subsurface and providing information on physical properties such groundwater units and rock type (ii) estimation of the aquifer/hydraulic properties and (iii) establishing groundwater flows, focusing on flow directions and hydraulic gradients, and (iv) developing a conceptual model for characterising the groundwater flow system. This approach provided initial characterisation that allows for better understanding of the aquifer resource for various needs such in groundwater resource development and management.

Sampling design

To assess the subsurface hydrogeology, which included mapping of groundwater units, depth and groundwater layers, using surface geophysical resistivity method, the area encompassing Voelvlei, Soetendalsvlei and the section of the Nuwejaars River to its confluence with the Soetendalsvlei from Eilandsdrift to Wiesdrif, was selected for the case study surveys on mapping of subsurface and, drilling of boreholes and piezometers. This was important due to that information and knowledge regarding the contribution of groundwater to those systems was limited this area.

In order to determine groundwater levels and conducting hydraulic test for establishing aquifer hydrogeological properties, 23 well-points and three (3) boreholes were drilled. These were not equipped with a pumped, and were used as piezometers for monitoring of water levels and conducting hydraulic tests. Existing boreholes were also used in measuring of hydraulic head to establish regional groundwater flow direction in the study area. The groundwater levels were monitored from November 2015 to May 2016, covering both wet and dry period.

Required data and sources

In this study, data on aquifer physical and hydraulic parameters such as transmissivity and hydraulic conductivity, water levels, subsurface resistivity were collected. Due to lack of data and information from literature, field measurements were the main source of data. Geological and topographic maps from the Council of Geoscience were used for sourcing information of the geology type and elevations within the study area. These were used to construct a hydrogeological conceptual model of the study area.

3.2.2 Study area description

This study focused on the Heuningnes Catchment which was used as a case study area for characterising aquifer hydrogeological properties in coastal regions. This catchment is located within the Western Cape Province in the Eastern Overberg region. It extends into the Agulhas Plains, situated along the southernmost tip of Africa (figure 5), and has a catchment area of about 1400km^2 (Pauw, 2012).

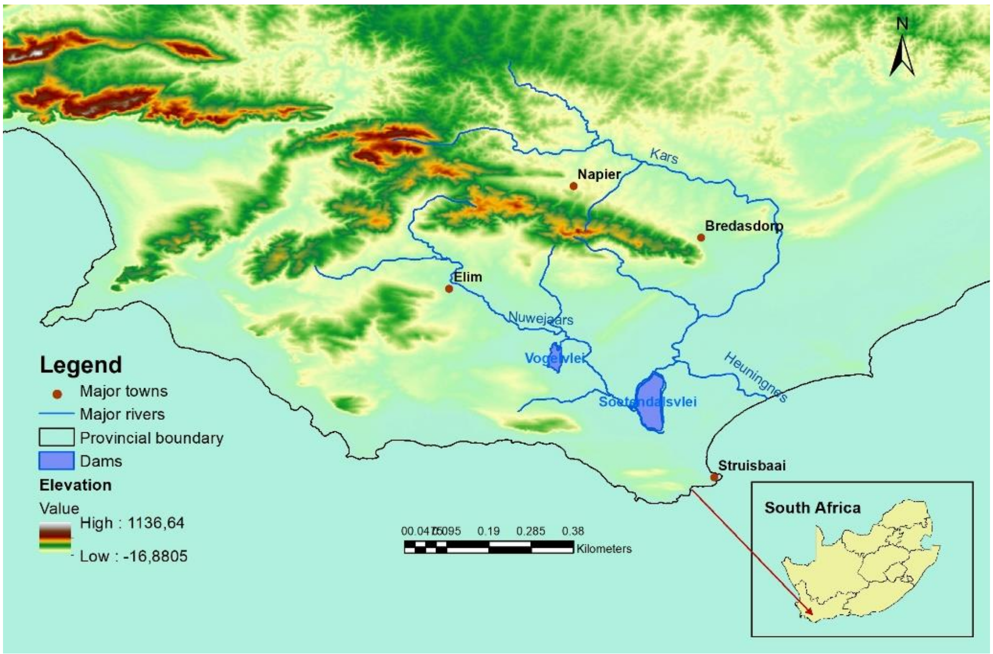


Figure 5: Location of the Heuningnes Catchment Agulhas Plain, Western Cape

The Heuningnes Catchment is classified as a tertiary catchment and constitutes five quaternary catchments, namely, G50B, G50C, G50D, G50E and G50F (figure 6). These quaternary catchments are nested within the tertiary, secondary and primary catchments accordingly, and they are described as units of similar runoff volumes (McCartney et al., 2003). The large part of this study is focused on G50C quaternary catchment.

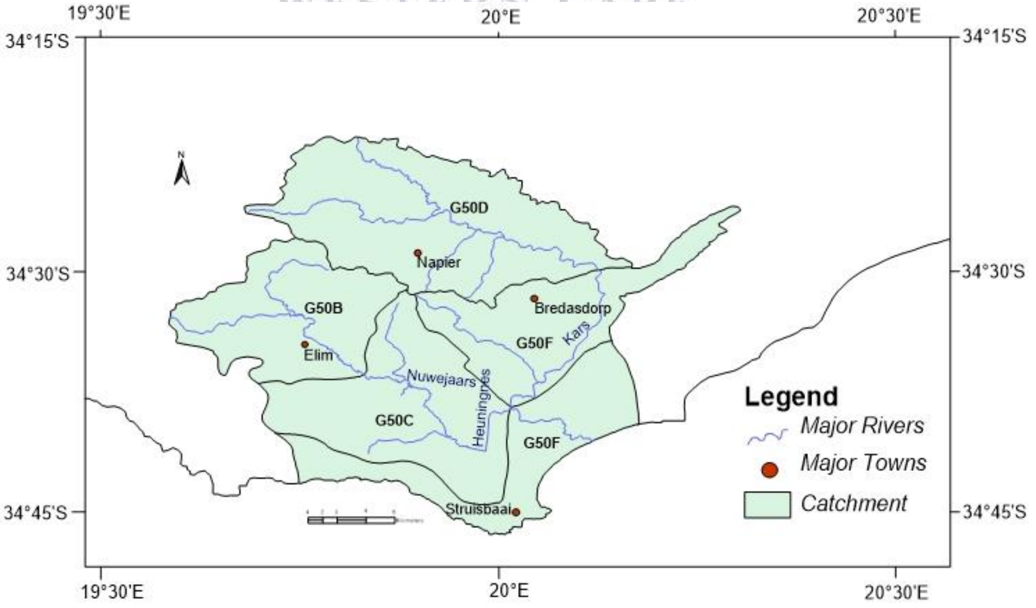


Figure 6: Quaternary catchment map of the Heuningnes Catchment

Influence of climate (rainfall and temperature) on groundwater availability

The Heuningnes Catchment experiences Mediterranean climate and falls within the Winter Rainfall Zone (WRZ) of South Africa. This type of climate is characterised by warm, dry summers and cool, wet winters.

Precipitation: rainfall

In the Heuningnes Catchment, rainfall patterns differ between the high elevated areas and the lower ones. Frontal rainfall is the most dominant type, while orographic rainfall partly dominates the upper hilly reaches of the catchment (Bickerton and Pierce, 1984). The mean annual rainfall varies between 400 and 600 mm per year (Pauw, 2012). High rainfall occurs in the winter months, consequently increasing water availability for groundwater recharge (figure 7).

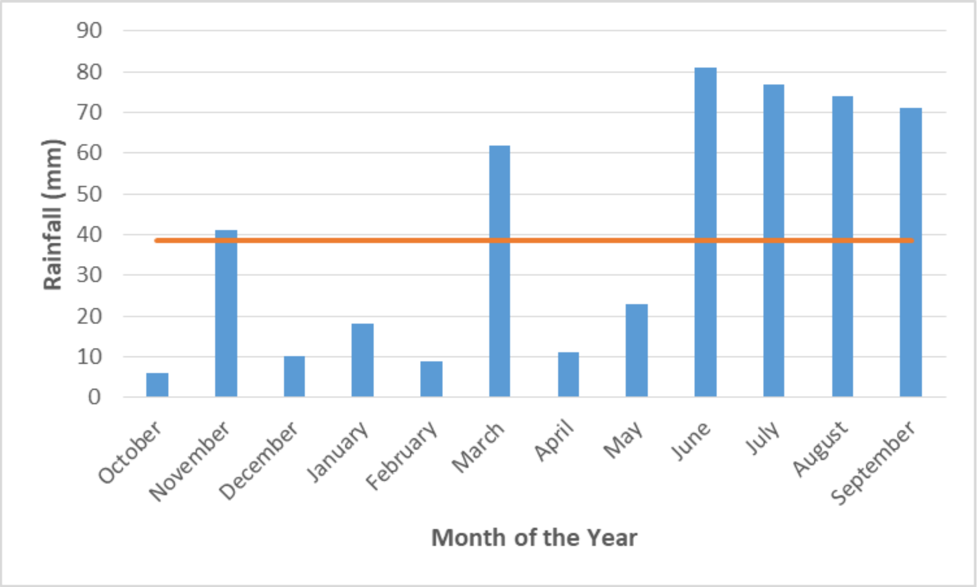


Figure 7: Monthly rainfalls (mm/month) in Heuningnes Catchment (data from DWA station no. G5E001)

Of the total annual rainfall, about 65% occurs in winter (Carr et al., 2006). The Mean Annual Precipitation (MAP) is approximately 447 mm per year (Pauw, 2012). However, on the mountain areas MAP can exceed 1000 mm while in the remaining part of the catchment exceed 600 mm (Brown et al., 2003). High evaporation rates are experienced in summer, and subsequently reducing water availability (figure 8).

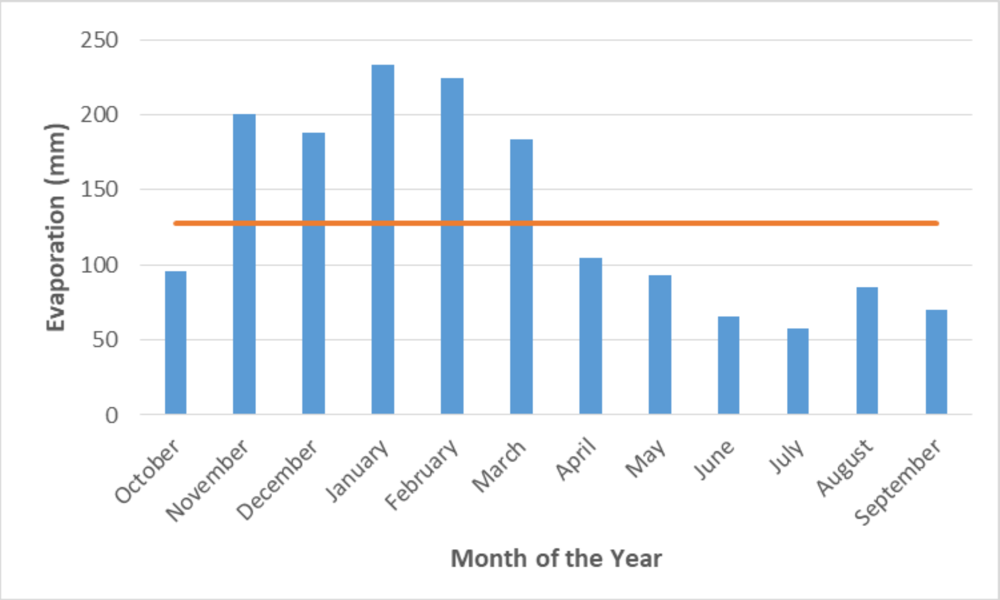


Figure 8: Monthly evaporation (mm/month) in Heuningnes Catchment (data from DWA station no. G5E001)

Temperatures

Average daily temperatures reach their maximum in summer month of January (about 28°C) and minimum in winter month of July (about 6°C) (Pauw, 2012). This has impact on the availability of water to recharge into groundwater during different times of the year.

Influence of geology on groundwater availability

The dominant geology types in the Heuningnes Catchment are Bredasdorp Group, Bokkeveld Group and Table Mountain Group (TMG) (figure 9). Outcrops of the intrusive Cape Granite Suite and Malmesbury Group also occur within the catchment (Bickerton and Pierce, 1984). The Bokkeveld Group and TMG belong to the Cape Supergroup rock formations and formed over 350 to 450 million years ago. Both the groups are intruded by the basement lithologies in the Heuningnes Catchment (Bickerton and Pierce, 1984).

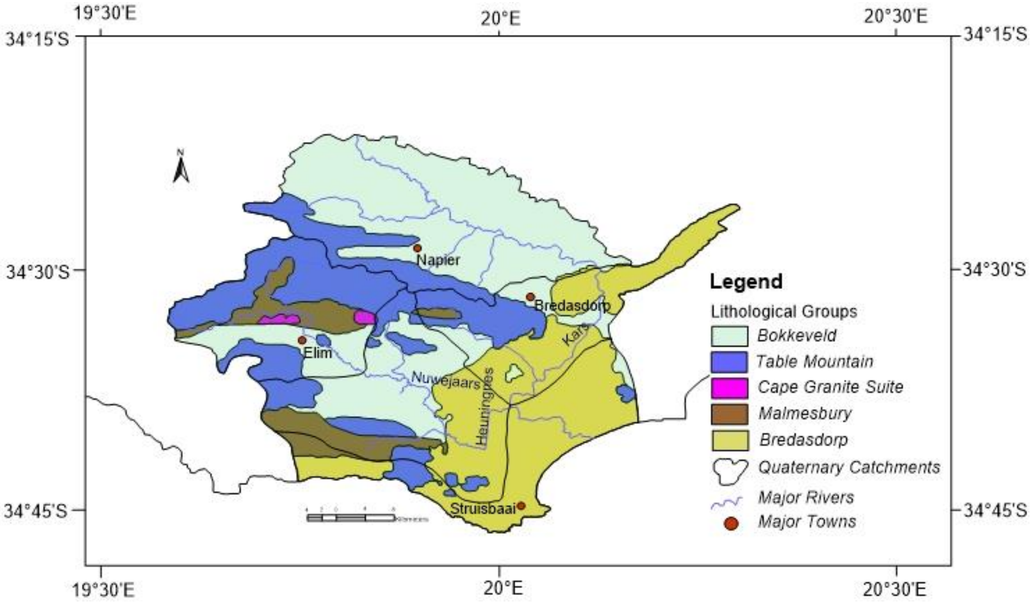


Figure 9: Geological map of the Heuningnes Catchment

Bredasdorp Group

The group overlies the Bokkeveld Group of the Cape Supergroup units, and is made of quaternary deposits. This geology (calcified dune sand and coastal limestone) dominates the areas around the Soetendalsvlei Lake and Heuningnes Estuary. Unconsolidated sands cover some areas around Struisbaai, and a section of the estuary (Bickerton and Pierce, 1984).

Bokkeveld Group

This geological group is sandwiched between the Bredasdorp Group and the Table Mountain Group (TMG). Fractures and faulting does occur within this formation. The Bokkeveld Group formation is susceptible to weathering, and is intruded by the basement lithologies. Within the Heuningnes Catchment, shale and sandy shale of the Bokkeveld Group dominate the area towards the eastward part of the catchment between Elim and the Soetendalsvlei Lake. Groundwater from this formation is commonly saline, which originate from the geology (Gordon et al., 2011).

Table Mountain Group (TMG)

The TMG overlies, and is intruded by the crystalline basement units of the Malmesbury and Cape Granite Suite groups. It forms the backbone of the Cape Fold

Belt Mountains (CFBM), being the lowest component of the Cape Supergroup (Brown et al., 2003). Mountain ranges such the Heuningsburg and Bredasdorpberge are some of the visible features of the TMG within the Heuningnes Catchment. Fracture and faulting dominates the weathering resistant geology. Rock types of the TMG include quartz, sandstone and shale which dominate the northern and western part of the catchment.

Cape Granite Suite and Malmesbury Group

The two geologies are basement crystalline formations which intrude into the overlaying groups, TMG and Bokkeveld. Patches of the Cape Granite Suite occurs on the pockets of the Malmebury Group in the north westerly part of the town of Elim. Outcrops of the Malmesbury Group occur along the south edges of the TMG formation Mountain ranges of Bredasdorpberg.

Faulting in the geology

In the study area, faulting is prevalent, with fault lines running almost east-west direction. Two major fault lines that runs southeast-to northwest also occur in the catchment (figure 10). Identifying these faults in the catchment is essential as they can act as groundwater boundaries that restrict or facilitate the movement of groundwater.

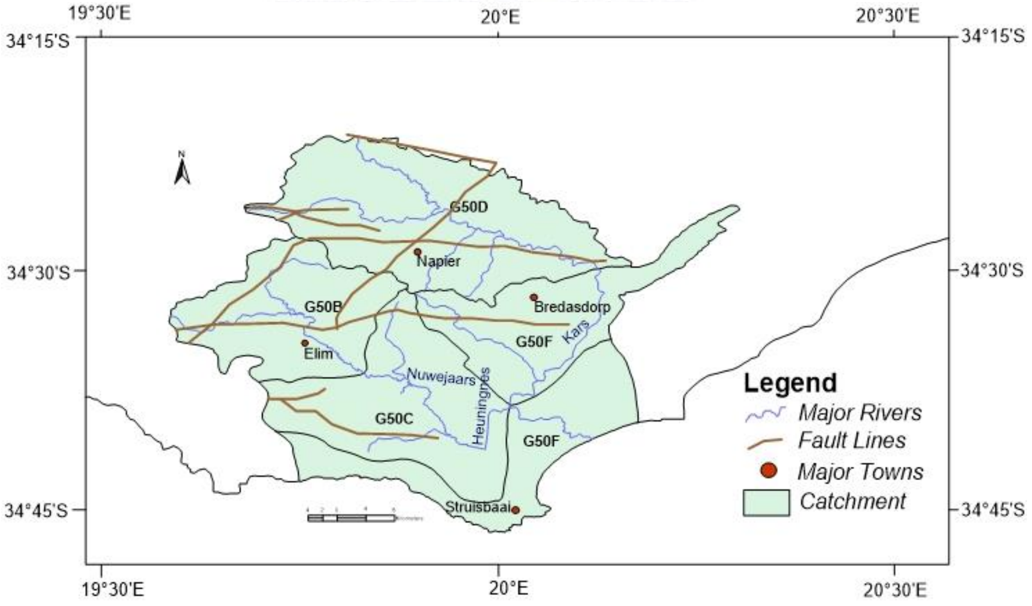


Figure 10: Geological fault map of the Heuningnes Catchment

In the catchment, faulting occurs mostly on the Bokkeveld and Table Mountain groups (figure 11), giving rise to secondary porosity in these formations. The characterisation of faults in these geologies is essential in gaining knowledge of the aquifer properties.

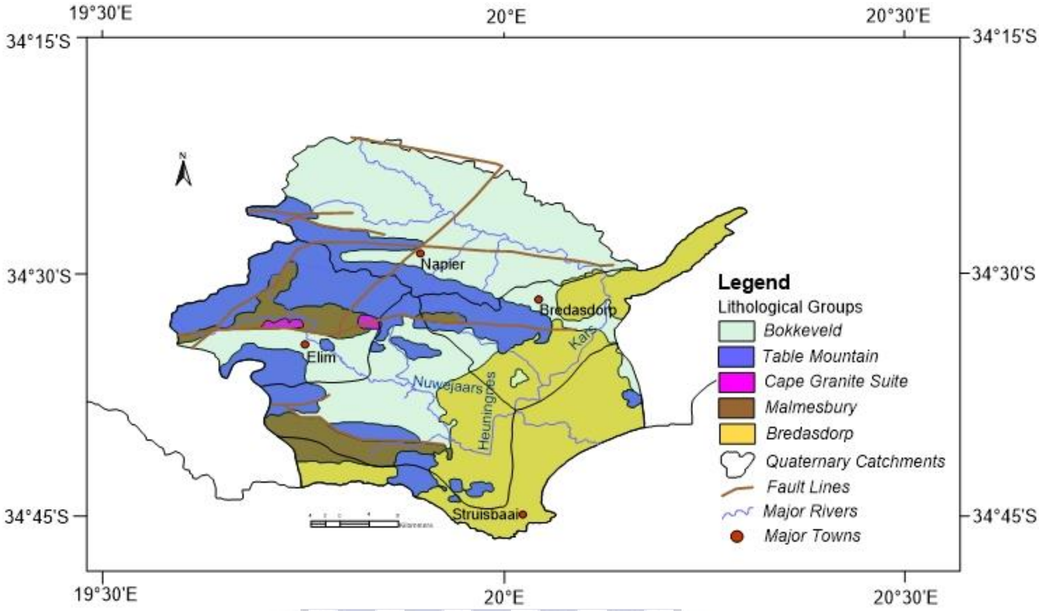


Figure 11: Faults and geology map

Implication of hydrogeological setting

Both primary and secondary aquifers occur within the catchment. Primary aquifers, formed from unconsolidated sediments which have been deposited as alluvium in floodplains of major river systems (Price, 2013). These aquifers typically occur in low rainfall areas and mainly recharged during high flows and flooding in wet seasons. Secondary aquifers on the other hand, are most widespread and extensive. These include the TMG quartzites and the Bokkeveld Group shales. The water in these aquifers is stored in and flows through the fracture and fault systems (Lasher, 2011).

The TMG aquifer has high yields due to much faulting and fracturing, and water quality is generally good, and of low TDS. On the other hand, the Bokkeveld aquifers are low yielding due to lesser degree of faulting, and water quality is generally poor, and of high TDS, usually inherent from the rock formation through which groundwater flows (La Maitrea, 2000). Aquifers of the Bokkeveld Group provide groundwater of moderately to highly salinity levels and consist mainly of shale materials.

The main aquifer types within the study area are fractured rock aquifers and alluvial aquifers. The principal groundwater system within the Heuningnes Catchment is of the TMG (table 1). Other “minor aquifers” occur, and these do not yield any substantial water to boreholes.

Table 2: Lithology and hydrostratigraphy of the dominant geology in Heuningnes Catchment (after Brown et al., 2003 and Blade et al., 2010)

Geological Group	Lithology (Rock type)	Hydrostratigraphy
Bredasdorp beds	Quaternary deposits	Limited aquifer
Bokkeveld	Shales, sandy shales	Low yielding (fractured rock system)
Table Mountain (TM)	sandstone quartzite, shale partings, shale, conglomerate,	High yielding aquifer (highly fractured rock system)
Cape Granite Suite	Basement rocks	Aquitard
Malmesbury		

Hydraulic properties

The TMG aquifers tends to be heterogeneous and anisotropic. This is due to the fractured and faulting nature of the TMG rocks. Hydraulic conductivity and storativity values have a range of 1.99 to 0.00199 m/d (Rosewarne, 2001 in Lin and Xu, 2006) and 0.0001 to 0.001(Duah and Xu, 2013) respectively. On the other hand, Bredasdorp Group aquifer properties are regionally homogenous and isotropic, due to their alluvial nature. Information on hydraulic conductivity, transmissivity and storativity is limited for this formation.

Recharge

Groundwater recharge is a major limiting factor on groundwater availability. This variable is important for assessing groundwater resources. In the TMG area, recharge has been stated as ranging from 1% to 55% of annual rainfalls using different type of methods (Duah and Xu, 2013). The recharge to groundwater is expected to vary with location due to the fractured nature of the aquifer system. On the other hand, little is known about recharge of groundwater in the Bredasdorp alluvial aquifer.

3.2.3 Selection and description of study sites

Four sites were selected for carrying out investigations on aquifer hydrogeological properties in the study area, and these are Site 1: Voelvlei, Site 2: Eilandsdrift-Wiesdrif, Site 3: Bosheuwel and Site 4: Soetendalsvlei (figure 12).

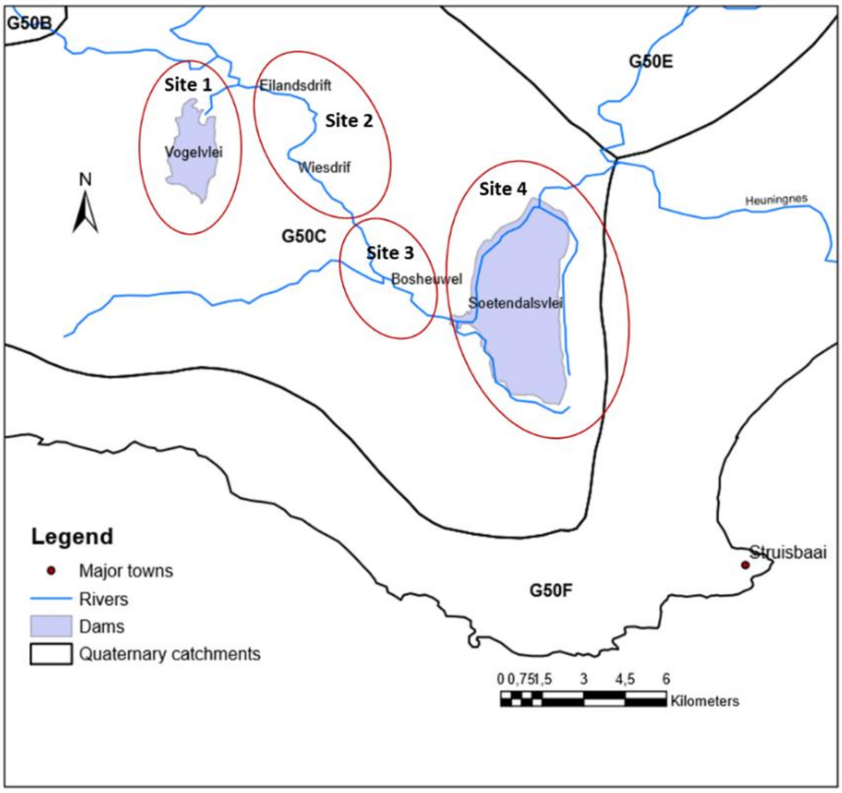


Figure 12: Location of study sites

These sites are located in the lower part of the catchment within quaternary catchment G50C. The sites are characterised by various wetland systems, and were selected partly because the area is strategically important for research and provides an opportunity not only to meet the objective of this study, but also address other pressing issues on the hydrology of the catchment, such as understanding groundwater interactions with wetland systems. The three sites provided a fair representation of the catchment groundwater conditions. On these sites, resistivity surveys were conducted, and subsequent to that, wellpoints and boreholes were drilled. This offered an opportunity to characterise the stratigraphic units of the aquifers at the selected sites.

3.3 Research methods

3.3.1 Data collection methods

In aquifer characterisation studies, the commonly applied methods globally are geological mapping and cross-sections, geophysical methods, drilling, hydraulic tests and remote sensing (Paillet and Reese, 2000; Botha et al., 2000; Tse and Amadi, 2008; Dippennar, 2008; Xu et al., 2009; Lasher, 2011; Vouillamoz et al. 2012). However, other case specific methods such Fluid Electrical Conductivity logging (FEC) are also employed. In this study, a combination of surface geophysical method, drilling and hydraulic tests was applied as the standard for aquifer characterisation in various geologic settings. This provided an integrated approach in determining aquifer characteristics, and properties like aquifer permeabilities.

The advantage of applying a combination of surface geophysical method, drilling and hydraulic tests is that, the methods complemented each other in terms of the type of data (qualitative and quantitative) that is obtained. Another advantage, is that these methods have a larger scale of application as they are not strictly limited to a certain geological setting. The limitation of these methods lies in the high cost of equipment involved and in borehole drilling process. Besides this limitation, this study used the stated methods as they provide reasonable data and have capacity to be employed for various geological settings. The methods employed are presented below in details, and these are discriminated as per the characteristics being investigated.

Subsurface mapping

The various methods employed in mapping of the subsurface in hydrogeological investigation are commonly surface and invasive geophysical methods, remote sensing including core and well logging. Since the advent of the application of geophysical methods in groundwater investigation, surface geophysical methods have become the standard for aiding in siting of new wells or well location investigations, and mapping of hydrogeologic units of shallow to relatively deep aquifers. Among surface geophysical methods (Electrical Resistivity methods; Electrical Resistivity Tomography; Electric Magnetism), Electrical Resistivity method was used in this study. The method has the capability to indicate the presence of dykes and position of weathered zones (Vereecken et al., 2005). It gives an image of the groundwater zones, and controlling properties, apart from climatic controls. In this study, the use of resistivity method assisted in borehole siting and producing site-conceptual models indicating flow directions of groundwater in the study area.

Unlike pumping tests and other point measurements methods, Resistivity geophysical method allows large scale characterisation of aquifers (Binley et al. 2010). The benefits of this method include providing a 2D profile of the subsurface resistivities and allows mapping of hydrogeologic units (shows water bearing zone; faults and weathered zone including water content) as indicated. Limitations of Electrical Resistivity method includes that, the method does not provide a spatial coverage of resistivity over an area but, along transect. Also, the application of the method requires prior knowledge of the catchment conditions, for example, if the area being investigated is a coastal or inland setting. Regardless of these limitations, this study, used Electrical Resistivity method for mapping of aquifer units within the study area.

Borehole drilling and sampling

Borehole drilling commonly involves making a vertical hole into the ground surface and taking samples of the aquifer materials at determined interval to establish their properties such as rock type, fracturing, faulting, texture and composition. Heavy machinery is used, with a drilling bit mounted on the drilling rod which is stationed on a truck. Various drilling methods include Percussion drilling for harder surface rock drilling and Mud-Rotary for drilling in soft, sandy and alluvial materials (Price, 2013). This study used Mud-Rotary drilling method for establishing characteristics of the aquifer materials and geological units within the study area.

Aquifer parameter estimation

In groundwater studies, important hydraulic parameters of interest are hydraulic conductivity (K) and specific yield (Sy), transmissivity (T) and storage coefficient, aquifer storage, well yield, specific capacity, well efficiency and aquifer productivity including other parameters such as safe yield, sustainable yield and blow yield (Busari and Mutamba, 2014). These parameters are crucial in groundwater investigations and management. For example, aquifer hydraulic conductivity parameter is of much interest when dealing with groundwater flows as it explains the properties of an aquifer to allow groundwater to freely move through it, while the transmissivity parameter is more important in groundwater developments as it explains the flow of groundwater readily to wells (Price, 2013). However, often these parameters are never determined concurrently. In this study, hydraulic conductivity (K), saturation thickness and transmissivity were analysed.

The commonly used methods in estimation of hydraulic conductivity, and transmissivities are field methods such as pumping tests; bailer tests and slug tests. However, in a study by Vouillamoz et al. (2012), an unconventional approach that employs both non-invasive geophysical methods and hydrogeological monitoring was used to estimate key aquifer parameters and water resources of an unconfined coastal aquifer. The application of these methods as in Vouillamoz et al. (2012) is however not a standard practice in groundwater resource investigations. In this study, slug test method was used. The advantage of this method is that it is quick and cheap to conduct and works well in low yielding aquifers, conditions which often is difficult to use pumping test on. The limitation include that the method provide a point-measurement, and not reprehensive of a large area. Nevertheless, this study used slug test method in order to determine aquifer hydraulic conductivities and transmissivities, due to the condition of the aquifer, which are low yielding.

Slug test is another type of hydraulic test used for low yielding wells and in situations where groundwater is contaminated, and is suitable for conditions in coastal areas where pumping tests can induce contamination of aquifers from saline water. The method provide point measurement and works as a single well test. There are two types of slug test, a falling head test and rising head test (MacDonald et al., 2008). The rising head test is conducted by instantaneously causing a change in the head by removing water from the piezometer, while a falling head is conducted by causing a change in the head by adding water to the piezometer and monitoring the recovery of the water level to its initial head. If a bailer is used to remove a slug, the test is often referred to as bailer test. This study used bailer test, and conducted rising head tests.

Aquifer productivity

In order to determine aquifer productivity, this study used the approach as in MacDonald et al. (2004), Banks et al. (2005) and Graham et al. (2009) of using borehole yields to represent the productivity of an aquifer. In this study, data on borehole yields were collected using a pump and a 20 litre bucket, and measuring the time it takes to fill the bucket during pumping. The advantage of using this approach is that it is cheap and provides accurate reliable results. The limitation of using this method is that, it is labour intensive and small variations in borehole yields may not be determined.

Groundwater flow dynamics

When determining groundwater flows and directions, the commonly applied methods are cross-sectional method, flow nets and three point method also known as triangulation (Heath, 1983). These standard methods involves determining hydraulic heads by measuring of the water levels in boreholes or piezometers installed in alluvial deposits (Freeze and Cherry, 1979). Freeze and Cherry (1979) define a piezometer as a tube or slotted pipe that is inserted into the ground for the purpose of measuring the hydraulic head in the subsurface at a particular point. Several piezometers and boreholes drilled, including existing boreholes in the study area were used.

With increased need to determine flow in complex setting and under different scenarios, models are common tools that are used in mapping groundwater flows and directions. In this study flow nets and cross-sectional methods were used for determining regional and local groundwater flow in the study area. Also, a hydrogeological conceptual model incorporating flows was developed, of which can be useful in understanding the role of groundwater in the hydrology of wetlands and rivers in the study area.

The advantage of applying a combination of a cross-sectional method and flow nets, is that both local, intermediate to reginal groundwater flows can be determined. The methods complement each other and allow for groundwater flows to be determined in situations where wellpoints are few. The limitation of these methods include failure to cover temporal flows, and that established flows are representative for a particular period of time. In addition, the methods do not capture vertical flows, but only apply to horizontal flows and in certain strict conditions. Irrespective of these limitations, this study used the above stated methods in order to determining groundwater flows directions at selected sites within the study area.

Using information from geological maps, an approximation of regional groundwater flow directions within the study area was carried out. The technique is analytical and manual in practice; however, software packages and programs exist to model flows.

Groundwater flow directions and hydraulic gradients

The direction of local groundwater flow can be determined from the differences in hydraulic heads between individual piezometers nested together (at least three in a triangular arrangement). In the case of horizontal flow, the hydraulic gradient can be calculated from the difference in hydraulic heads and the horizontal distance. For vertical component of groundwater flow, which is particularly important to understand the interaction between groundwater and surface water, a piezometer nest may be installed, with two or more piezometers set in the same location at different depths.

For vertical flow, hydraulic gradient can be calculated from the difference in hydraulic heads and the vertical distance. Furthermore, vertically distributed piezometer data can be used to draw lines of equal hydraulic head for the construction of a flow field map. This map shows the groundwater flow behaviour in the vicinity of a surface water body. The piezometer method provides point measurements of hydraulic head. The equipment is quick and easy to install, and measurement analysis is straightforward (Kalbus et al., 2006). Therefore, this method is appropriate for small-scale applications and allows a detailed survey of the heterogeneity of flow conditions in the subsurface. In this study, head difference in piezometers postulated on a geophysical models, were used in order to develop a conceptual model of groundwater flow at selected sites within the study area.

3.3.2 Data analyses methods

In addressing the objectives of this study on mapping of groundwater units, estimation of the aquifer parameters, establishing groundwater flow directions and flow system, and developing a hydrogeological conceptual model of groundwater flow. The following methods were used for data analyses and interpretation in this study.

Subsurface mapping

Analysis of field resistivity data, including model interpretation were carried out using RES2DINV software programme. Two dimensional (2D) resistivity models generated using the software, were used to identify and interpret the aquifer hydrogeologic units and features. The RES2DINV is a standard for carrying out inversion of surface geophysical data. The wide application and acceptability, is the most benefit of using this software tool.

Borehole or well profiling

Well samples which indicate the type of materials that were penetrated through, during well drilling were photographed. Subsequent to that, graphical profiles indicating the geological materials and their associated depth were produced. This allowed for analysis of the aquifer materials from different wellpoints to be compiled into a cross-section profile.

Aquifer parameter

The commonly used methods in the analysis of bailer tests/slug tests data, are Hvorslev (1951), Cooper et al. (1967), Papedopulus et al. (1973) and Bouwer and Rice (1976). This study used Bouwer and Rice (1976) and the Hvorslve (1951) methods for estimating aquifer hydraulic conductivity. The methods are applied for unconfined and confined aquifer conditions, and used for both fully and partially penetrating wells (figure 13).

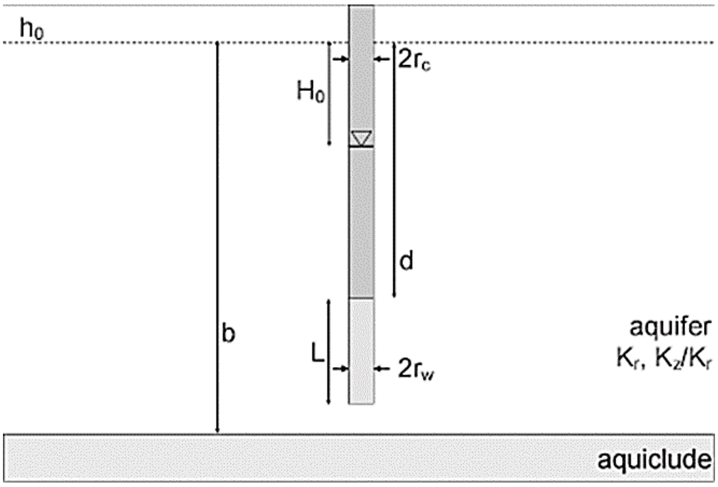


Figure 13: Typical control well configuration for slug test in unconfined aquifer with fully submerged well screen (http://www.aqtesolv.com/bouwer-rice.htm)

The Bouwer and Rice method is represented by the following equations:

Equation 2: Equation for estimating hydraulic conductivity (Bouwer and Rice, 1976)

$$K = \frac{rc^2 \ln(Re/rw)}{2 \cdot Le} - \frac{1}{t} \ln\left(\frac{h0}{h}\right)$$

where K is hydraulic conductivity (L/T), rc is the radius of the well casing (L), rw is the radius of the well (including gravel envelope) (L), Re is the radial distance over which head is dissipated (L), Le is the length of the screen (L), t is the time since h=h0 (T), h0 is the drawdown at time t=0 (L) and h is the drawdown at time t=t (L). For partial penetrating wells, and fully penetrating wells, Bouwer (1989) has presented a methods of estimating In(Re/rw) on the equation as follows.

Equation 3: Partial penetrating wells

$$\mathbf{\ln(\boldsymbol{Re/rw}) = \left[\frac{1.1}{\ln(\boldsymbol{Lw/rw})} + \frac{\boldsymbol{A} + \boldsymbol{B}\ln[(\boldsymbol{b} - \boldsymbol{Lw})/\boldsymbol{rw}]}{\boldsymbol{Le/rw}}\right]^{-1}}$$

Equation 4: Fully penetrating wells

$$\ln(Re/rw) = \left[\frac{1.1}{\ln(Lw/rw)} + \frac{C}{Le/rw}\right]^{-1}$$

where Lw is the length of the well in the aquifer, b is the thickness of the saturated material and A, B, C are dimensionless numbers represented in the following diagram.

On the other hand, the Hvorslev method is used for confined aquifers. However, Bouwer (1989) observed that the methods can be applied for unconfined conditions also. This was based on the observation that the water table boundary in an unconfined aquifer has little effect on slug test results unless the top of the well screen is positioned close to the boundary (Fabbri et al., 2012). Therefore, the Hvorslev solution for confined aquifers can be applied to approximate unconfined conditions. The basic Hvorslev (1951) equation, if the length of the piezometer is more than 8 times the radius of the well screen (Le/rw >8) (Fabbri et al., 2012), is the following.

Equation 5: Hydraulic conductivity equation by Hvorslev (1951)

$$K = \frac{rc^2 \cdot \ln\left(\frac{Le}{rw}\right)}{2 \cdot Le \cdot t0}$$

where rc is the radius of the well casing (m), Le is the length of the well screen (m), rw is the radius of the well screen (m), t0 (s) is the basic time lag and the time value (t) is derived from a plot of field data. Generally, t37 (s) is used, which is the time when the water level rises or falls to 37% of the initial hydraulic head H0 (m), the maximum difference respect the static level (Fabbri et al., 2012). Stress adjustment time lag and other sources of error are negligible in the Hvorslev (1951) analytical solution (Duffield, 2007).

For estimating aquifer transmissivity from slug test data, which cannot be directly done, this study used the Darcy’s Equation of flow to estimate the aquifer transmissivities. The equation estimate transmissivity as the product of the aquifer hydraulic conductivity and the aquifer saturation thickness (see equation 6 below).

Equation 6: Equation for estimating Transmissivity using Darcy’s law

$$T = Kb$$

where T represents the transmissivity in m^2/day, K is the hydraulic conductivity in m/s, and b saturation thickness of the aquifer in metres (m).

In order to determine borehole yields, which are used as indices in explaining aquifer productivity. The yields of boreholes, were approximated from the ratio of volume of water over time, and the time it takes to make that volume, often give in litre and time is seconds.

Tools for aquifer parameter analysis

The commonly used Softwares for analysing hydraulic tests data are AQTESOLV, Flow Characteristic (FC) -Excel programme and MLU (Multi-Layer Unsteady state). However, analysis can also be carried out manually using Excel spread sheets. AQTESOLV is regarded as the world leading software of pumping test data analysis with a wide application. This study used AQTESOLV software which has Bouwer and Rice (1976) and the Hvorslve (1951) solutions for methods estimating the aquifer hydraulic conductivity, with capacity to do analysis of high graphical quality (Duffield, 2007).

Aquifer productivity

This study used the approach as described in Tadesse et al. (2010), Banks et al. (2005) and Graham et al. (2009) for assessing aquifer productivity. In order to assess the groundwater resource of different aquifers, aquifer productivity which is mainly based on transmissivity (indicator parameter) variable, were analysed using borehole yields. The productivity of the aquifer were given as indices (for instance high, moderate and low) based on the values of borehole yields. The advantage of using this approach is that borehole yields data is often readily available and cheap to collect. In addition, yield data can readily be measure from even individual boreholes, while this may not be with other variables. The limitation of this approach is that borehole yields may not indicate the “full” productivity of the aquifer.

Mapping groundwater flow directions

This study used flow nets method, to determine regional groundwater flow directions. Using flow nets, the flow direction of groundwater are determined by mapping equipotential lines, which joins points of equal head and represent the height of the water table or potentiometric surface in confined aquifers (Heath, 1983). From the equipotential lines, flow lines are then constructed perpendicular to the equipotential lines. These lines indicate the direction of groundwater flow. Several software packages are available for mapping groundwater flow directions such as Surfer graphical software, MATLAB, Grapher (Golden software), Jplot and Python. This study used Surfer 9 graphical software in producing a map of flow nets indicating groundwater flow direction in the study area.

3.4 Ethical consideration

In this study, some of the study sites were located in private boundaries such as farms and a park (SANparks Cape Agulhas), with the area characterised by cropped fields and protected vegetation such as Fynbos and Renos`terveld species. As a result, a permission to carry out the research in such case was required, of which was submitted to the relevant authorities. All the relevant precaution were adhered to, in order to ensure that all the legalities and requirements are met as per the ethics of this study.

3.5 Limitations of study

This thesis is more of a case study and has limitation on data acquisition over the entire catchment. In addition, the study is only focused on determining the key hydrogeological properties of the aquifer, such as aquifer permeabilities, borehole yields and aquifer productivity classes, including groundwater flow directions. As a results, this study does not provides full characterisation of the aquifers. This is because other hydrogeological properties such as fracture and faulting network, including aquifer storativity were not covered in this study, as their analysis were beyond the capacity of the study. This study, thus provided preliminary understanding on aquifer properties; an approach not comprehensive in itself.

CHAPTER 4: USING RESISTIVITY SURVEYING FOR SUBSURFACE MAPPING

4.1 Introduction

This chapter is based on mapping of aquifer hydrogeological units using Electrical Resistivity method. It address objective one (1) of the study, which is to establish the groundwater units by determining their water saturation, resistivities, depths and thicknesses, thereby improving an understanding of the aquifer properties in the study area. The purpose of this chapter is to provide a description of the aquifer units important in siting of new wells for drilling. A description of the methods is presented, followed by key results, discussion and interpretation of such findings. Lastly a summary of chapter is presented.

4.2 Methods used

This study used Electrical Resistivity method for mapping of the subsurface and aquifer properties within the study area. Special attention was given to the identification of hydrogeological layers and features such as faults and groundwater zones. This was essential in order to assess the potential occurrence of groundwater within the study area, important in the siting on new wells. Investigations of the subsurface hydrogeology were thus carried out for selected sites in the Heuningnes Catchment. Of the four study sites selected in this study, three sites were chosen for conducting resistivity surveys. These were Site 1: Voelvlei, Site 2: Eilandsdrift – Wiesdrif, and Site 4: Soetendalsvlei (figure 14). Site 3: Bosheuwel (SANparks Offices), which forms part of the study sites selected for investigation in this study, was not selected for this purpose due issues of accessibility.

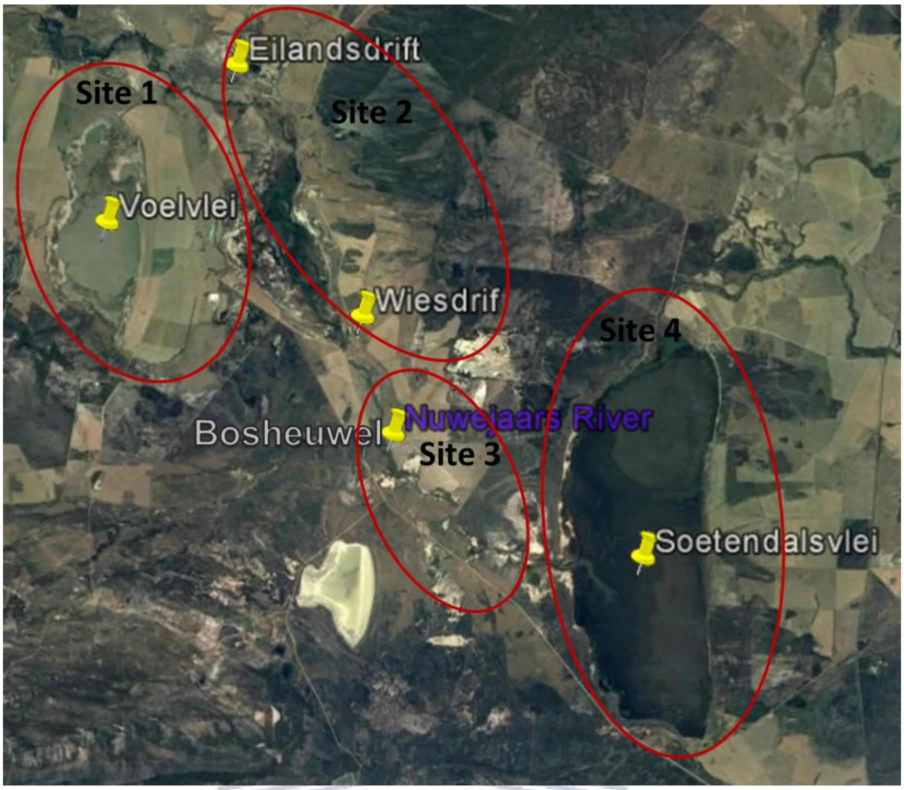


Figure 14: Satellite image of the study sites

The three sites, Voelvlei, Soetendalsvlei and Eilandsdrift -Wiesdrif were chosen due to their location near wetland and river systems. These systems are important water resources within the catchment. In addition, the role of groundwater in supporting these systems, has not been established within the catchment. Thus, the geophysical resistivity surveys in the vicinity of these systems provided the opportunity to establish connectivity of the wetlands and Nuwejaars River system to the aquifers system.

A total of eleven (11) resistivity traverses were conducted between September-October months 2014, at the three selected sites (figure 15). These were conducted perpendicular to the water bodies, with the traverses extending away from the edges of the water bodies. The distance covered varied between 160m for a small area to 240m for a larger area.

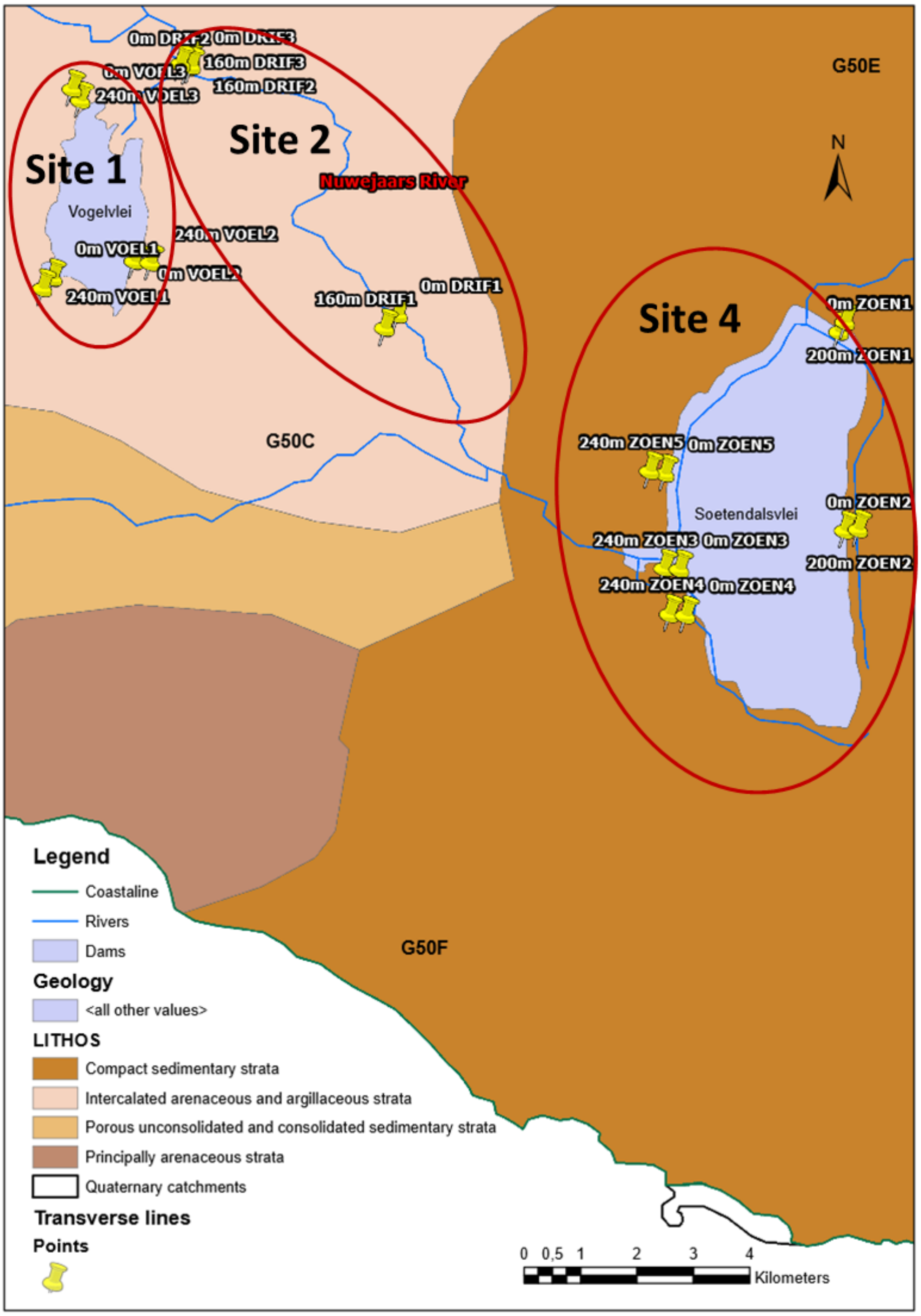


Figure 15: Location map of the geophysical survey transvers

An Abem SAS 4000 Terrameter and ES 10-64 switching unit were used during field resistivity surveys (figure 16). Four multicore cables and stainless steel pegs were used. The both “roll-along” for covering long distances and “single” survey techniques for short distance, were applied depending on the site conditions such as accessibility.

Figure 16: Resistivity surveys being conducted

The Wenner measuring protocol with an electrode spread of 160 meters (4 meter electrode spacing) was used, which yields a maximum investigation depth of approximately 30 meters. Electrodes were hammered approximately 30 cm into the ground. Since most part of the ground was wet, wetting of soils for minimizing soil resistance was not needed. However, at some sites the ground had to be wetted with water in order to induce conduction. Input current varied between 20 and 200 milli amperes.

A dumpy level with a graduating staff was used to take elevation measurements of the resistivity transvers. This was important to measure, in order for uneven surface or topography of the sites to be represented on the slope of the transvers on the resistivity models. Latitude and longitude coordinates of the resistivity transects were taken using a handheld GPS units. The coordinates were taken per 40m distance after each measurement for plotting transvers lines in the study area map. Naming of the transect lines, was based on the order in which the surveys were conducted.

The RES2Dinv inversion program was used to invert the measured data after being manually and mathematically filtered. This program made it possible to produce 2D geoelectrical or resistivity models of the subsurface, showing formations with varying resistivities. Resistivity models were interpreted based on the1:125,000 existing geological map (3419C, 3419D-Gansbaai, 3420C-Bredasdorp) of the Geological Survey. Known resistivities for particular geological materials and water type as provided in Palacky (1988) were also used to make interpretations of the models (figure 17).

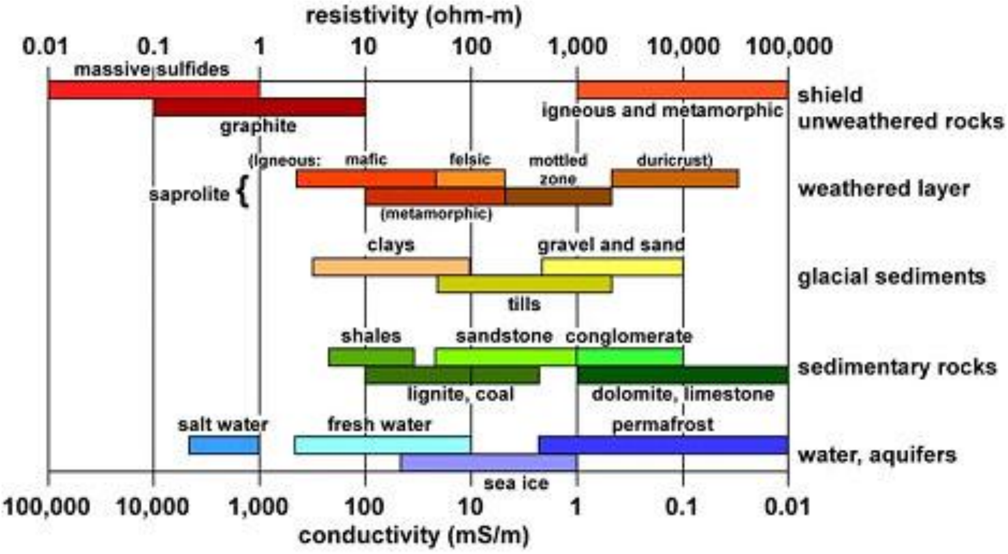


Figure 17: Typical range of electrical resistivities of selected earth materials (Palacky, 1988)

4.3 Mapping subsurface

Of the eleven resistivity surveys that were carried out, four traverses representing three sites (site1 Voelvlei; site2 Eilandsdrift –Wiesdrif and site4 Soetendalsvlei) were chosen for the results presentation. These are traverse VOEL3, ZOEN1, ZOEN2 and DRIF1, and provide a representation of the conditions mapped in the three sites. Site soil conditions and topography are provided along with the respective resistivity models.

4.3.1 Site 1: Voelvlei

Site conditions: the soil condition of transect lines at Voelvlei site indicated dry to relatively wet conditions. The topography of transect lines; VOEL1, VOEL2 and VOEL3 (figure 18; see appendix 1 for geoelectric model VOEL1 and VOEL2), dropped towards the vlei/wetland edge, with VOEL3 having flat a topography way from the vlei.

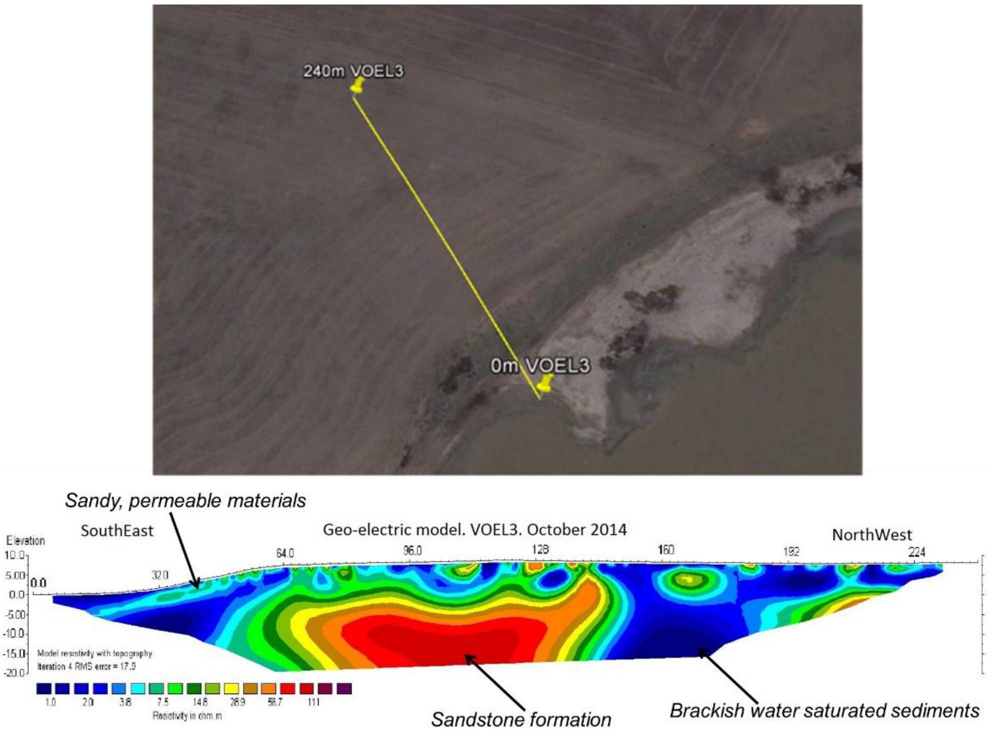


Figure 18: Electrical resistivity model at traverse VOEL3, Voelvlei site

4.3.2 Site 2: Eilandsdrift -Wiesdrif

Site conditions: at Wiesdrif (figure 19), soil conditions were relatively wet, to being moist towards the banks of the Nuwejaars River. Dry soils were observed after the road away from the river banks. At Wiesdrif, only one transect line (DRIF1) was made to right bank site of the river. On the other hand, two transect lines (DRIF2 and DRIF3) were surveyed at Eilandsdrift. The soil conditions at the site, were relatively dry along the survey line DRIF3, while traces of wet soils occurred north of the transect line DRIF3 and west of DRIF 2. During the resistivity surveys, the electrodes were wetted with water at some points to reduce the high resistivity of the soils or electrodes.

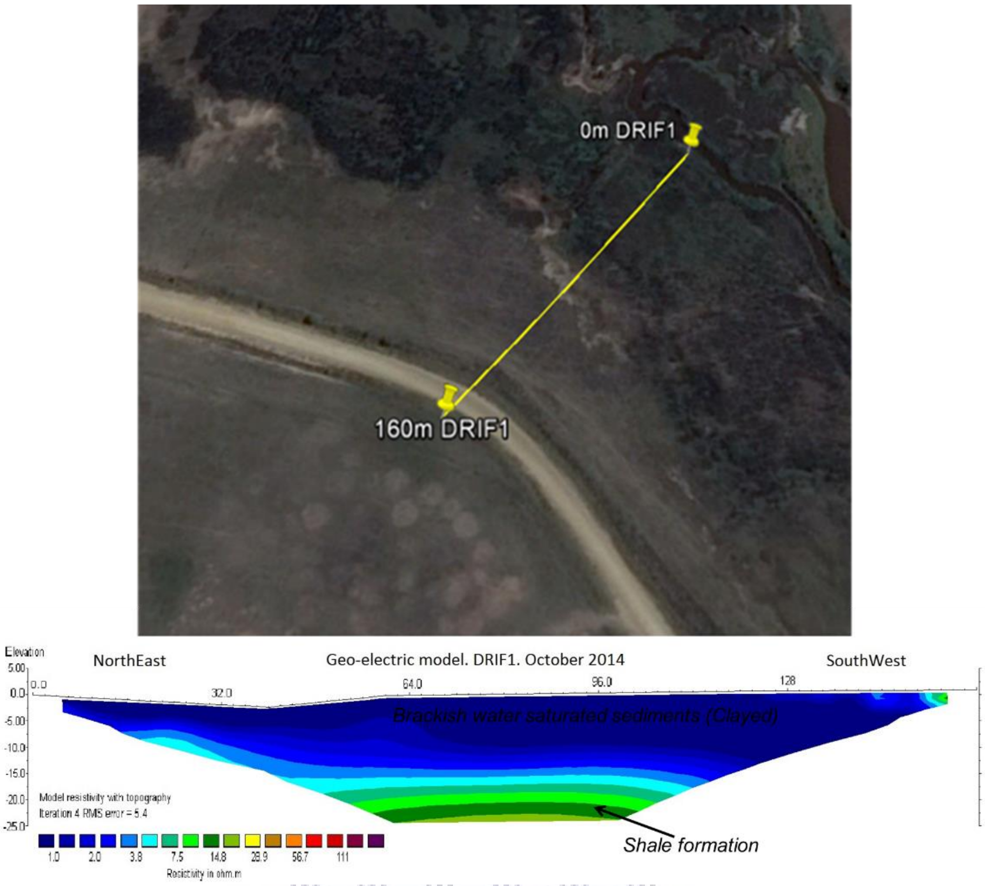


Figure 19: Electrical resistivity model at traverse DRIF1, Wiesdrif site

4.3.3 Site 4: Soetendalsvlei

Site conditions: At Soetendalsvlei site, the soil conditions were moist to wet and presented high conductivity conditions. The topography of the transect lines (ZOEN1, ZOEN3 and ZOEN4) was relatively flat, except for transect lines ZOEN2 and ZOEN5, which both have a topography that slopes towards the lake water edges (figure 20 and 21; see also appendix 1).

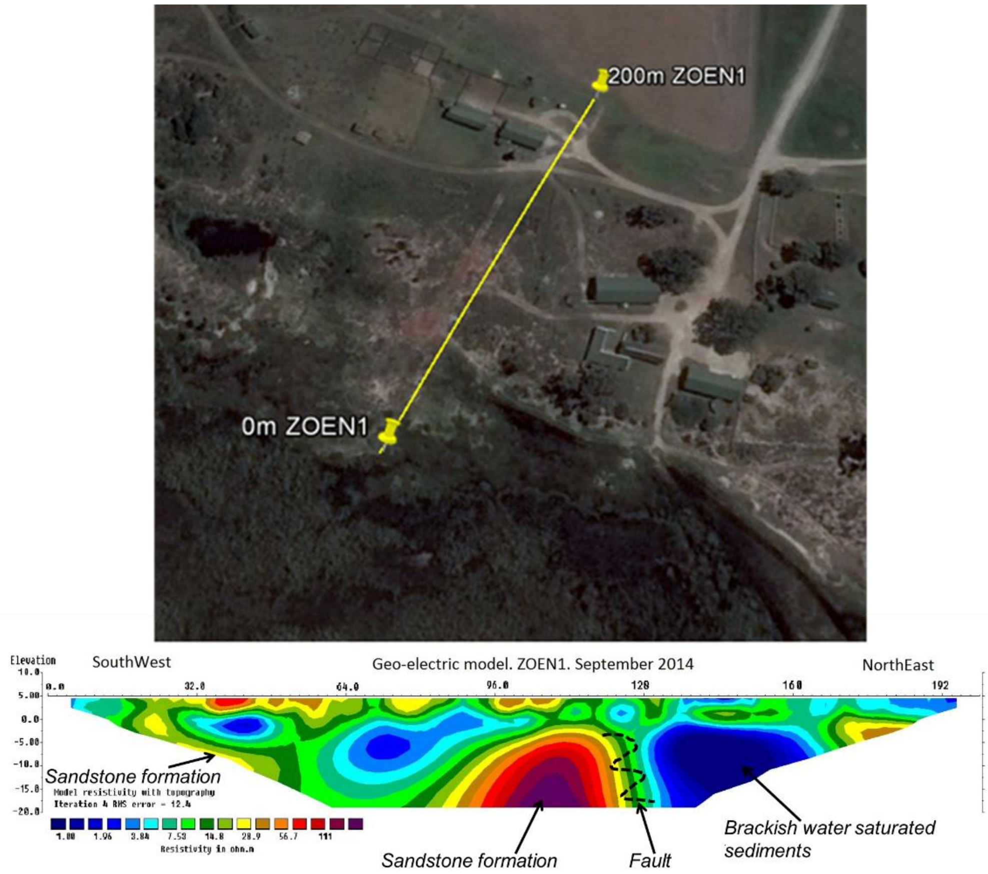


Figure 20: Electrical resistivity model at traverse ZOEN1, Soetendalsvlei site

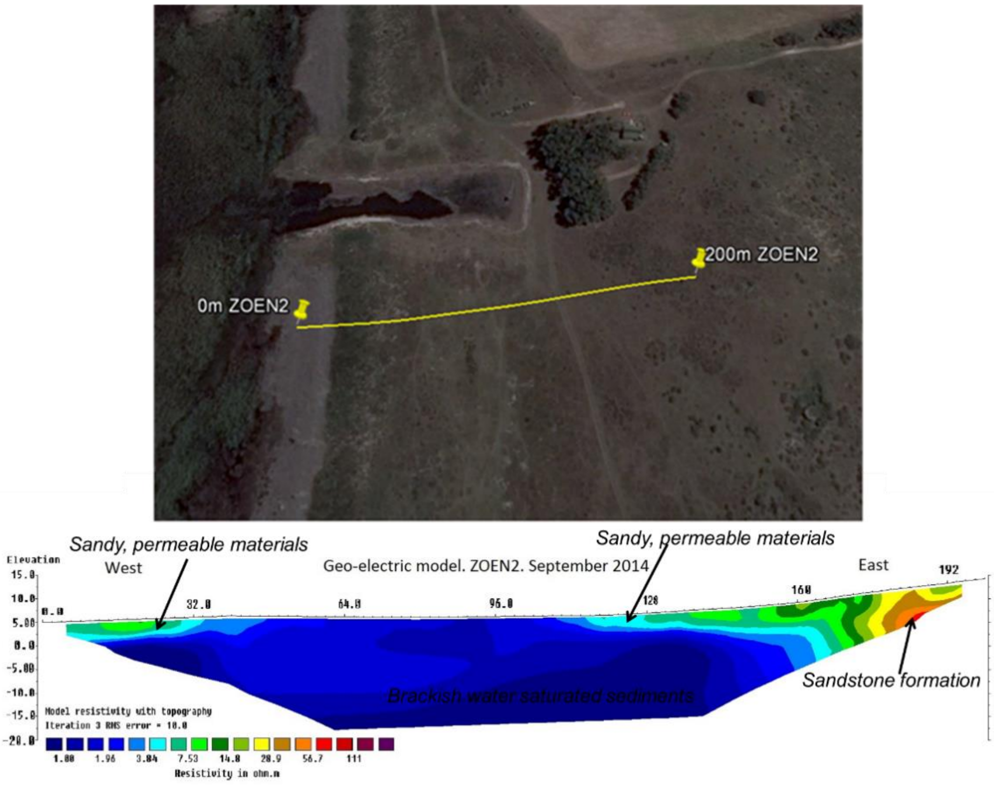


Figure 21: Electrical resistivity model at traverse ZOEN2, Soetendalsvlei site

For all the resistivity models (see also appendix 1), the inverse model resistivities ranged from less than (1 ohm.m) to slightly more than (111 ohm.m). Most of the models showed low resistivity conditions (less than 1 ohm.m), which are expected for a wetland dominated environment with history of marine transgression (Bickerton and Pierce, 1988).

On the entire models, about four layers were observed: a layer of resistivities below 2 ohm.m; with resistivities of between 2 ohm.m and 7 ohm.m; of resistivities between 7 ohm.m to 30 ohm.m; and of resistivities greater than 111 ohm.m. These were interpreted as brackish water saturated layer with clay; sand, permeable layer; shale layer; and sandstone layer, in the order. The interpretations were based on the geological information of the 1:125,000 study area geological map (3419C, 3419D-Gansbaai, 3420C-Bredasdorp). A layer with resistivities values between 30 ohm.m and 111 ohm.m was interpreted as weathered sandstone of which often overlies the high resistive layer of resistivities greater than 111 ohm.m. At transect ZOEN1, a fault structure was observed that cuts slightly vertical between the high resistive sandstone layers and, very low resistive layer saturated with brackish water (less than 2 ohm.m).

In terms of drill targets for groundwater exploration, the high resistive sandstone (more than 111 ohm.m) provides for a good groundwater exploration target for expectedly high yielding boreholes. Brown et al. (2003) indicated that the rock type is normally associated with high fracturing, and was susceptible to faulting. Fractures and faults are known to be good groundwater conduits in secondary aquifers, and hence the rock forms an important media for groundwater occurrence in the catchment.

The sand permeable layer of resistivities between 2 ohm.m and 7 ohm.m provides potential targets for shallow groundwater exploration at relatively low costs as would exploring the sandstone which mostly occurs at deeper depth of more than 30 m. On the other hand, it is noted that, a distinction between clay saturated layer and brackish water saturated layer could not be developed. The two layers fall within the same range of resistivity values of between 0 ohm.m and 2 ohm.m, thus making interpretation of the layers challenging and difficult to differentiate.

Palacky (1988) has indicated that, the high conductive nature of clay materials when saturated with fresh water and high salinity of groundwater conflicts in some cases, as both resulted in low conductive layers of similar resistivity values. This uncovers the limitation of the resistivity method being applied in coastal areas with clay dominated layers, as brackish groundwater becomes an issue to deal with during interpretation of the resistivity models.

Though, the electrical resistivity method indicated to have some limitation in providing a clear distinction between layers of similar resistivity ranges as observed on the resistivity models, and also stated in Palacky (1988). The method proved to be effective and to certain degree suitable for investigating the presence of groundwater in a coastal areas.

4.4 Chapter summary

This chapter investigated the shallow groundwater and subsurface stratigraphy at three selected sites (Site 1: Voelvlei, Site 2: Eilandsdrift -Wiesdrif and Site 4: Soetendalsvlei) in the Heuningnes Catchment using Electrical Resistivity method. Overall, a maximum of four layers of different resistivity value ranges were observed. These were interpreted as brackish water saturated layer (with clay); sand, permeable layer; shale layer; and sandstone layer based on geological information. However, the models did not provide a clear distinction between clay saturated layer and the brackish water saturated layer. Potential sites for siting of new boreholes for groundwater development were identified. The study uncovered the effectiveness of the use of Resistivity method with geological information, in making interpretation and characterizing of the subsurface. With the integration of Electromagnetic sounding method the Resistivity method can prove to be the most appropriate choice for groundwater investigation within the study area. The findings in this study provide insights on sites that can be drilled for groundwater exploration, and show possible water-type variations in the subsurface. Although, the results are not conclusive, but they provide basis for further research work on groundwater quality and flow dynamics.

CHAPTER 5: BOREHOLE AND WELLPOINT DRILLING AND SAMPLING

5.1 Introduction

This chapter also is based on the objective one (1) of the study, and focuses on drilling of wellpoints intended for monitoring of groundwater levels and conducting hydraulic tests. The purpose of this chapter is to provide a description of the subsurface materials and lithology that constitute the aquifer units. Drilling of wellpoints offered an opportunity to characterise the aquifer materials by establish their subsurface stratigraphy and hydrogeologic units in the target areas. In addition, it serves as an alternative method to geophysical resistivity surveys for mapping the subsurface.

5.2 Methods used

This study used Mud-Rotary drilling method for establishing characteristics of the aquifer materials and geological units within the study area. In Mud-Rotary drilling water is pressured down the hole, flushing the drill cuttings to the surface. The cuttings are then deposited into a flow pit, from which the water is pumped and used in the drilling process (figure 22). The water used during drilling is mixed with chemicals that helps to carry debris and prevents the formation from collapsing during installation of the casing.

Figure 22: Mud-Rotary drilling

During drilling, samples were collected at one (1) meter interval, and photographed to identify the composite rock materials. The benefits of using Mud-Rotary method is that, drilling can be successful conducted through sandy, alluvial, clay and unstable gravel beds with weathered materials, a condition that characterised the study area. Its limitation however lies in that samples of the aquifer materials during drilling can only be retrieved as loose sediments from the drill fluid. As a result, the samples do not provide actual representation of in situ conditions, and thus not useful for detailed analysis.

Between the months of June to October 2015, 23 piezometers and 3 boreholes were drilled in the Heuningnes Catchment for groundwater monitoring and investigations. The wellpoints were drilled by the Institute for Water Studies (IWS) at UWC as part of the Water Research Commission (WRC) project titled: *"Finding 'new' water in an 'old' catchment: the case of the Heuningnes Catchment, Breede-Overberg Water Management Area"*. The drill sites were selected based on the geophysical resistivity survey results, conducted in 2014. In some cases where access to the survey locations was challenging, drilling sites were located in the vicinity of the surveyed areas. As a results, blind drilling was applied to some of the piezometers and boreholes. Of the 23 piezometers, six (6) were located around the coast line of the Voelvlei, eight (8) along the stretch of the Nuwejaar River between Eilandsdrift and Wiesdrif, two (2) at Bosheuwel (SANparks offices) and seven (7) around the coast line of the Soetendalsvlei Lake. The arrangement of the piezometers was such that it made it possible for determining both local and reginal groundwater flows in the study area.

5.2.1 Wellpoints drilling

Using a larger diameter drilling steel-pipe rods, pilot drilling of wellpoints was initiated at the West-North shores of the Soetendalsvlei (figure 23). However, at this site the jetting could only go as deep as 2 to 3 m before as a hard surface was encountered. At these depths, jetting could not be continued due to the hardness of the surface.

Figure 23: Test drilling hole at Soetendalsvlei lake site

Due to the indicated field technicalities that were experienced, it was concluded that the Hydraulic Injection method was not suitable for well pointing at the three target sites and a new method was proposed, which is Mud-Rotary method. This method uses large machinery vehicles and equipment, and is able to penetrate through hard rock formation during drilling.

5.2.2 Mud-Rotary drilling

Mud-Rotary drilling was used for drilling through the different shallow formations or lithologies within the study area. Though, Mud-Rotary drilling was used in locations with a mix of clay and sand, there was an attempt to use hydraulic jetting in location with sandy materials (figure 24). This initiate however, was hampered by the abrupt occurrence of near surface hard materials that could not be penetrated through by the hydraulic jetting method.

Figure 24: Mud-Rotary drilling and hydraulic jetting method

Drag (blade) drilling bit, was used in Mud-Rotary drilling (figure 25). This made it possible for penetrating hard formations such as clay and calcrete formations during drilling. In the study area, the method however proved futile, as the under laying hard rock formations occurred at shallow depth, and could not be penetrated through during drilling. As a result, this affected the depth of the piezometers which represent the extent to which soft formations occur.

Figure 25: Mud-Rotary drilling bit

Throughout the drilling process, samples of the formations of the wellpoints were taken a 1 m interval, by collecting the material pushed out of the hole by water pressure using a spade (figure 26). These were put together for onsite analysis of the type of material sampled.

Figure 26: Sampling during Mud-Rotary drilling

Though the sample quality was poor, the samples collected could still be analysed. This made it possible to determine the formation that have been perpetrated during drilling. The issue of poor sample quality however, was inherent from the drilling method. This is because, the sediments samples came on the surface while already mixed with water and mud from the flow pit.

5.2.3 Design and installation of piezometers

A 70-80 mm diameter black irrigation pipe was used to make the piezometers (figure 27). The pipes were slotted, with slots size approximately 0.8 mm. The screen spacing was 3 mm. This allowed for water to enter the well from the formation and at the same time prevented sand materials bigger than 3 mm from entering the well, thus blocking the well screen. The screen length of the piezometers was set as one third of the total wellpoint depth.

Figure 27: Piezometer slots

PVC pipes of 120 mm diameter were used for boreholes casing (figure 28). For boreholes, the pipe slots were also approximately 0.8 mm in size, and the screen making about one third of the total wellpoint depth. The screen spacing was about 3 mm.

Figure 28: PVC casing used in boreholes

The piezometers were labelled as PZ1 to PZ23, starting with the piezometers South of the Voelvlei and ending with the ones located SouthEast of the Soetendalsvlei Lake (figure 29).

Figure 29: Numbering order of piezometer

Borehole numbering also follow the same order, and are named from BH1 to BH3. After installations, the boreholes and piezometers were purged and clean out mud that remained in the well after drilling (figure 30).

Figure 30: Purging boreholes and piezometers

Subsequent to the process of purging boreholes, borehole yields were determined, from flow data. Moreover, it was observed that, during the purging process that the boreholes could not sustain pumping size, which is 1.5 litres per second. The boreholes dried out within 3 to 5 minutes of pumping, and this affected the possibility of conducting pumping tests for estimating hydraulic properties. A complete design sketch of the piezometers and boreholes is shown in figure 31 and 32 below.

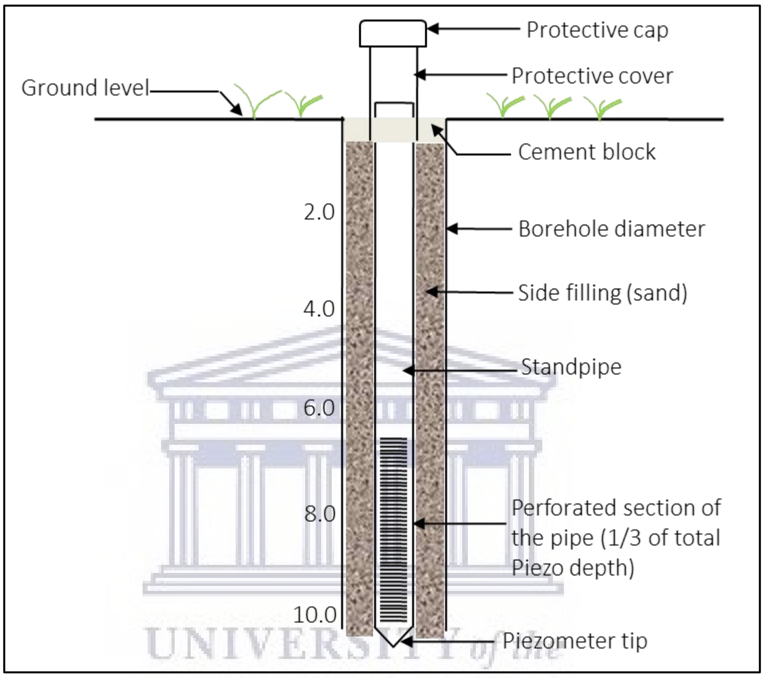


Figure 31: Schematic design of piezometers

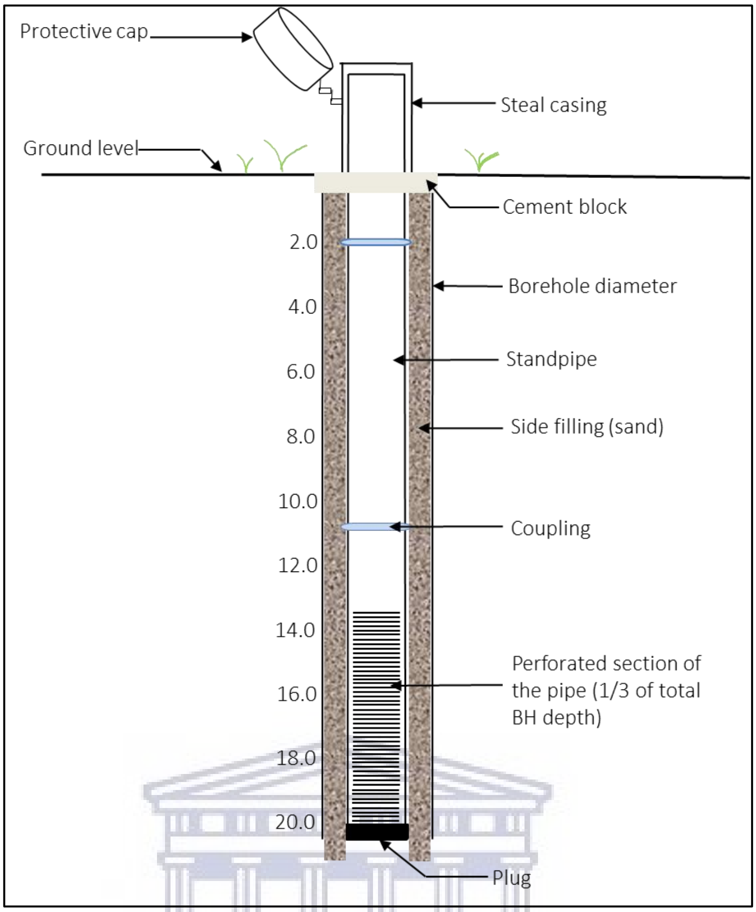


Figure 32: Schematic design of boreholes

These designs were deemed acceptable for groundwater monitoring and performing pumping tests and slug tests, important for estimating hydraulic conductivity and transmissivity of the formations.

5.3 Drilling sample profiles

5.3.1 Voelvlei site

Six (6) wellpoints of between 3.5 to 9.9 m were drilled along the coast line of the Voelvlei. Sampling revealed the following lithostratigraphy.

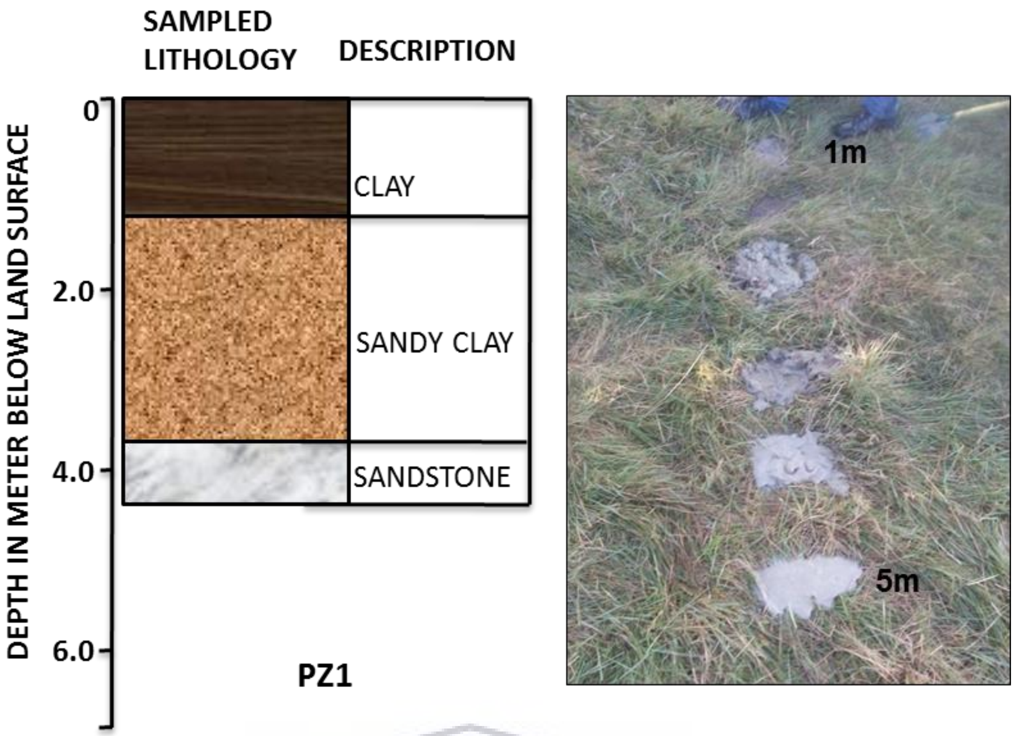


Figure 33: PZ1 well profile

At Voelvlei, PZ1 well profile shows that the piezometer penetrated through clay, sandy clay, and sandstone materials (figure 33). The sandstone formation under laying sandy clay materials could not be penetrated through during drilling due to the hardness of the rock. As a result, the piezometer depth of which was supposed to be 5 m was left at a depth of 4. 20 m. The same situation was experienced at PZ2 (figure 34). The occurrence of hard rock formations at shallow depth, at Voevlei was also revealed during the geophysical resistivity surveys, which were conducted as a pre-drilling program.

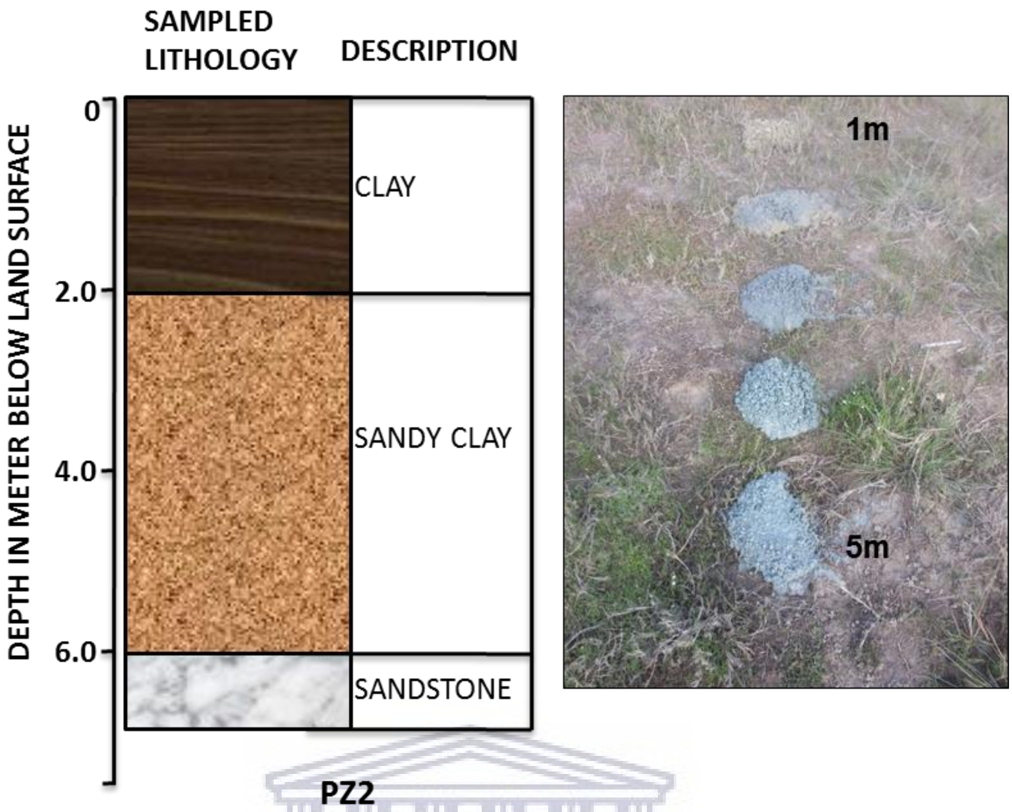


Figure 34: PZ2 well profile

At PZ2 clay materials, occur at depth of between 0 to 2 m, sandy clay between 2 to 6 m and sandstone at 6 m to unknown depth. The profile of the lithologies is similar to that in PZ1.

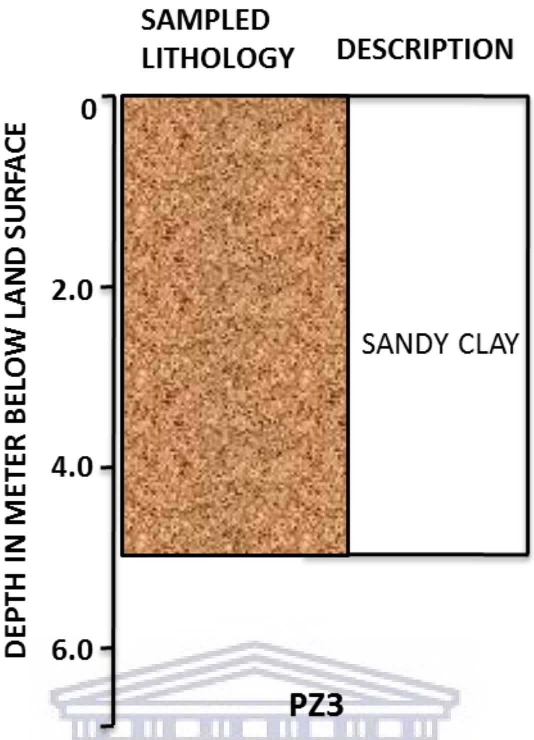


Figure 35: PZ3 well profile

At PZ3, the sampled lithology was sandy clay throughout the drilling process (figure 35). The sandy clay formation occurred at depth of 0 to approximately 5 m.

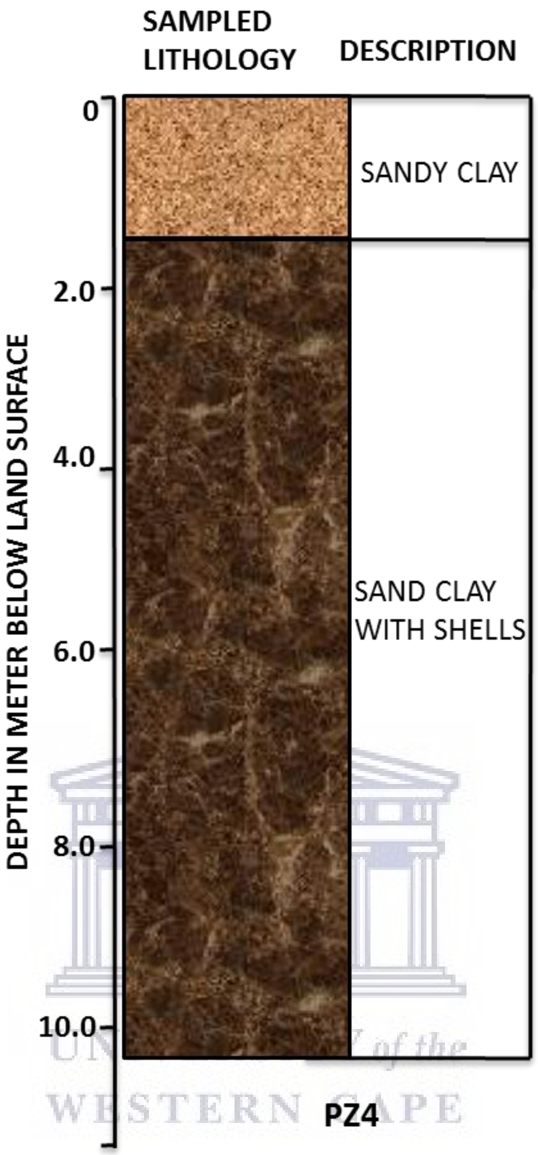


Figure 36: PZ4 well profile

At PZ4, a sandy clay layer overlaid a layer of sand clay material with marine shells (figure 36). The sandy clay layer occurs at depth of 0 to approximately 1.5 m, while the sandy clay with shells occurs at depth of approximately 1.5 to 10 m. The sandy clay layer with shells probably belong to the Bokkeveld Group geology, which is known to have deposit of marine shells.

5.3.2 Eilandsdrift -Wiesdrif

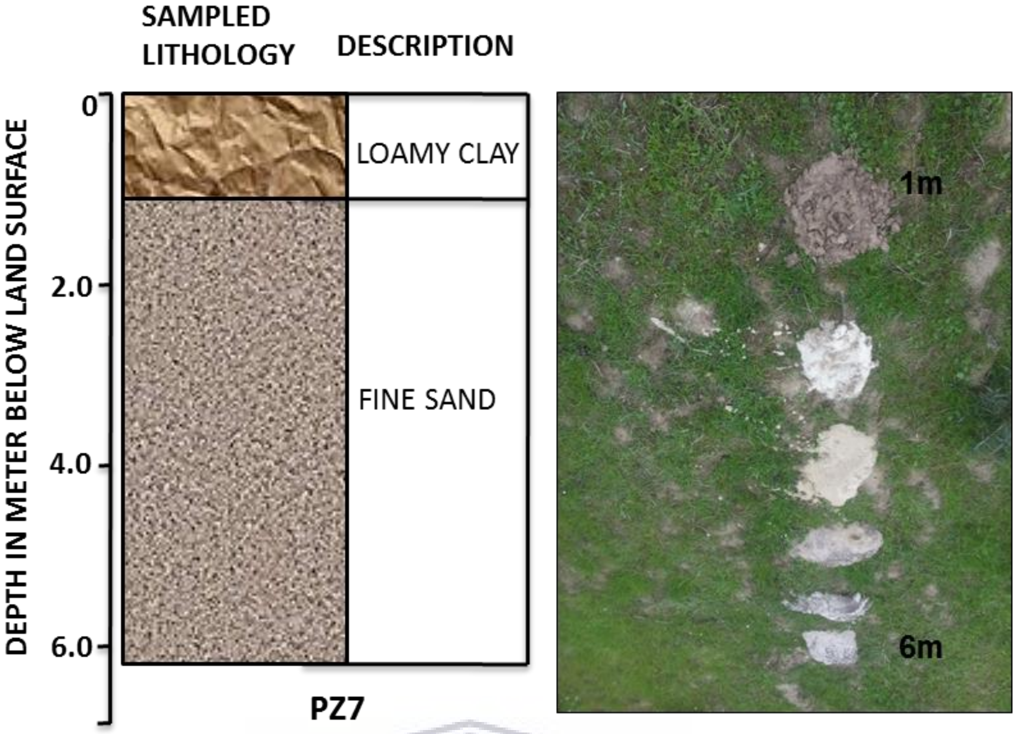


Figure 37: PZ7 well profile

At PZ7 which is located along the stretch of the Nuwejaars River, the well profile shows that loam clay materials overlay fine sand materials of depth of between 1 to 6 m (figure 37). The nature of the formations indicate that at some point along the river, where fine sand formation occurs, the under laying aquifer maybe connected to the river system.

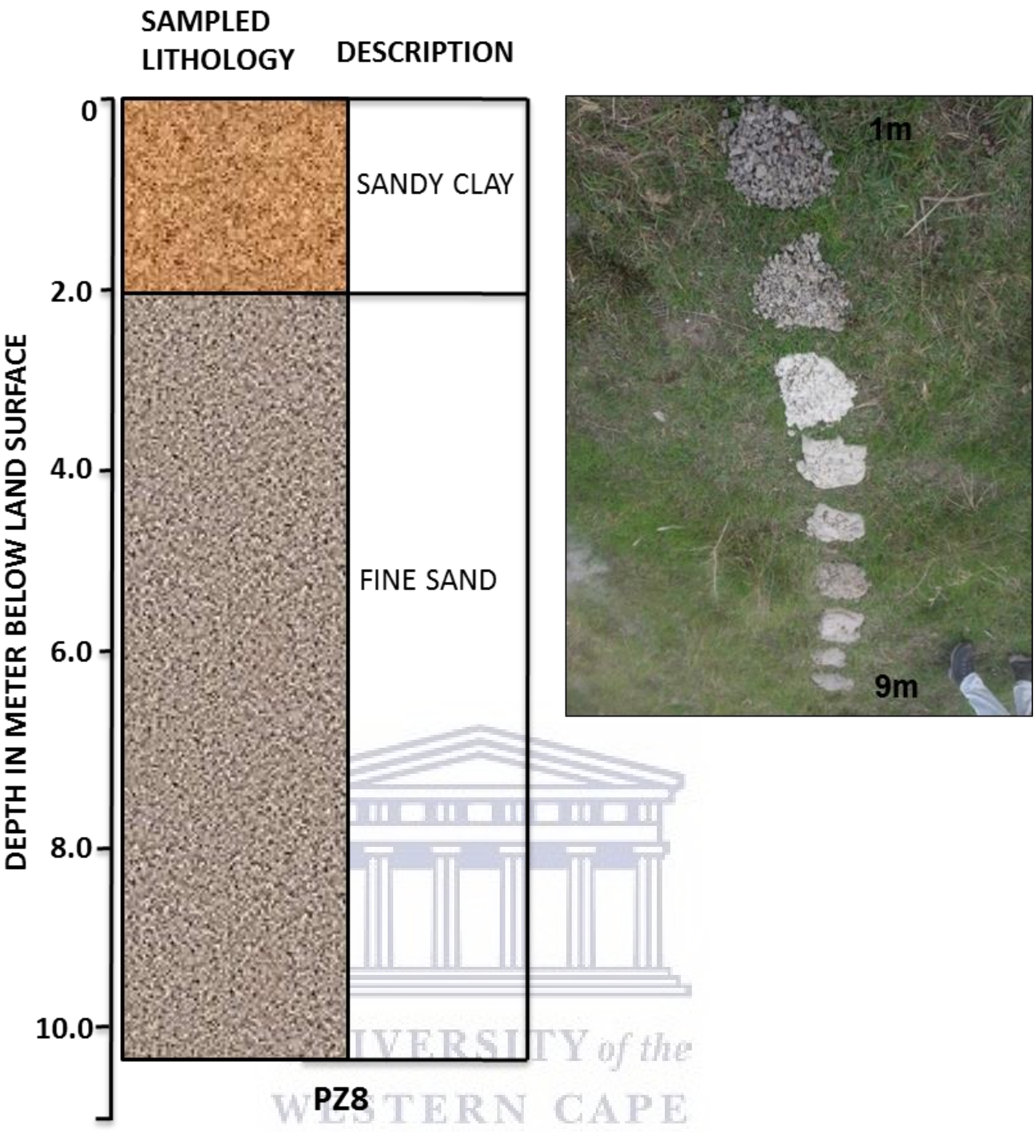


Figure 38: PZ8 well profile

At PZ8, fine sand underlay sandy clay layer at depth of approximately 2 m from the ground surface (figure 38). The depth of the fine sand layer extend beyond the drilled depth of the piezometers, which is approximately 10 m.

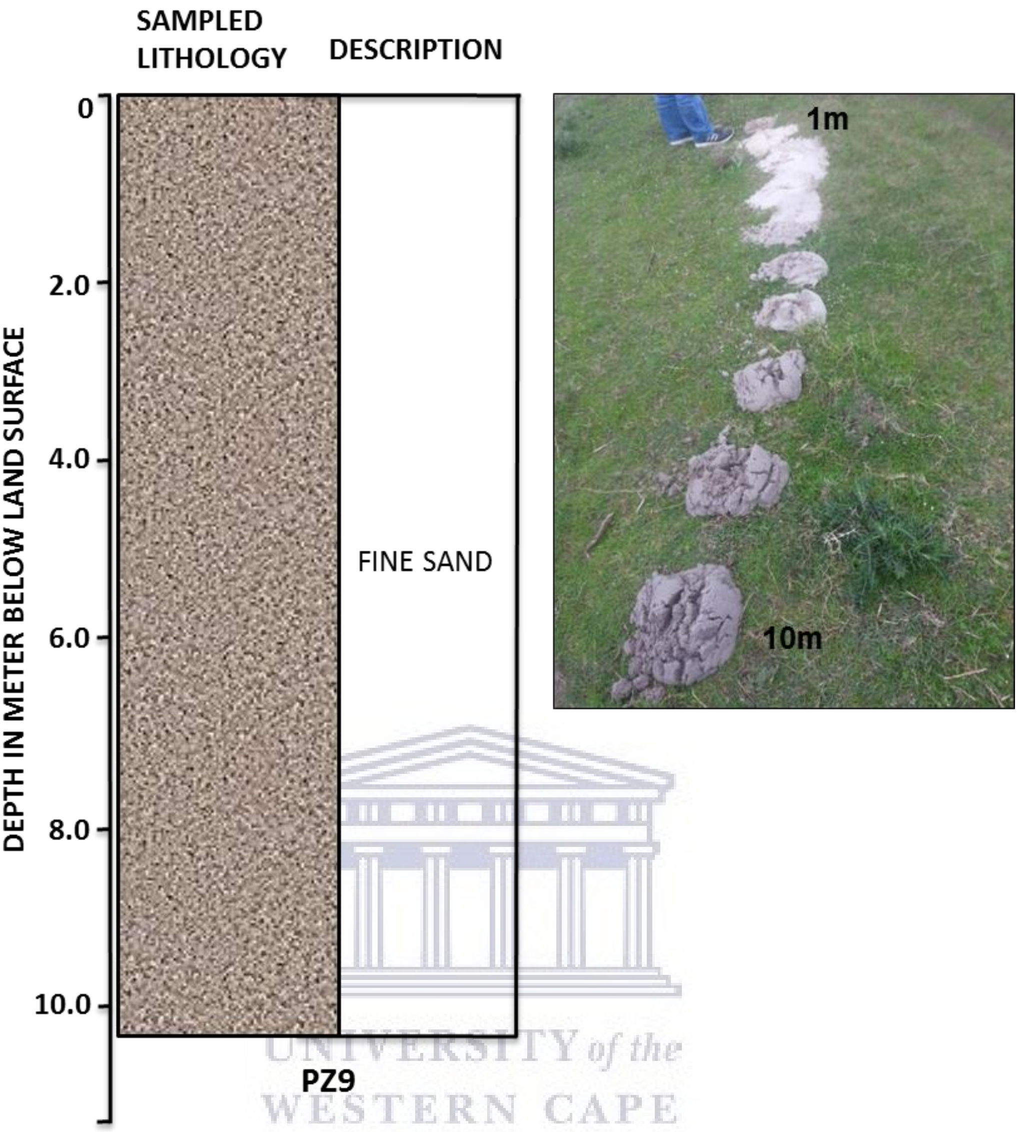


Figure 39: PZ9 well profile

At PZ9, which is on the right bank of the Nuwejaars River, the fine sand layer occurs at depth of 1 to 10 m (figure 39). At some point during drilling of PZ9 piezometer, the well wall collapsed, as the fine sand formation was unstable.

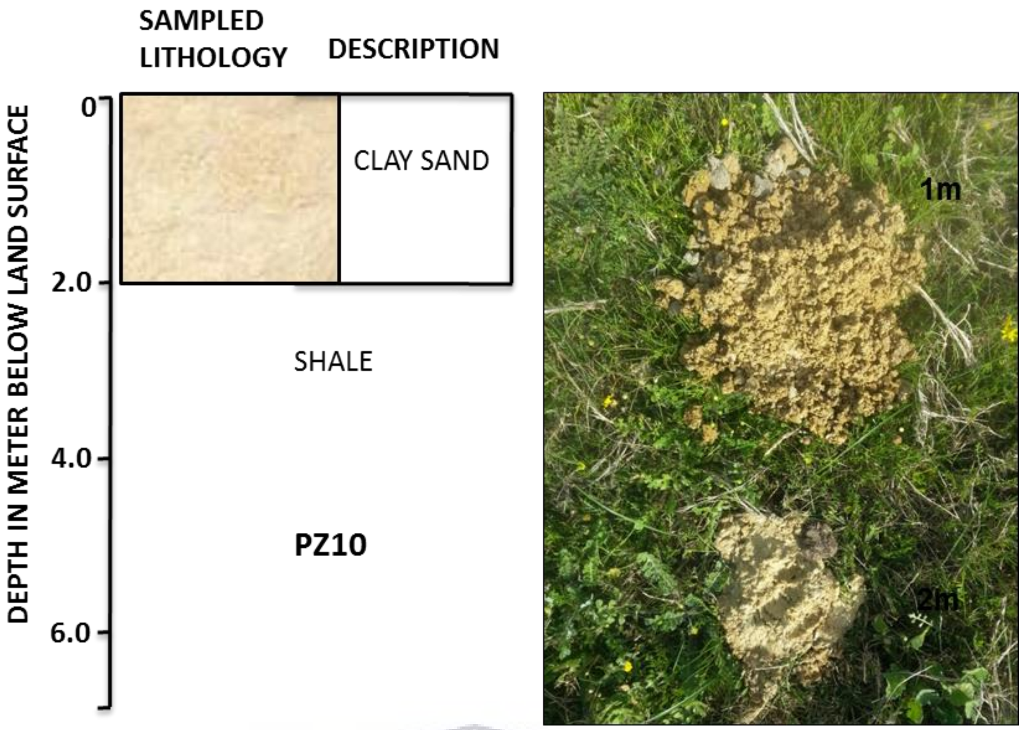


Figure 40: PZ10 well profile

At PZ10, the well could only be drilled to the depth of 2 m, due to the hardness of the materials encountered (figure 40). The sampled materials were clay sand of calcarous nature. The Mud-Rotary drilling used in this study could not prenetrate pass through this formation.

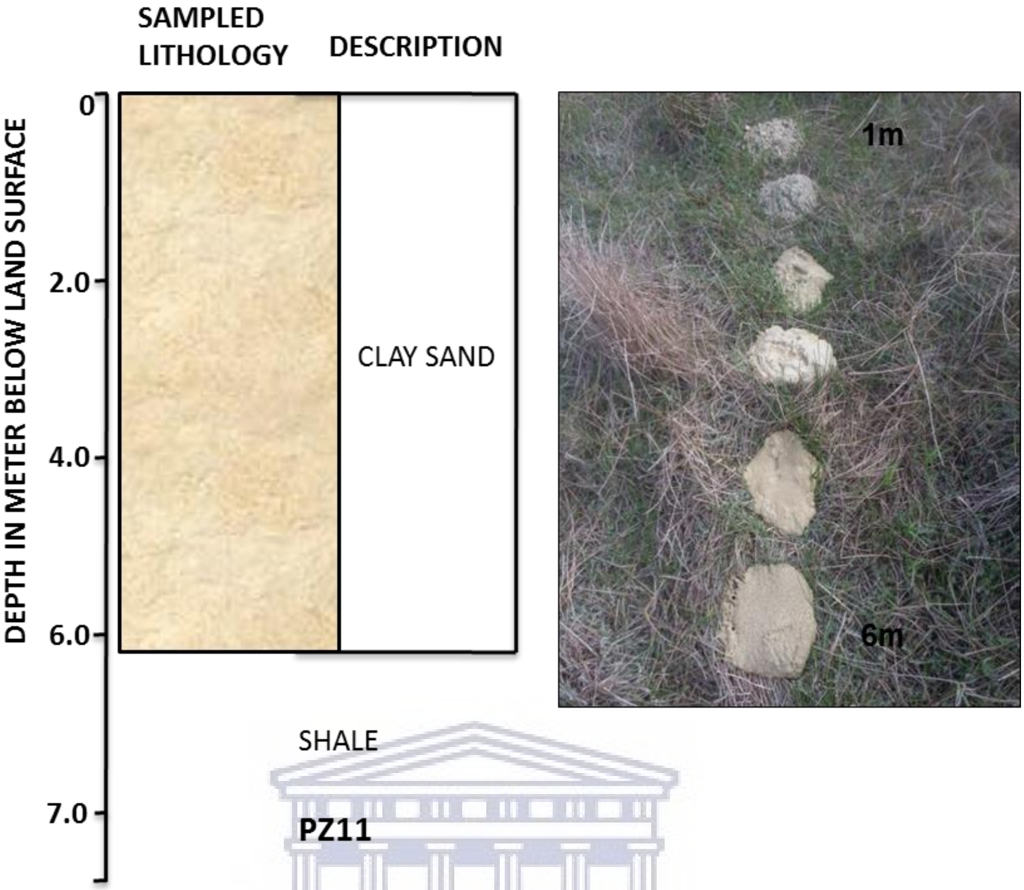


Figure 41: PZ11 well profile

At PZ1, clay sand materials were sampled at the depth of 1 to 6 m from the ground surface (figure 41). At depth of approximately 6 m, a hard rock layer of shale was encountered.

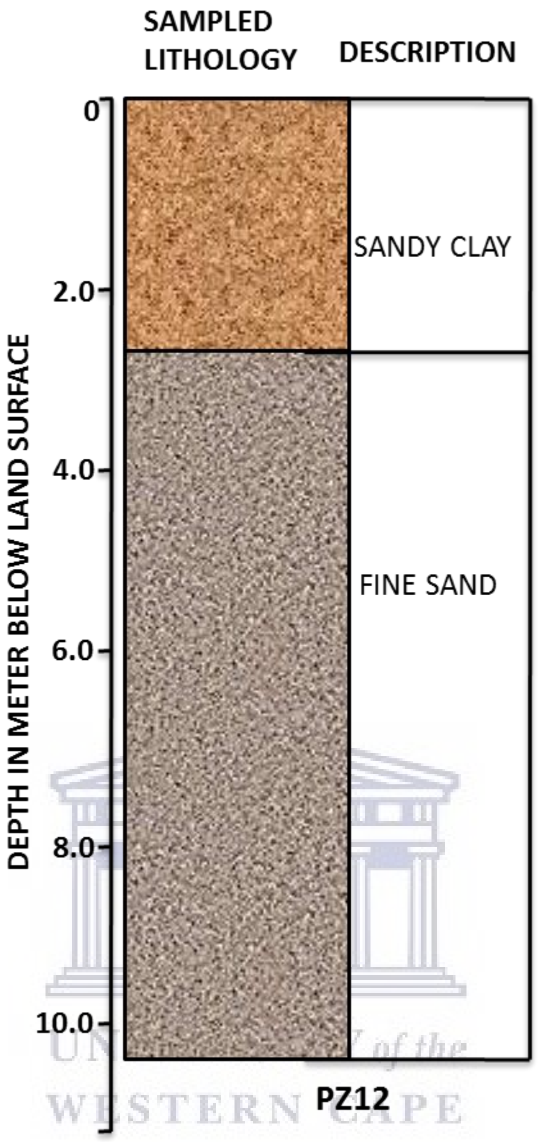


Figure 42: PZ12 well profile

At PZ12, which is located immediately on the stretch of the Nuwejaars River, sandy clay materials were sampled at depth of approximately 3 m, overlaying the fine sand materials (figure 42). Fine sand materials were sampled at depth of approximately 3 to 10 m. The fine sand materials layer similarly was encountered at PZ7, PZ8 and PZ9.

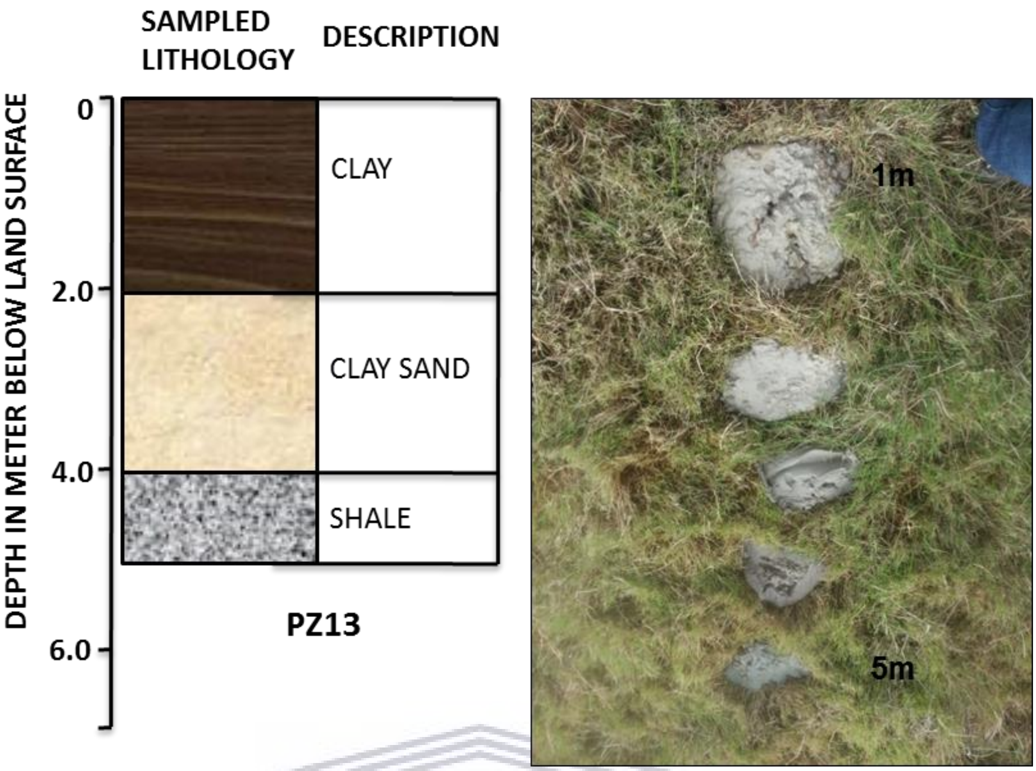


Figure 43: PZ13 well profile

At PZ13, clay, clay sand and shale layers were sampled at depth of 2 m, 4 m and 5 m in the order (figure 43). Shale layer which is a hard rock was encountered at depth of about 4 m. The occurrence of shale layer at such depth was also observed on the resistivity models.

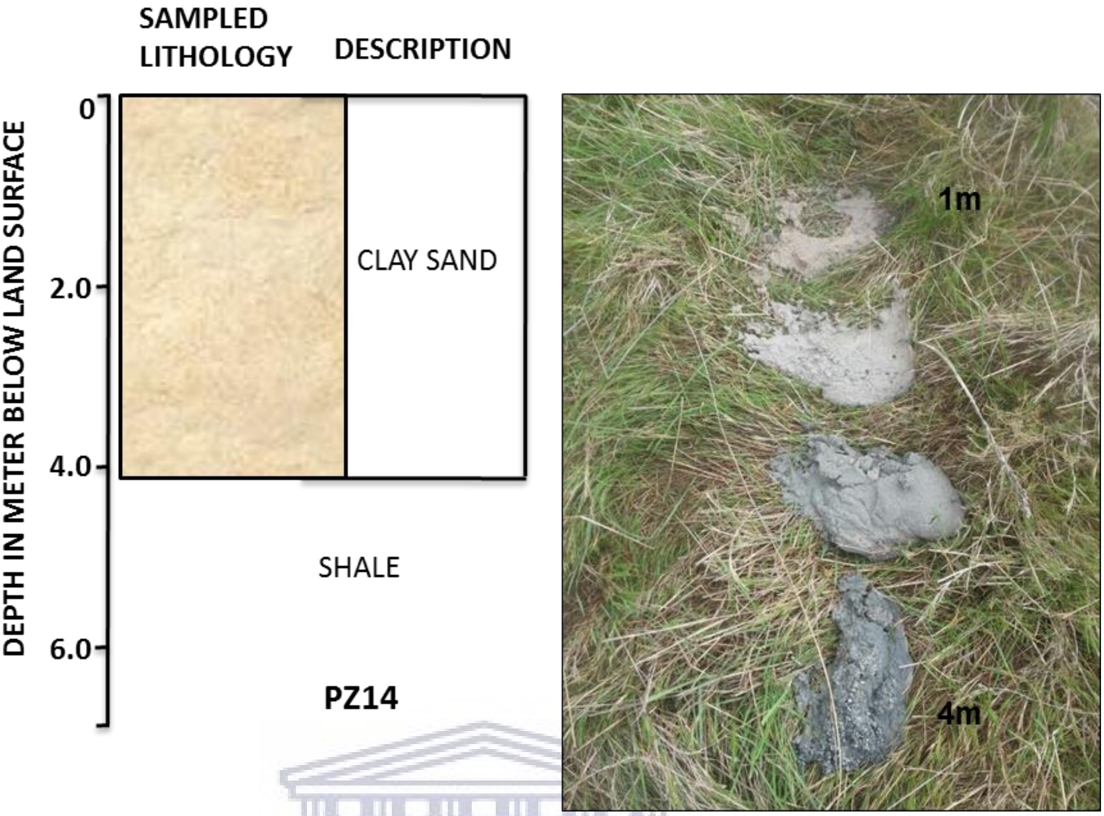


Figure 44: PZ14 well profile

At PZ14, a shale layer was also encountered, at depth of 4 m, overlaid by the clay sand layer (figure 44). In the proximity of the PZ14 well at the study site, an outcrop of the shale layer can be seen exposed at the left bank of the river, NorthEast of the piezometers.

5.3.3 Bosheuwel site (SANparks offices)

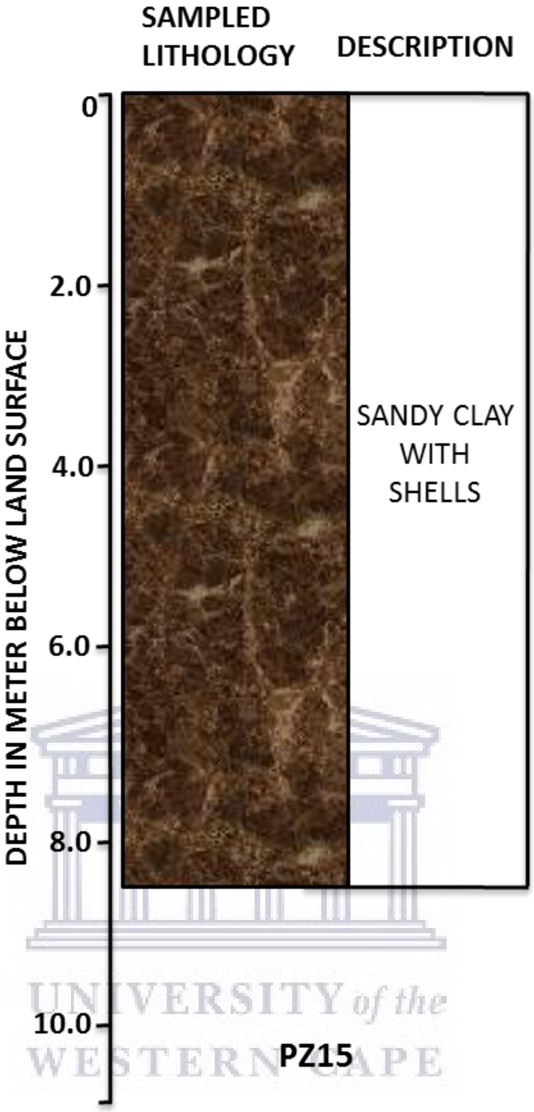


Figure 45: PZ15 well profile

At PZ15, sandy clay material with shells were sampled throughout the well column (figure 45). The sampled materials are probably of the Bokkeveld or Malmesbury group. The outcrop of these formations is exposed at the study site (SANparks offices).

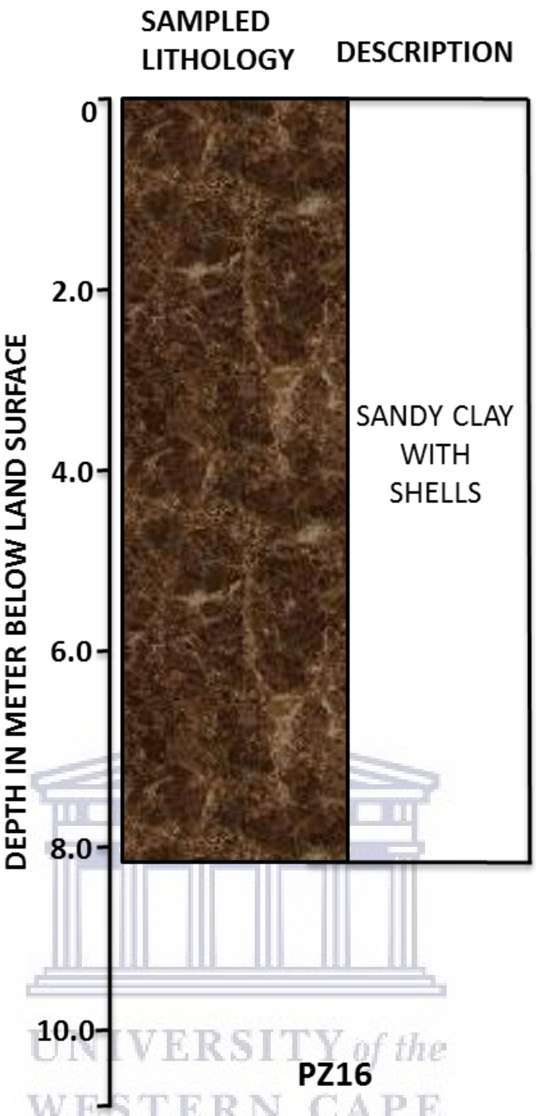


Figure 46: PZ16 well profile

At PZ16, which is located 50 m from PZ15, sandy clay materials with shells. Similarly to those encountered at PZ15, the sandy clay materials were also sampled throughout the well column at PZ16.

5.3.4 Soetendalsvlei site

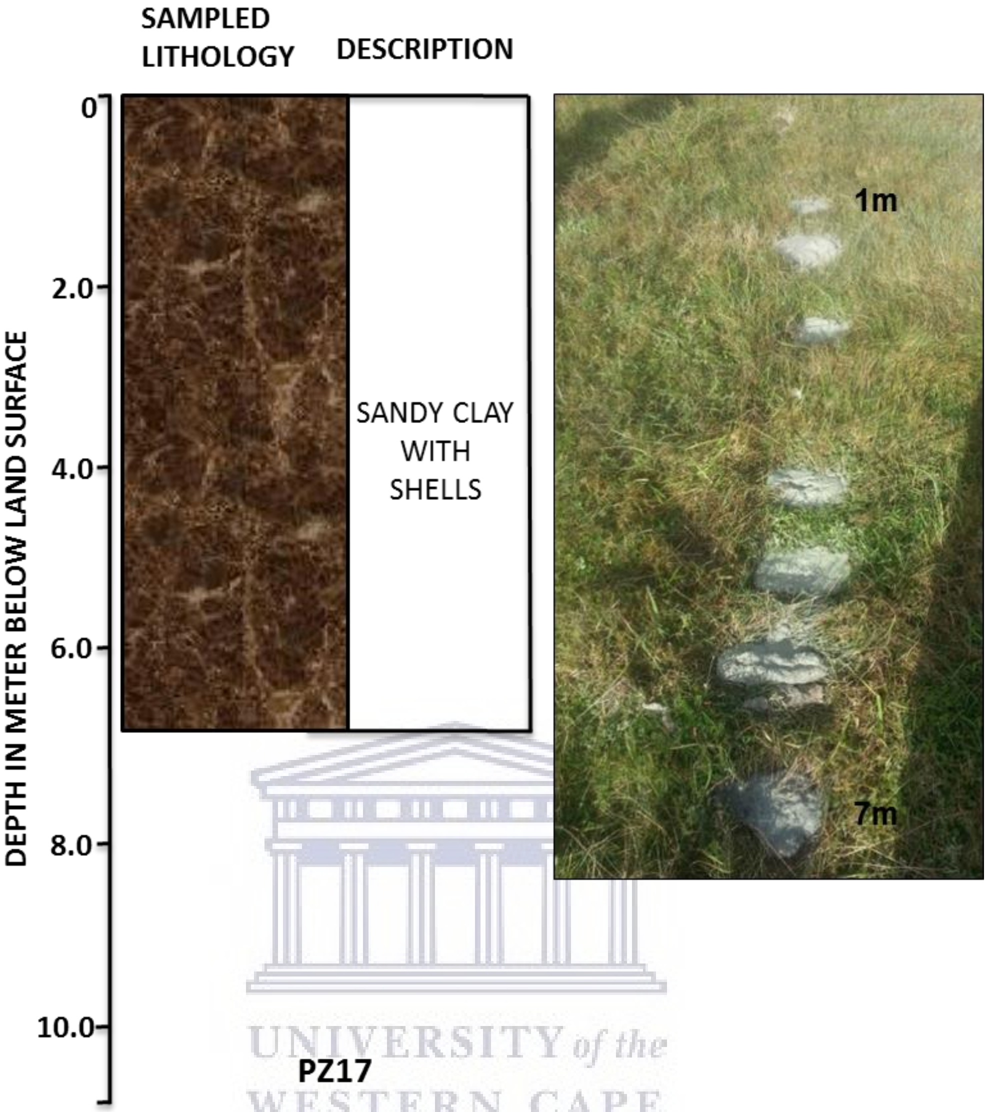


Figure 47: PZ17 well profile

Sandy clay materials with marine shells were also sampled at PZ17 at Soetendalsvlei site (figure 47). The site is on the same stretch as PZ15 and PZ16.

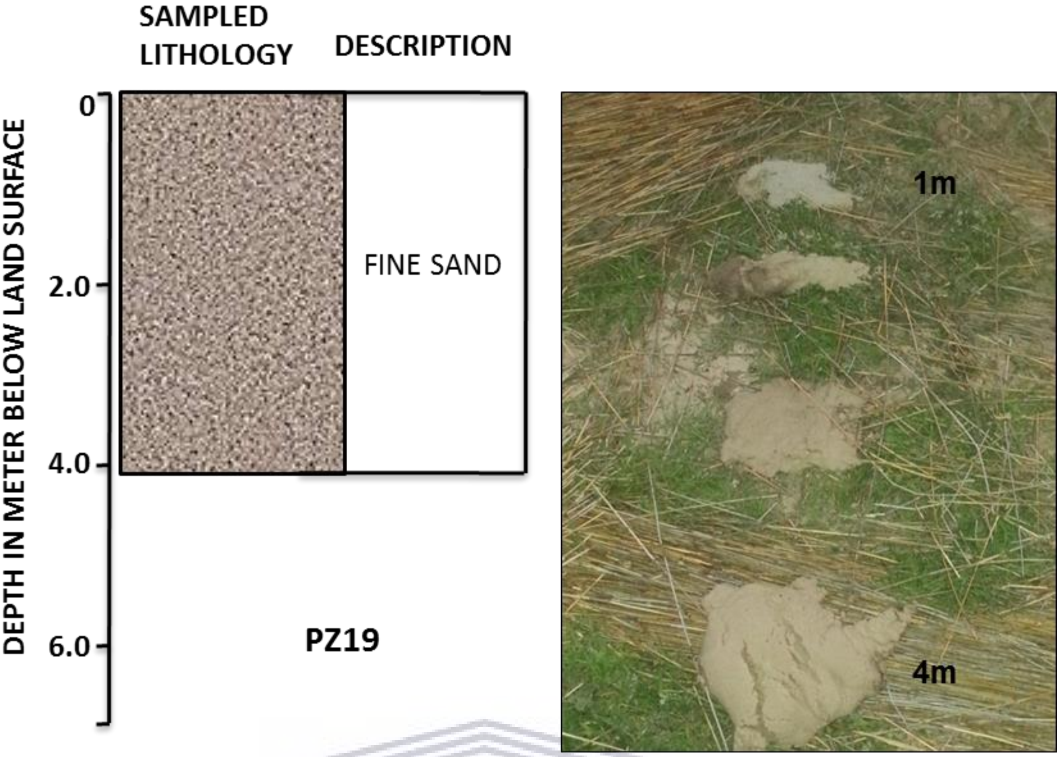


Figure 48: PZ19 well profile

Fine sand materials were sampled at PZ19, NorthEast of the Soetendalsvlei Lake (figure 48). At PZ19, the sand extended to the depth of 4 m. A hard rock layer was encountered at 4 m depth, and probably sandstones of the TMG that underlay that sand formation.

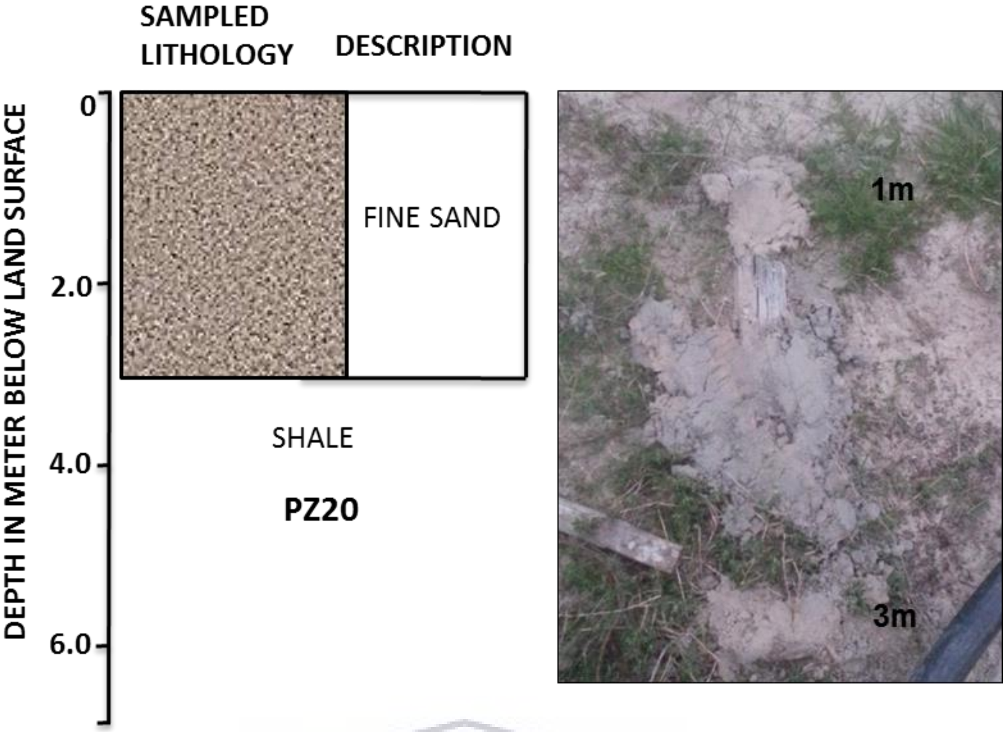


Figure 49: PZ20 well profile

Fine sand materials extending to the depth of 3 m were also sampled at PZ20 which is located 20 m from PZ19 (figure 49). A hard rock was also encountered at the depth of 3 m. PZ20 is located closer to the edges of the Soetendalsvlei Lake.

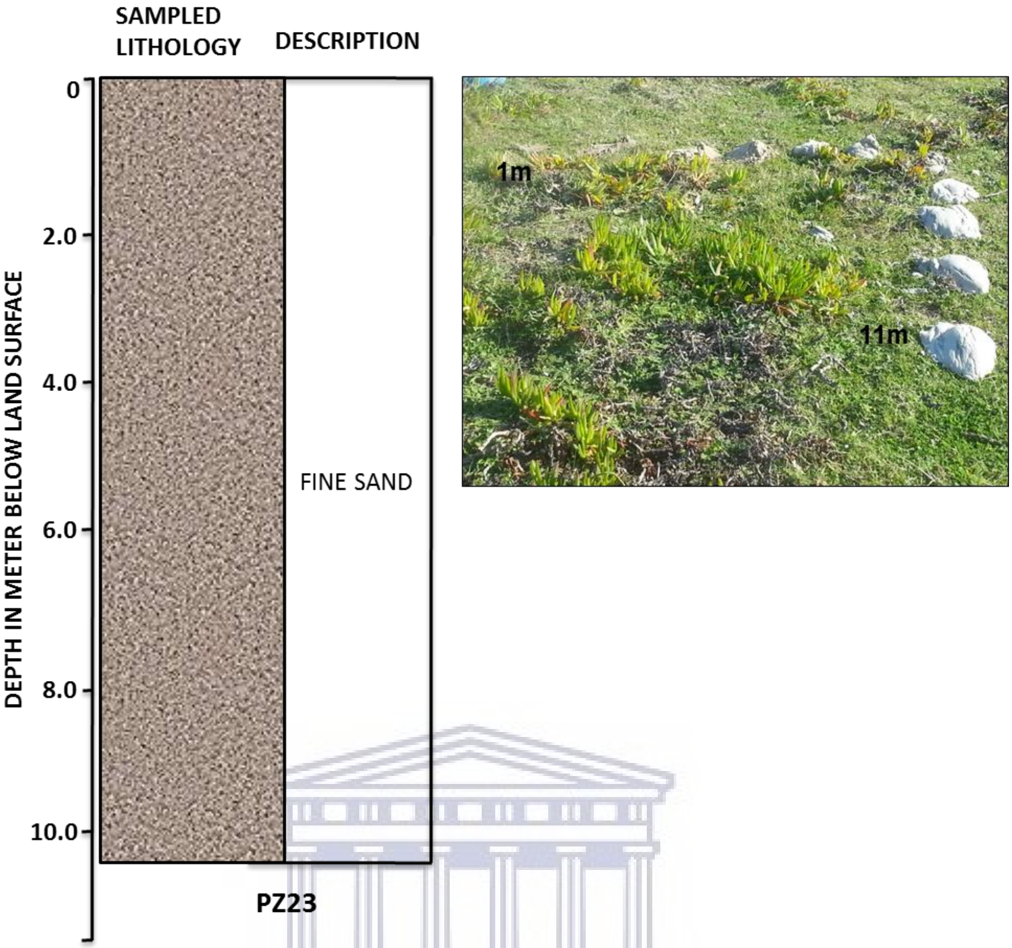


Figure 50: PZ23 well profile

At PZ23 located east of the Soetendalsvlei, fine sand was also sample throughout the well column to the depth of 11 m, which was the designed depth of the piezometer (figure 50).

5.3.5 Long profile cross section

The long cross sectional profile of the sampled aquifer materials covers the four study sites, the Voelvlei, Eilandsdrift -Wiesdrif, Bosheuwel and Soetendalsvlei sites (figure 51).

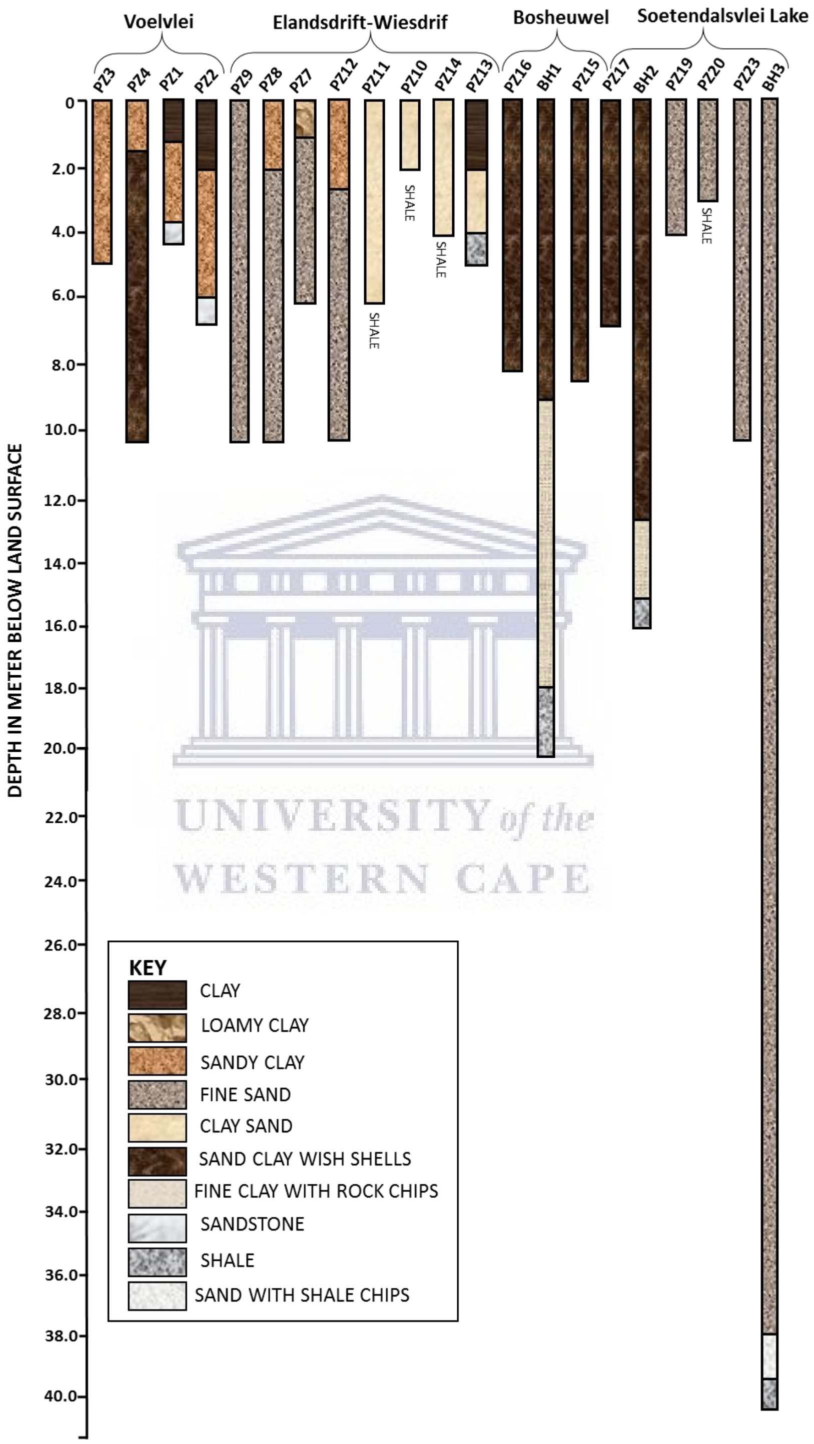


Figure 51: Cross sectional profile of well samples

The cross sectional profile of wellpoints shows that shallow alluvial materials and clay materials with marine deposits (mollusc shells) overlay a layer of hard rock, mainly shale. The shale layer occurs at depth ranging from 2 m to 40 m. The profile also indicates that the fine sand materials that form the primary aquifer occurred at Soetendalsvlei and Eilandsdrift -Wiesdrif sites. On the other hand, sandy clay and sand clay materials with marine shells were the dominated layers at Voelvlei and Bosheuwel sites. The profiles information agrees with the results of the resistivity models, in which shallow clay and sandy layers of moderate to high conductivity were mapped. In addition, the resistivity models revealed that, hard rock layers overlay shallow alluvial materials, similarly to the interpretation of the cross sectional profile.

5.4 Chapter summary

This chapter focused on drilling of boreholes and piezometers intended for monitoring of groundwater levels and conducting hydraulic tests. The well profiles revealed that fine sand materials dominated the area of Soetendalsvlei and Eilandsdrift -Wiesdrif sites, while sandy clay and sand clay materials with marine shells dominated the area of Voelvlei and Bosheuwel sites. From the profiles, is further revealed that a layer of shale underlay most of the alluvial materials in the study area. The shale layer occurred at depths ranging from 2 m to 40 m. The occurrence of hard rock formations at shallow depth at Voevlei, as revealed by profiles, similarly was revealed during the geophysical resistivity surveys. The well profiles of drilling samples provided an important information which would aid further, the interpretations of the geophysical surveys results in this study.

CHAPTER 6: ESTIMATING HYDROGEOLOGICAL PARAMETERS

6.1 Introduction

This chapter provides an assessment of the aquifer hydraulic properties within the case study areas. The chapter is based on objective two (2) of the study, and through use of hydraulic tests provides estimate of the hydraulic properties which determines hydraulic characteristics of the aquifer hydrogeological system. This chapter fills the gap in geophysical studies and drilling which did not provide estimates of the aquifer hydraulic properties such as hydraulic conductivity transmissivity, and borehole yields. As a result, these methods alone did not allow for a complete characterisation of the aquifers. However, hydraulic test allow for estimation of the hydraulic conductivity and transmissivity. In addition, during hydraulic tests borehole yields can be determined. The chapter methodology is present first, followed by key results and discussion, and chapter summary in the order.

6.2 Methods used

6.2.1 Water level monitoring

Monitoring of groundwater levels in piezometers was conducted between 11 November 2015 and 27 May 2016. A sounding water level meter was used to measure the groundwater levels (Figure 52). The groundwater levels were measured at an unfixed interval depending on the accessibility of the sites. Due to some of the piezometers being dry during dry periods, and some area being inaccessible due to water logging in the rainy season, the data showed some gap in water levels data for some of the days.

Figure 52: Measuring groundwater levels

6.2.2 Borehole yields

Hydraulic tests were carried out in monitoring wells recently drilled by the University of the Western Cape (figure 53). As part of the activity to determine the aquifer properties namely hydraulic conductivity and transmissivity, borehole yields from the three borehole were measured, subsequent to borehole purging exercise (figure 54).

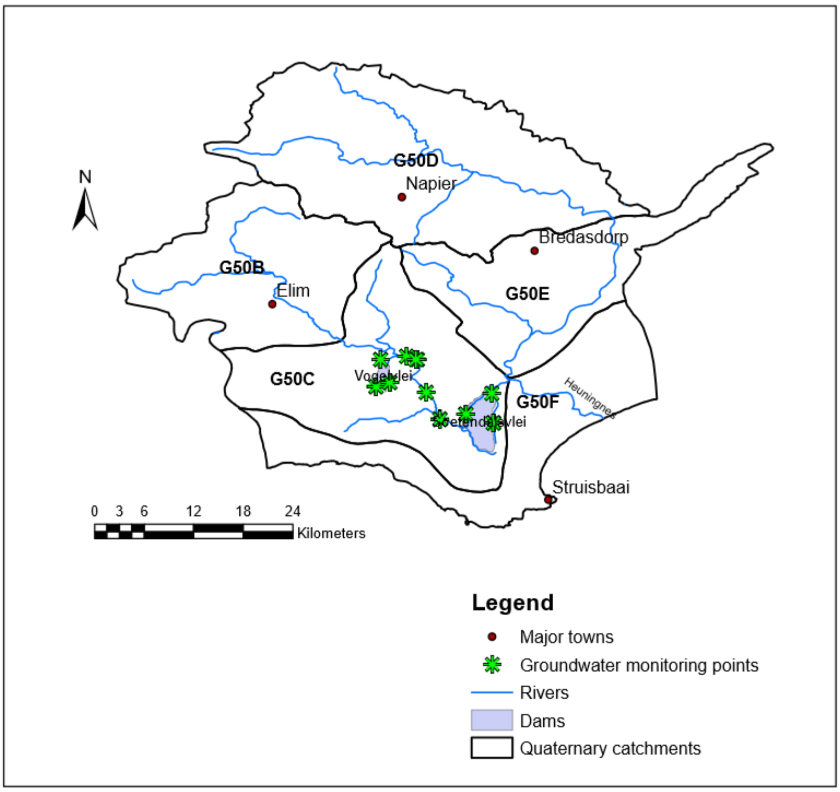


Figure 53: Recently drilled groundwater monitoring wells

Figure 54: Measuring borehole yields

6.2.3 Slug test

A rising head slug test was carried out in piezometers using bailers, and recording the water level rise using Hoboware data loggers (figure 55 and 56). The test was conducted by removing water in the piezometers using bailers, after which a pressure transducer was placed in the piezometer for measuring the height of the water column as it rise. Recovery in piezometer was observed from the time a maximum head change was cause until the piezometer reached a static steadiness. The pressure transducer was left in the piezometer for 30 minutes, monitoring the water level rise.

Figure 55: Performing slug test

Figure 56: Measuring water level recovery using data loggers

The use of slug test over pumping test were based on the observations during borehole purging exercise. Pumping at a rate of 0.5 litre per second, the boreholes dried out within 3 to 5 minute of pumping. Due to the low yielding of the boreholes, a slug test was opted over pumping test. The slug test data was analysed using Bouwer-Rice (1976) and Hvorslev (1951) slug test solutions for estimation of hydraulic conductivities.

The slug/bailer test data, was analysed using both Bouwer and Rice (1976) and Hvorslev (1951) solutions to determine hydraulic conductivities in AQTESOLV software. The analysis were performed using recommended head range to display the range of normalised head recommended by Butter (1997) for matching the Bouwer and Rice solution. This is because the piezometers did not have a filter pack drainage, as required.

The study used visual curve matching method for estimations of the parameters, effective for straight-line solutions. However, when the water level stand below the screen length, this creates negative values for water level depth to screen. As a result, the Bouwer and Rice (1976) solution gives, negative hydraulic conductivity. However, this is not the case with the Hvorslev (1951) method. Yet, the Hvorslev method is also criticized for its simple approach that create over estimation of the hydraulic conductivity. To estimate the hydraulic conductivity from the slug test plots using a straight line data match. A section of the data approximating a straight line and indicating an acceptable test was used in the analysis, while a section plotting as a curved line, usually at beginning or end of the test was excluded in the analysis process.

6.3 Water level monitoring and borehole yields

Monitoring of groundwater levels was conducted in boreholes and piezometers. This enabled the study to determine the responses of groundwater level to rainfalls (figure 57). The results present averages of monthly water levels in all monitoring wells plotted against monthly rainfalls within the study area. The monitoring exercise thus provided an initial insight regarding direct groundwater recharge from rainfall.

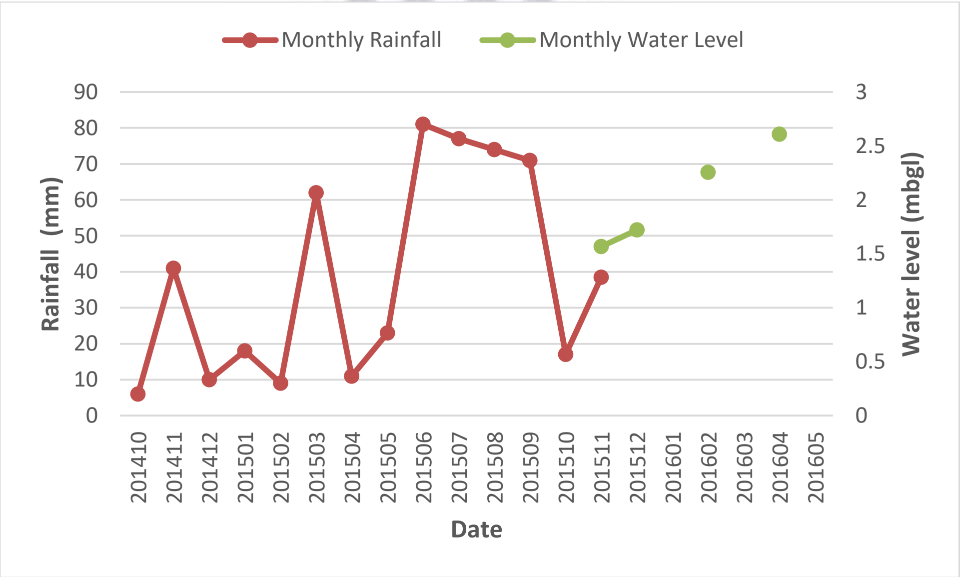


Figure 57: Monthly rainfall against average water levels

In the all the monitoring wells, groundwater levels show an increasing trend from soon after October rainfalls. Within the catchment, October is the last month of winter rainfall period. The upward trend after the last rainfalls, may be due to the lag time in recharge and the resulting rise in water table level. However, the data is not conclusive as it does not covers the entire rainy period.

From the month November to May, the trend in groundwater level showed an increase in water level (figure 55 and 56).

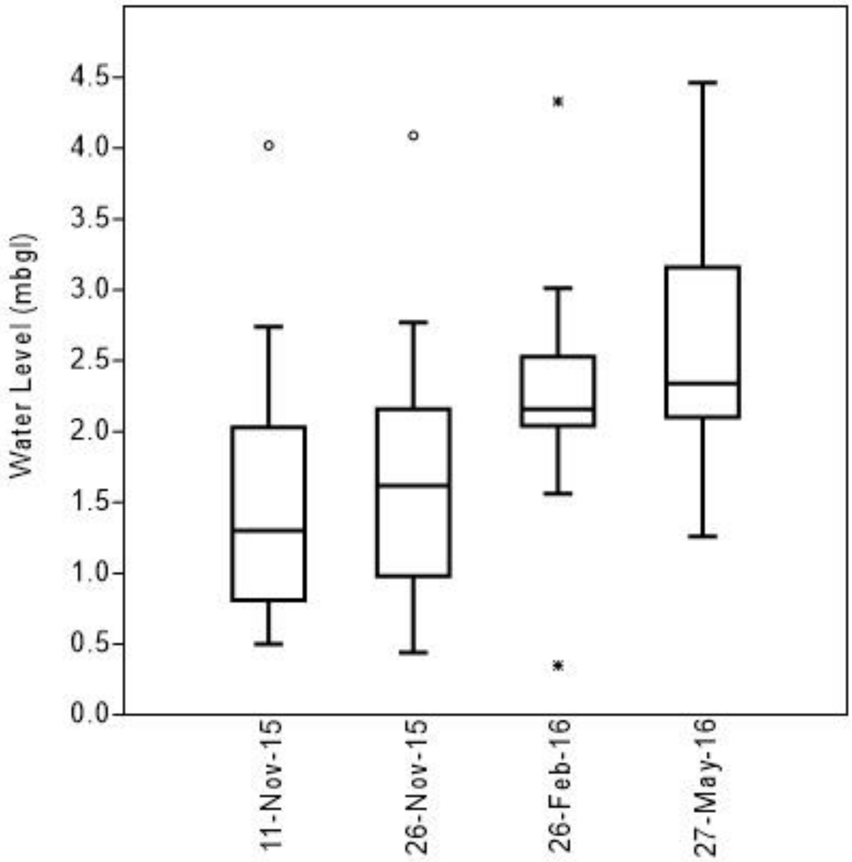


Figure 58: Box plot of water level drop over time during the dry period

From the month November 2015 to May 2016, the trend in groundwater level indicated by the box plots shows an increase in median water level over time (figure 58).

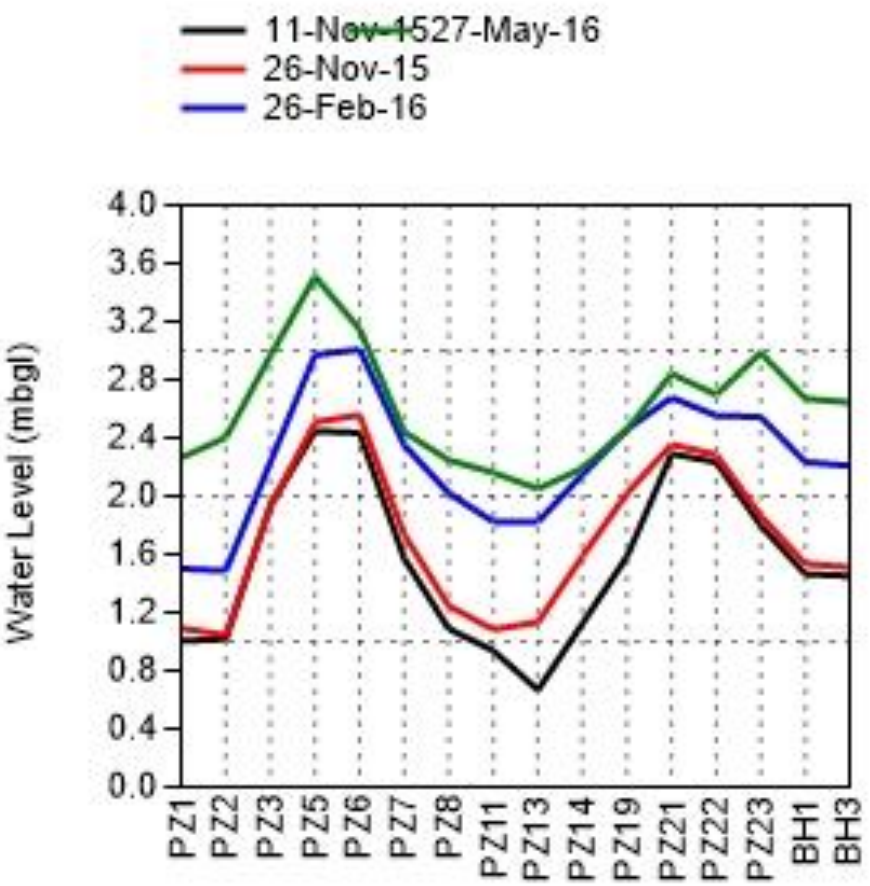


Figure 59: Water level trends over time

In all the piezometer an increase in water level was observed throughout the period from November 2015 to May 2016. The highest water level was observed in piezometer PZ13 at depth of about 0.7 meter below ground level (mbgl), closer to the surface, while the lowest water level was observed, in PZ5 at approximate depth of 3.5 mbgl (figure 56).

The borehole yield data from the three boreholes within the study area, indicated a generally low yielding formations, with borehole yield estimates ranging from 0.49 to 0.72 l/s (table 3). This can be an indication of less permeable formation of the boreholes. Of the three boreholes, BH2 located at Soetendalsvlei site, had a slightly higher yield compared to BH1 and BH3.

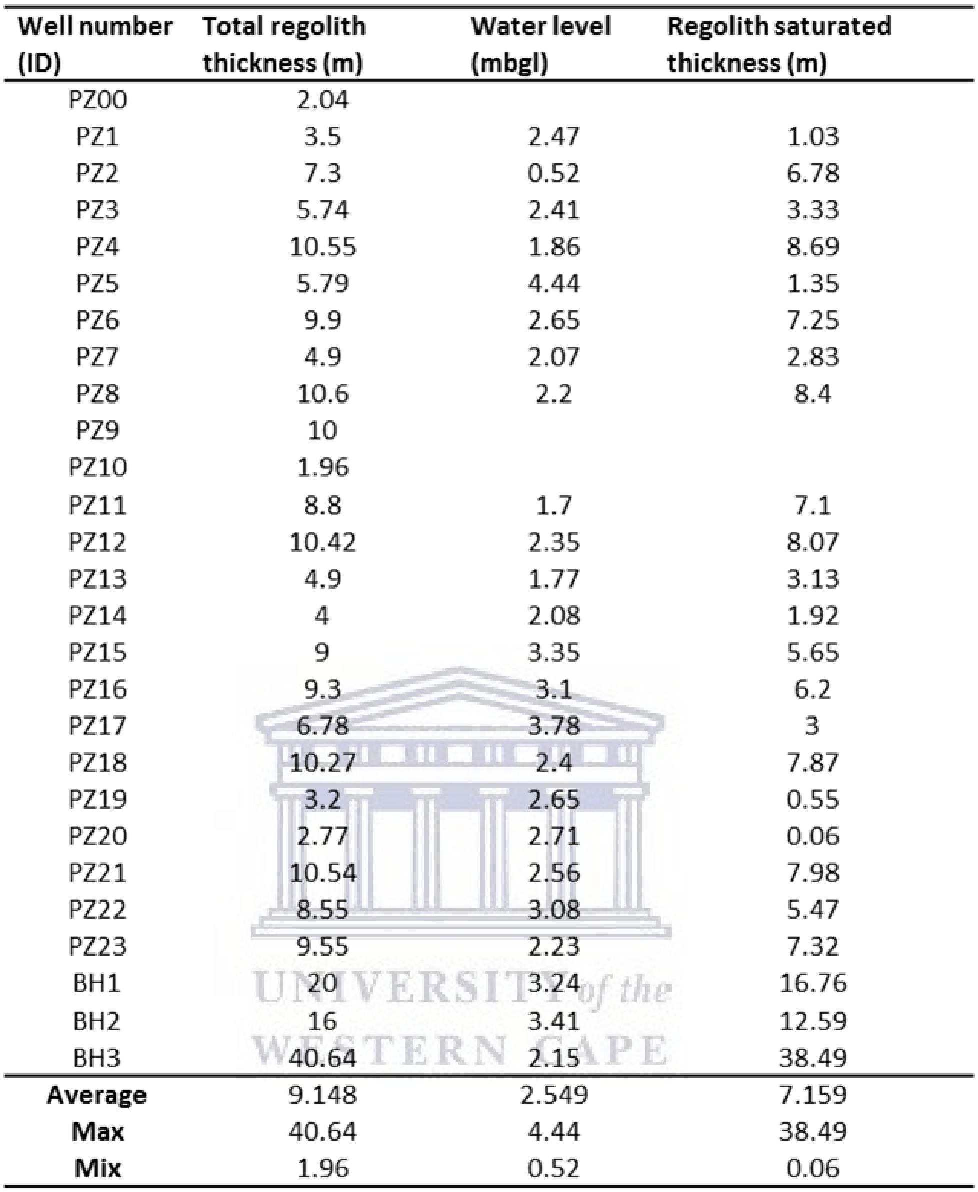
Table 3: Borehole yields and aquifer productivity class

Well ID	Borehole yield (l/s)	Aquifer/borehole productivity class (MacDonald et al., 2012)
BH1	0.49	Low
BH2	0.72	Low-moderate
BH3	0.45	Low
Average	0.55	Low-moderate

In term of aquifer productivity, low yields of generally less than 1 l/s can be associated with less productive aquifers (MacDonald et al., 2012). The productivity of the aquifers can be classified as low to low-moderate as indicated in MacDonald et al. (2004).

Using groundwater level data and total regolith thickness, aquifer saturation thickness was determined (table 4). Regolith saturation thickness represented the part of the aquifer materials that is wholly filled with water. The average value of the saturation thickness in the study area is 7.16 m. Maximum and minimum saturation thickness are 38.49 m and 0.06 m respectively. The small average value of the saturation thickness indicates that groundwater occurred as thin lenses in the aquifer materials.

Table 4: Aquifer saturation thickness



Well number (ID)	Total regolith thickness (m)	Water level (mbgl)	Regolith saturated thickness (m)
PZ00	2.04		
PZ1	3.5	2.47	1.03
PZ2	7.3	0.52	6.78
PZ3	5.74	2.41	3.33
PZ4	10.55	1.86	8.69
PZ5	5.79	4.44	1.35
PZ6	9.9	2.65	7.25
PZ7	4.9	2.07	2.83
PZ8	10.6	2.2	8.4
PZ9	10		
PZ10	1.96		
PZ11	8.8	1.7	7.1
PZ12	10.42	2.35	8.07
PZ13	4.9	1.77	3.13
PZ14	4	2.08	1.92
PZ15	9	3.35	5.65
PZ16	9.3	3.1	6.2
PZ17	6.78	3.78	3
PZ18	10.27	2.4	7.87
PZ19	3.2	2.65	0.55
PZ20	2.77	2.71	0.06
PZ21	10.54	2.56	7.98
PZ22	8.55	3.08	5.47
PZ23	9.55	2.23	7.32
BH1	20	3.24	16.76
BH2	16	3.41	12.59
BH3	40.64	2.15	38.49
Average	9.148	2.549	7.159
Max	40.64	4.44	38.49
Mix	1.96	0.52	0.06

6.4 Slug test responses

Based on the slug test analysis results using the Bouwer and Rice (1976) and Hvorslev (1951) solutions, the normalised head vs time plot were produced which indicate the behaviour of the tests. In all the piezometers, recovery in the head change over time was observed (figure 60 to 62, and appendix 2). The response of the piezometers generally show overdamped conditions. Overdamped conditions may indicate low permeabilities, while underdamped response may occur in aquifers of high hydraulic conductivity.

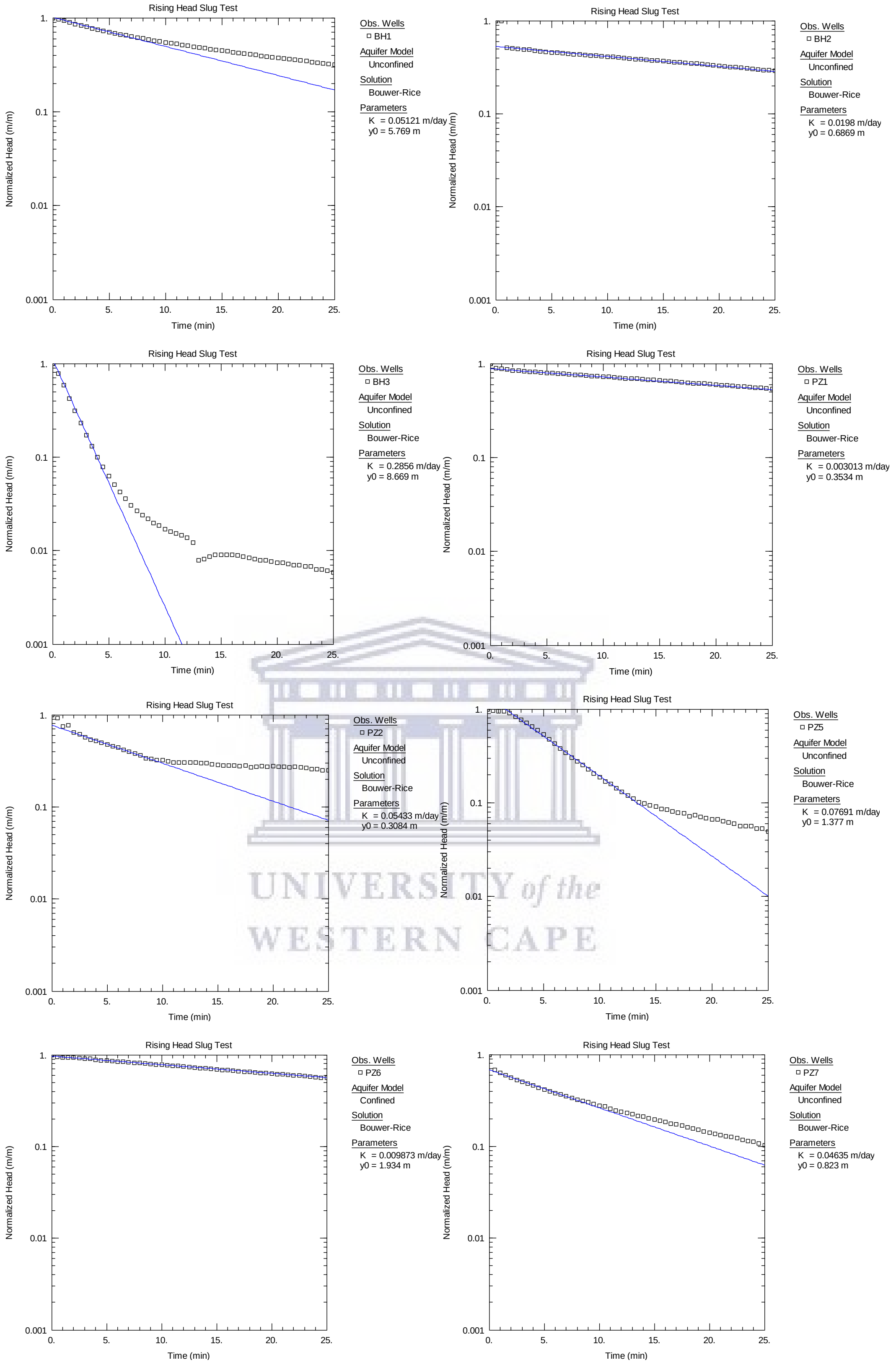


Figure 60: Normalised head vs time plot for wells: BH1, BH2, BH3, PZ1, PZ2, PZ5, PZ6 and PZ7

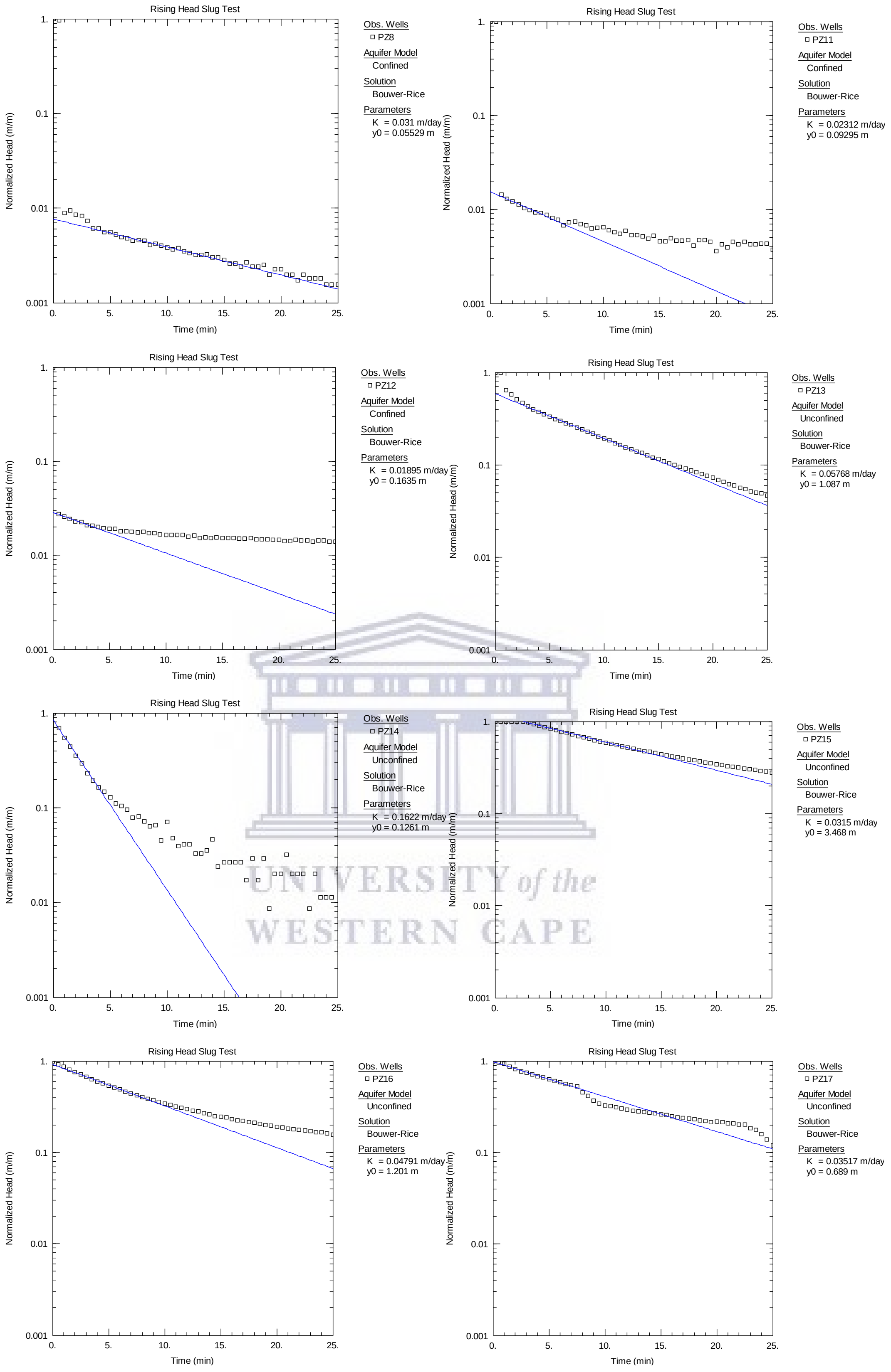


Figure 61 Normalised head vs time plot for wells: PZ8, PZ11, PZ12, PZ13, PZ14, PZ15, PZ16 and PZ17

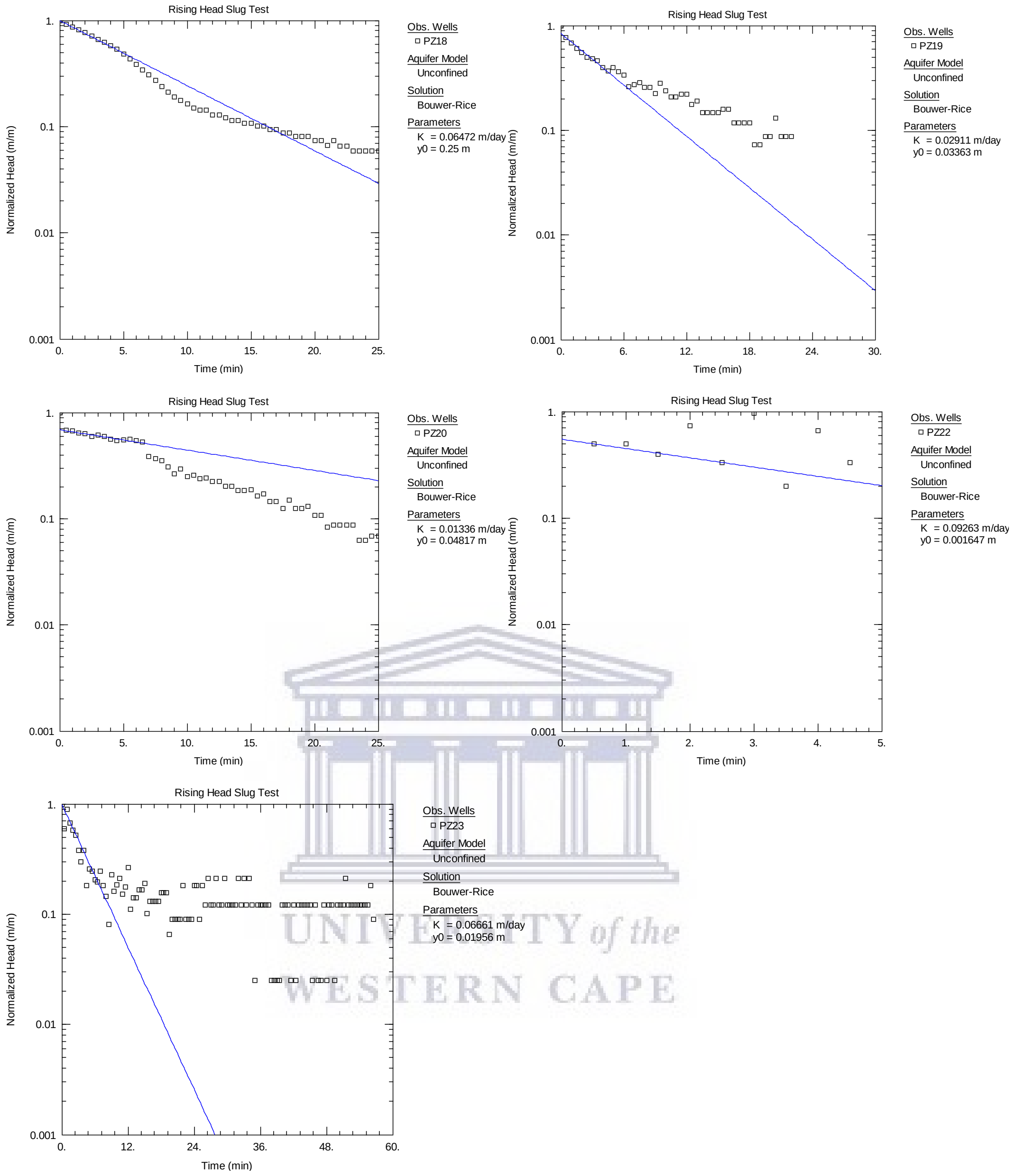


Figure 62 Normalised head vs time plot for wells: PZ18, PZ19, PZ20, PZ22 and PZ23

The normalised head vs time plots for BH1, BH2, PZ1, PZ5, PZ6, PZ12, PZ13, PZ15, PZ17, PZ18, PZ19 and PZ20 shows similar pattern of near straight line response (figure 60 to 62). In addition, they exhibit a gradual response or recovery process in the piezometers after the instantaneous change is the well head was effected. This condition which result in a near straight line or straight line plots, is typical for an overdamped well/piezometer (Duffield, 2007). On the other hand, PZ22 and PZ23 plots show an oscillation in the recovery response, indicative of underdamped well conditions.

6.5 Aquifer parameter estimation

The results on aquifer parameter estimation, using the Bouwer and Rice (1976) and Hvorslev (1951) solutions are presented in table 5. Hydraulic conductivity estimates are generally small ranging from 0.0148 to 1.9850 m/day for the Hvorslev solution, and from 0.0030 to 0.2856 m/day for the Bouwer and Rice solution. The geomean is 0.1167 and 0.0383 m/day respectively.

Table 5: Hydraulic conductivity and transmissivity estimates

Well (ID)	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**
Analysis method	**Hvorslev (1951)**		**Bouwer-Rice (1976)**	
PZ00				
PZ1	0.1602	0.1650	0.0030	0.003
PZ2	0.0732	0.4965	0.0543	0.368
PZ3				
PZ4				
PZ5	0.9094	1.2277	0.0769	0.104
PZ6	0.0148	0.1070	0.0099	0.072
PZ7	0.0918	0.2599	0.0464	0.131
PZ8	0.0453	0.3804	0.0310	0.260
PZ9				
PZ10				
PZ11	0.0789	0.5599	0.0231	0.164
PZ12	0.0571	0.4610	0.019	0.153
PZ13	0.1633	0.5111	0.0577	0.181
PZ14	0.4025	0.7728	0.1622	0.311
PZ15	0.0451	0.2548	0.0315	0.178
PZ16	0.0803	0.498	0.0479	0.297
PZ17	0.0712	0.2135	0.0352	0.106
PZ18	0.0962	0.7573	0.0647	0.509
PZ19	1.9850	1.0918	0.0291	0.016
PZ20	0.1347	0.0081	0.0134	0.001
PZ21	0.0710	0.5669		
PZ22	0.1478	0.8085	0.0926	0.507
PZ23	0.2972	2.1755	0.0666	0.488
BH1	0.0668	1.1201	0.0512	0.858
BH2	0.0307	0.3869	0.0198	0.249
BH3	0.3615	13.9141	0.2856	10.993
Max	1.9850	13.9141	0.2856	10.993
Min	0.0148	0.0081	0.0030	0.0008
Geomean	0.1167	0.4843	0.0383	0.1540

Transmissivity estimates on the other hand ranged from 0.0081 to 13.9141 m^2/day for the Hvorslev solution, and from 0.0008 to10.993 m^2/day for the Bouwer and Rice solution. The geomean for transmissivity is estimated as 0.4843 and 0.1540 m^2/day respectively. The small estimates in hydraulic conductivity and transmissivity using both methods indicated a low permeability environment. The Hvorslev (1951) solution give higher estimates of hydraulic conductivity value as compared to the Bouwer-Rice (1976) solutions. This disparity in hydraulic conductivity estimates in the two methods was also reported also in Duffield (2007).

At all the sites within the study area, high values of hydraulic conductivities were estimated at Eilandsdrift - Wiesdrif and Soetendalsvlei, while low hydraulic conductivities values were estimated at Voelvlei (Table 6).

Table 6: Mean hydraulic conductivity and transmissivity estimates using Hvorslev (1951) and Bouwer-Rice (1976) solutions

	Hvorslev (1951)			**Bouwer-Rice (1976)**	
Study sites	**K (m/day)**	**T (m^2/day)**	**AST (m)**	**K (m^2/day)**	**T (m^2/day)**
Voelvlei	0.112	0.3221	2.8753	0.0188	0.054
Eilandsdrift - Wiesdrif	0.1312 0.0623	0.5651 0.5219	4.3077 8.3735	0.045 0.0426	0.1938 0.3567
Soetendalsvlei	0.1586	0.582	3.6695	0.0486	0.1617

The reason for the low values of hydraulic conductivity at Voelvlei site may be due to the presents of less permeable and shallow sandy-clay formations. On the other hand the slightly higher estimates at Eilandsdrift - Wiesdrif and Soetendalsvlei may be due to the presents of sandy formation which have high permeability. The aquifer saturation thickness (AST) ranged between 2.9 m and 8.4 m, indicating the aquifer formations and materials were very shallow as established by geophysical and drilling results.

6.6 Chapter summary

This chapter addressed the second objective of the study which is to evaluate aquifer hydrogeological properties using hydraulic tests, for characterizing the aquifer permeability. Using borehole yield data, aquifer productivity in the study area were classified as low to moderate, indicating a generally low yield formations, with yield estimates ranging from 0.49 to 0.72 l/s. Hydraulic conductivity and transmissivity estimates were very small, and ranged between 0.0030 and 0.2856 m/day and from 0.0008 to10.993 m^2/day respectively. This indicated a generally poor or low yielding aquifer formation in the study area. The geology of the area which is dominated by poorly fractured hard rock formations can be reason for low hydraulic conductivity estimates. In general, the results on hydraulic conductivity and transmissivity estimates indicate that groundwater occurs in less permeable formations, as also indicated by the geophysical resistivity survey and drilling results. These findings are supported by Falga`s et al. (2011), indicating that aquifers in coastal areas were generally of low groundwater potential.

CHAPTER 7: FLOW DYNAMICS OF GROUNDWATER

7.1 Introduction

This chapter is based on objective three (3) of the study, which is to determine groundwater flow directions using flow nets and hydraulic head difference method for local flows in the study area. The chapter contribute to an understanding of groundwater flow systems at local, subregional and regional scale within the catchment. The chapter methodology is present first, followed by key results and discussion, and lastly chapter summary.

7.2 Methods used

This study used flow nets and cross sectional method for determining groundwater flow directions within the study area. Using flow nets to determined groundwater flow directions, Kriging interpolation method in Surfer programme was applied to produce flow nests indicating regional to intermediate groundwater flows within the study area. On the other hand, local groundwater flow directions were determined from cross sections based on hydraulic head measurements (figure 63). This approach was used due to that the driving force for groundwater flow in unconfined aquifers is the head gradient (Price, 2013). The local flows were determined using water level data and resistivity models indicating layers of groundwater and condition in the subsurface that either facilitated or impeded such flows.

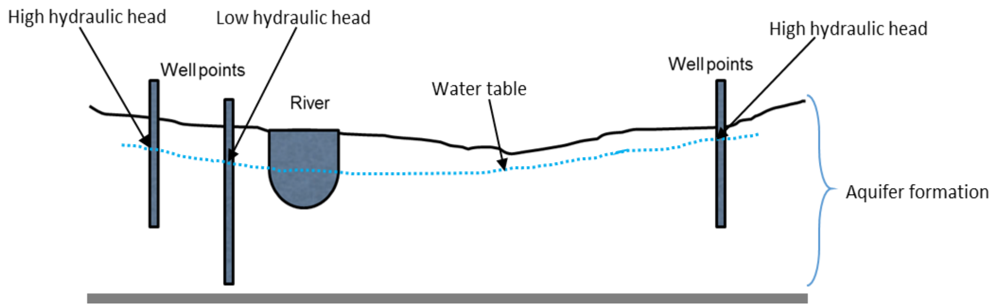


Figure 63: Cross sectional groundwater flow schematic

7.3 Local groundwater flows

Local groundwater flow was investigated at three sites within the study area to indicate the typical or expected directions of groundwater flow at particulars sites. The sites at which the investigations were conducted are, the Voelvlei, Eilandsdrift-

Wiesdrif and Soetendalsvlei sites. Piezometers drilled along the geophysical transects were used, and their water level measured to indicate their hydraulic head to determined flow directions.

7.3.1 Voelvlei and Eilandsdrift -Wiesdrif sites

In order to determine groundwater local flow directions at Voelvlei and Eilandsdrift -Wiesdrif sites (figure 64), hydraulic head were measured in in monitoring wells PZ3 and PZ4, and PZ13 and PZ14 located along a cross sectional profile (figure 65 and 66). At Voelvlei, the water level head in PZ4 located near the water edge of the wetland was lower than in PZ3 located further away from wetland. This indicated that flow directions of groundwater were towards PZ4 and wetland. The flow directions mimic the topography at the site.

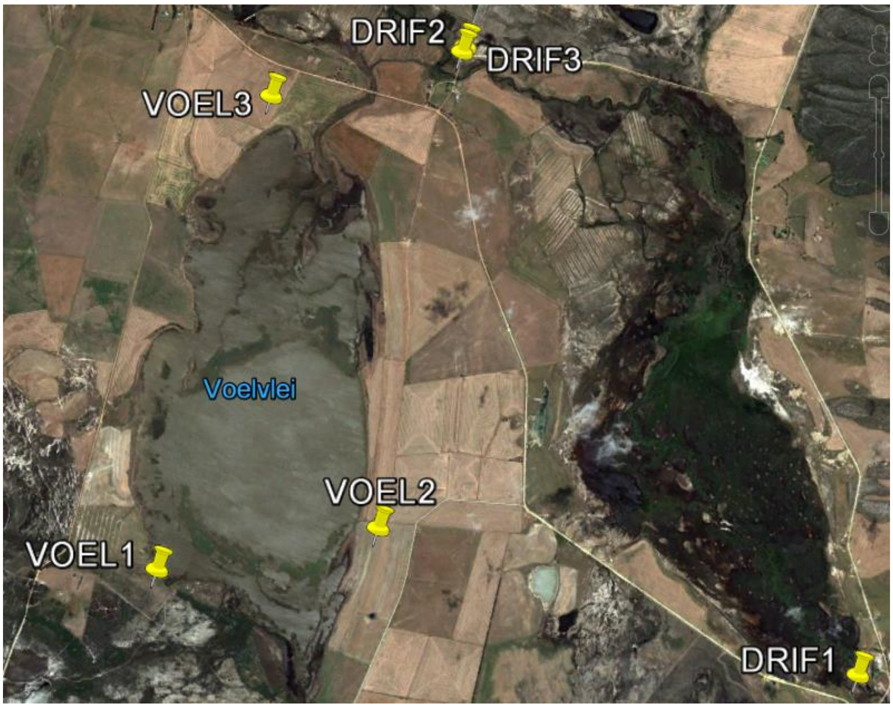


Figure 64: Location map of groundwater flow transects at Voelvlei and Eilandsdrift -Wiesdrif sites

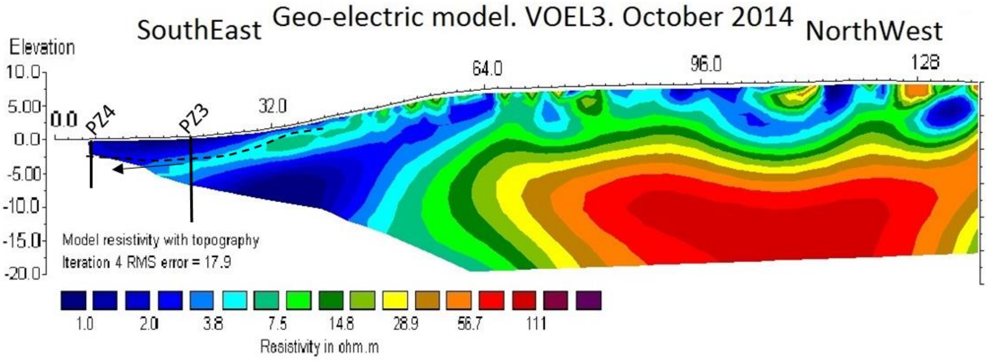


Figure 65: Local flows at transect 3, Voelvlei site

At Eilandsdrift -Wiesdrif site, the water level in PZ13 was high than in PZ14 (figure 66). This indicated that local groundwater flow directions might be towards PZ14, located at the edges of the Nuwejaars River.

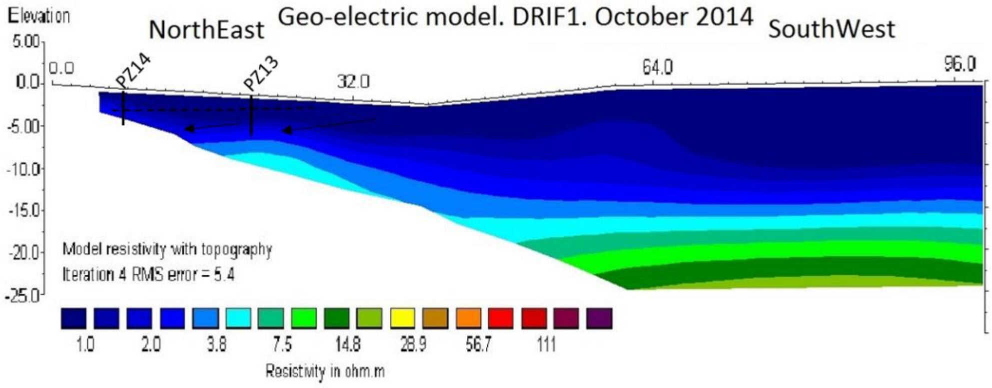


Figure 66: Local flow at transect 1, Eilandsdrift -Wiesdrif site

7.3.2 Soetendalsvlei site

At Soetendalsvlei site (figure 67), PZ17, PZ16 and BH2 along transect 5, and PZ21, PZ23 and BH3 at transect 2 were used for determining local groundwater flow at the site.

Figure 67: Location map of the transvers

At Soetendalsvlei, flow directions of groundwater are generally assumed to be towards the lake in the Westerly direction (figure 68 and 69). At transect 2, the groundwater flow directions follow the land surface slope, which is sloping away from the lake. Similarly at transect 5, flow is also towards the lake in the Eastward direction (figure 69).

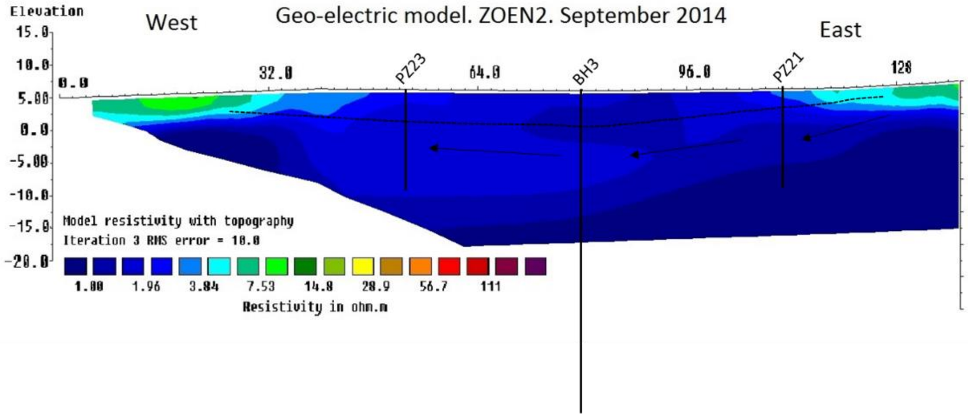


Figure 68: Local groundwater flow at transect 2, Soetendalsvlei lake site

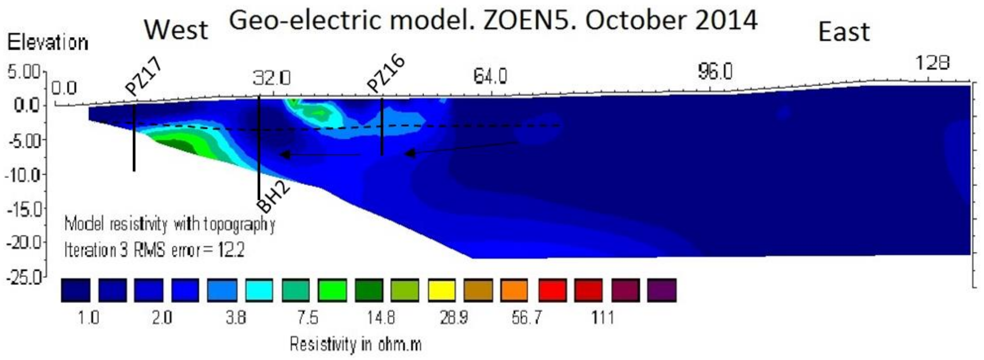


Figure 69: Local groundwater flow at transect 5

7.4 Regional-intermediate groundwater flows

The groundwater flow contour map indicates that flow was towards areas of low groundwater levels in meters above mean sea level (mamsl) (figure 70). These areas are depression such as river channels, and the wetland systems. Based on this finding, it can be stated that regional to intermediate flow in the study area is influenced by the immediate surface conditions, which most dominate at local scale, mainly the flat topography in the catchment.

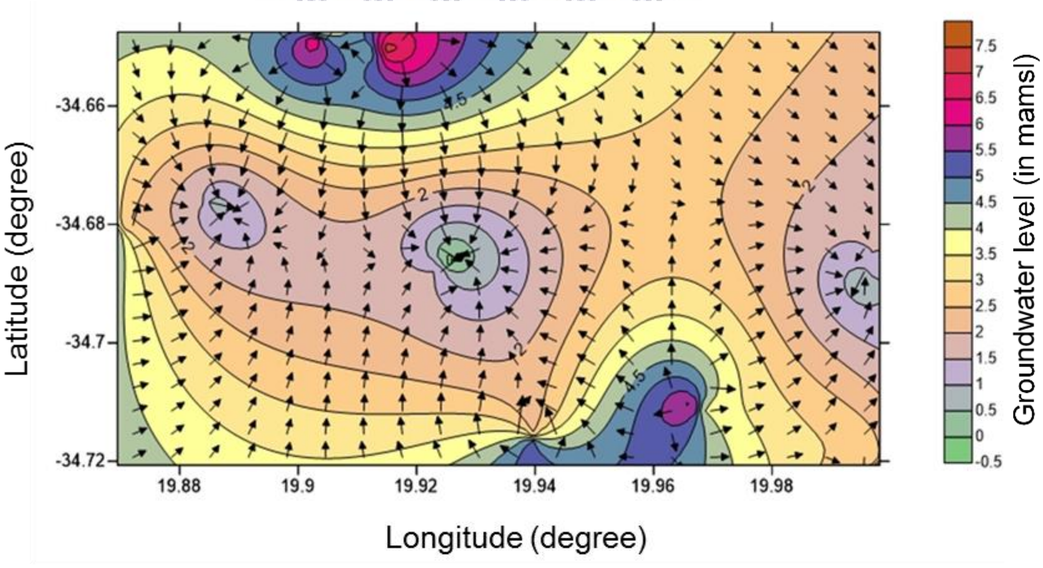


Figure 70: Groundwater flow contour map

7.5 Chapter summary

This chapter established regional and local groundwater flow within the Heuningnes Catchment focusing on the area along the Nuwejaars River between Voelvlei and Soetendalsvlei Lake. The objective was to determine groundwater flow directions in order to characterise the groundwater flow system in the catchment. The relationship between the water level heads at measured wellpoints and borehole, indicated that groundwater flow directions were generally towards wetland systems and river channel. This indicated that groundwater might be discharging or feeding into streams and wetlands in the study area. The result indicated that groundwater flow in shallow formations within the catchment likely followed the topography. The findings in this chapter provide an insight into the connections between the shallow aquifer, wetlands and river within the study area.

CHAPTER 8: CONCEPTUAL DESCRIPTION OF GROUNDWATER FLOW SYSTEM

8.1 Introduction

This chapter address objective four (4) of the study, and presents a hydrogeological conceptual model in attempt to provide a unified characterisation of the aquifers. The model is based on data and information available in the literature and presents an initial conceptualisation of the aquifer systems in the study area. The use of this approach over use of numerical models, is due to limitations on data availability in the study area. The chapter also provides a description of the hydrogeological characteristic of the aquifers. These include providing a description of the aquifer geological properties, hydrogeological boundaries, groundwater sources and quality, groundwater potential, recharge and discharge including flow system. Specific components of the hydrogeological model in the chapter are presented, and this is followed by a section on the groundwater flow conceptual model of the study area. An updated model of the groundwater flow systems is later provided based on observations which were made during field visits. Lastly, is presented a summary of the chapter.

8.2 Hydrogeological conceptual model of the study area

8.2.1 Hydrogeological setting

The prevailing geology within the catchment are Bredasdorp beds, Bokkeveld Group, Table Mountain Group (TMG), and basement rock of Malmesbury Group and Cape Granite Suite (Toens, 2001). These geologies have an implication on the hydrogeological system within the coastal area. They form aquifers with varying characteristics, including aquitards which represents less transmissive formations. Within the study area, shallow aquifers were associated with outcrop of formations and materials notably of Bredasdorp beds that overlies geologies of the Bokkeveld group and those deep units of the Cape Super group up to basement rock (Toens et al., 1998; Toens, 1996, 2001). On the other hand, secondary aquifer were associated with the TMG geology.

8.2.2 Aquifer boundaries

Regional hydrogeological boundaries were identified in Xu et al. (2009), and are located far outside the Heuningnes Catchment. This may well be an indication that the catchment was located in a discharge area of the regional system, with recharge taking place outside its perimeters, particularly true for deep fractured rock aquifers with high outcrop degree both in the northern and western parts of the catchment. The extent of the hydrogeological system outside the catchment may prove to be problematic for investigations of groundwater resource at local scale to site specific cases. This may also be true for planning and management of groundwater resources based on quaternary catchment concept used for surface water resources.

However, regional systems are often a form of subunits, which shows variable variations in hydrogeologic properties, topographic form and climatic conditions (Xu et al. 2009). Within the study area, topographic, stream courses, faults may act as boundaries that dictate on local horizontal flow of groundwater. These conditions are practical in shallow intergranular aquifers such as those of Bredasdorp beds. In fractured rock aquifers, faults and mountain ranges are common boundary features.

8.2.3 Groundwater sources

Within the study area, groundwater abstraction points are mainly spring (sp) and boreholes (bh) (figure 71). The distribution of these groundwater sources is such that boreholes are clustered in the eastern part of the catchment, while springs occur mostly in the western part.

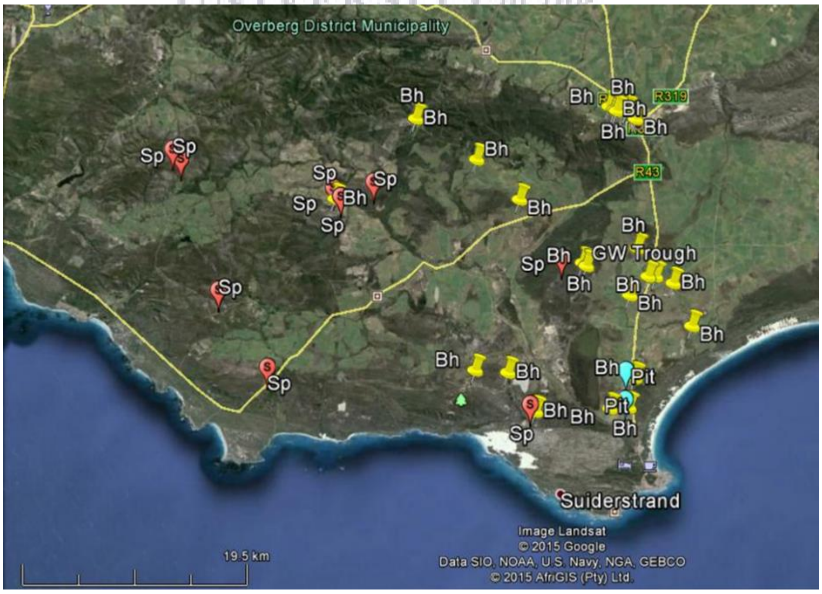


Figure 71: Distribution map of groundwater sources in the Heuningnes Catchment

This distribution is important in aquifer characterisation as it provides preliminary insight into groundwater occurrence, recharge and discharge zones. In this case, springs occurring within the study area represented groundwater discharge points in the catchment.

8.3 Groundwater flow conceptual model

A groundwater flow conceptual model was developed to provide an initial framework for understanding of groundwater flow systems within the study area. This included an initial conceptualisation of the flow systems and directions. Adding hydrogeological features such as geology, water table, groundwater sources, discharges, flows and boundaries, an updated groundwater flow conceptual model was develop which provides a unified description or characterisation of the aquifers.

8.3.1 Initial conceptual model of groundwater flow

Based on the initial conceptualisation of the groundwater flow, the flow system consisted of regional, intermediate and local flows. Regional groundwater flows in the catchment were generally in the South-easterly direction, and were assumed to follow topography which is flat towards the Indian Ocean (figure 72). From the conceptual model, wetlands and rivers act as zones of either groundwater discharge or recharge.

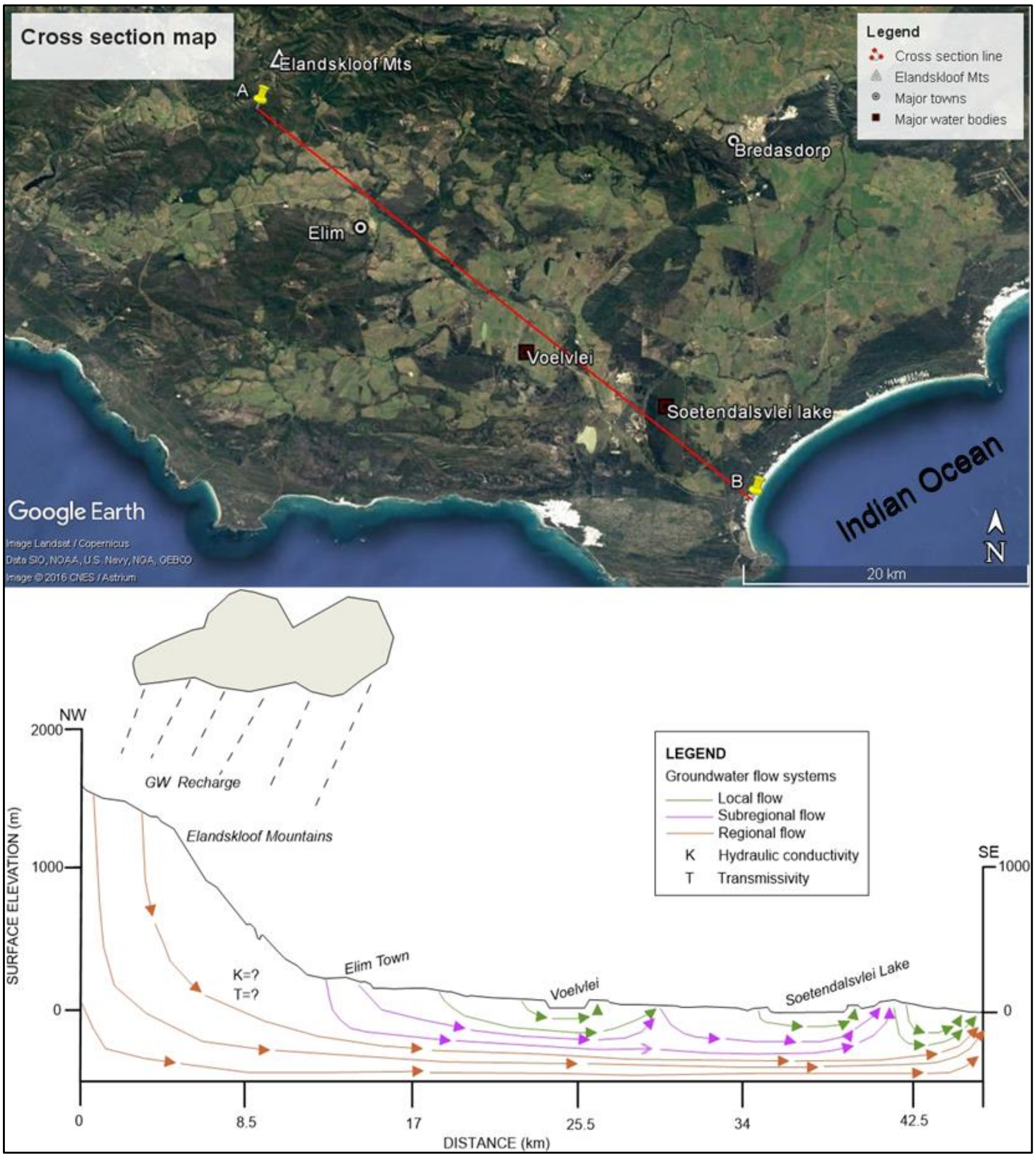


Figure 72: Plan view of the cross section and initial groundwater flow conceptual model

Intermediate and local flows were assumed to be nested within regional flows and also following the topography. Due to the generally flat topography across the Heuningnes Catchment, groundwater flows were assumed to be generally slow.

8.3.2 Updated conceptual model of groundwater flow

The updated groundwater flow conceptual model included features such as geology, water table, groundwater sources, discharges and flows, and boundaries (figure 73). The conceptual model revealed a rather compacted groundwater flow systems. These systems are limited depending on the extent of the geology of the water bearing rock. In this case, flow were indicated on the Bredasdorp beds, sandy shale and shales of the Bokkveld Group, and the sandstone and quartz of the Table Mountain Group.

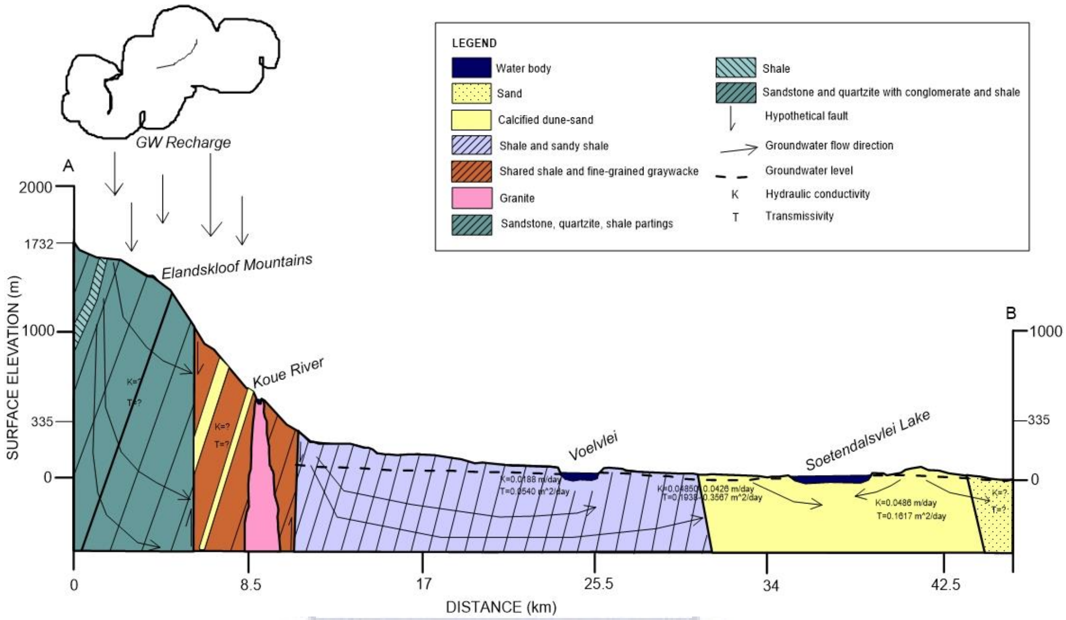


Figure 73: Updated groundwater flow conceptual model

The model also indicated that regional groundwater flows were generally in the South-easterly direction, and influenced by the topography of the catchment. On the other hand, the model indicated that local groundwater flows directions were towards surface depression such wetlands areas, lake and rivers channels within the catchment. Further, the groundwater flow conceptual model indicated that the catchment was dominated by local and intermediate flows, as compared to regional flows.

8.4 Chapter summary

The objective of this chapter was to develop a conceptual model describing the hydrogeological properties and groundwater flow system in order to provide a unified characterisation of the aquifers properties within the study area. The updated conceptual groundwater flow model, revealed a rather compacted regional groundwater flow systems within the study area. The model also indicated that regional groundwater flows were generally in the South-easterly direction, and mainly influenced by the topography of the area. In addition, the model revealed that, groundwater occurrence in the study area might be limited. Further, the conceptual model indicated that groundwater was likely to feed stream flows and wetlands depressions that served as groundwater discharge zones. Thus, further monitoring of groundwater levels and stream levels, show to conducted, to establish patterns of interaction.

CHAPTER 9: CONCLUSION AND RECOMMENDATION

9.1 Conclusion

This study was focused on characterising aquifers in the coastal region of the Heuningnes Catchment in the Western Cape. The aim of the study was to improve understanding of hydrogeological properties in coastal aquifers, in order to inform groundwater development and management options. This included understanding key properties of the aquifers, and groundwater units, including flow directions. The study used an integration of geophysical surveys, drilling, and hydraulic tests as methods to characterise the aquifers. As a result, data on resistivies variation of formations, drilling samples, water levels and slug test were analysed, in an attempt to characterise aquifers in the study area. The resistivity survey results indicated that shallow aquifer formations and materials in the study area were limited in extent and of poor potential. This was supported by the results of the well profiles which revealed consolidated sandy material overlay hard rock formation that occurred at shallow depths. In addition, the findings indicated that the saturation thickness of the aquifers was also small, with an average value of 7.16 m, and a range of between 38.49 m and 0.06 m. The findings also indicated that hydraulic conductivity (K) and transmissivity (T) were generally poor and small, ranging from 0.0030 to 0.2856 m/day and from 0.0008 to10.993 m2/day accordingly. The productivity of the aquifers were classified as low to moderate, with borehole yields averaging at 0.55 l/s. These findings were indicative of a low permeability environment with low yielding formations. Regarding local and regional groundwater flows, the findings in this study indicated that groundwater flow directions were locally towards depressions such as wetlands and river channels. The updated conceptual groundwater flow model, revealed a rather compacted groundwater flow systems, in which local and intermediate flow were dominant. These findings in this study support the view that aquifers in coastal regions were predominantly characterised by shallow depth, patchy distribution and low potential.

9.2 Recommendations

This study recommend the use of an integrated approach in characterising shallow coastal aquifer. This is because, this approach allow for complementary data and information to be collected, on the aquifer physical and hydraulic properties. The study also recommends the use complementary surface geophysical method that can address the issue of differentiating clay saturated layer from brackish water saturated layer, which have the same range of resistivity values of between 0 ohm.m and 2 ohm.m. With the integration of Electromagnetic sounding method the Resistivity method can prove to be the most appropriate choice for groundwater investigation within the study area. In addition, the study suggest use of slug test for estimation of hydraulic properties due to the low yielding nature of the aquifers in the study area. Further, the study recommend that studies should be conducted on groundwater recharge, as it is an important component in aquifer characterisation (Attandoh et al., 2013). Moreover the study recommends future studies to include a detailed study on groundwater flow system, directions using methods using tracer methods like isotopes and chemistry, including numeric models.

LIST OF REFERECES

Adelana, S. M., MacDonald, A. M., Adelana, S., & MacDonald, A. (2008). Groundwater research issues in africa. *Applied Groundwater Studies in Africa, IAH Selected Papers on Hydrogeology, 13,* 1-7.

Adelana, S., Xu, Y., & Vrbka, P. (2010). A conceptual model for the development and management of the cape flats aquifer, south africa. *Water SA, 36*(4)

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.

Baloochestani, F. (2008). Estimation of hydraulic properties of the shallow aquifer system for selected basins in the blue ridge and the piedmont physiographic provinces of the southeastern US using streamflow recession and baseflow data.

Banks, D., Morland, G., & Frengstad, B. (2005). Use of non-parametric statistics as a tool for the hydraulic and hydrogeochemical characterization of hard rock aquifers. *Scottish Journal of Geology, 41*(1), 69-79.

Barlow, P. M. (2003). *Ground water in fresh water-salt water environments of the atlantic* Geological Survey (USGS).

Bickerton, I., & Pierce, S. (1984). Estuaries of the cape. *Part II: Synopses of Available Information on Individual,*

Binley, A., Cassiani, G., & Deiana, R. (2010). Hydrogeophysics: Opportunities and challenges. *Bollettino Di Geofisica Teorica Ed Applicata, 51*(4)

Blake, D., Mlisa, A., & Hartnady, C. (2010). Large scale quantification of aquifer storage and volumes from the peninsula and skurweberg formations in the southwestern cape. Water SA, 36(2), 177-184.

Brown, C., Colvin, C., Hartnady, C., Hay, R., Le Maitre, D., & Riemann, K. (2003). Ecological and environmental impacts of large-scale groundwater development in the table mountain group (TMG) aquifer system: Water research commission, south africa. *Discussion Document, WRC Project K, 5*

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

Butler Jr, J. J. (1997). *The design, performance, and analysis of slug tests* Crc Press.

Carr, A. S., Thomas, D. S., Bateman, M. D., Meadows, M. E., & Chase, B. (2006). Late quaternary palaeoenvironments of the winter-rainfall zone of southern africa:

Palynological and sedimentological evidence from the agulhas plain. *Palaeogeography, Palaeoclimatology, Palaeoecology, 239*(1), 147-165.

Chowdhury, S. H., Iqbal, M. Z., & Szabo, J. P. (2003). Comprehensive approach of groundwater resource evaluation: A case study in the chippewa creek watershed in ohio (1). *The Ohio Journal of Science, 103*(5), 134-143.

Conrad, J., Nel, J., & Wentzel, J. (2007). The challenges and implications of assessing groundwater recharge: A case study–northern sandveld, western cape, south africa. *Water SA, 30*(5), 75-81.

Dippenaar, M. A. (2008). *Characterisation of some Fractured-Rock Aquifers in Limpopo Province, South Africa: Review and Case Study,*

Duah, A. A., & Xu, Y. (2013). Sustainable utilisation of groundwater resources under climate change: A case study of the table mountain group aquifer of south africa. *Climate change-realities, impacts over ice cap, sea level and risks* () InTech.

Duffield, G. M. (2007). AQTESOLV (pumping tests, constant-head tests and slug tests) software for Windows.

Fabbri, P., Ortombina, M., & Piccinini, L. (2012). Estimation of hydraulic conductivity using the slug test method in a shallow aquifer in the venetian plain (NE, italy). *AQUA Mundi, 3*(2), 125-133.

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

Freeze, R. A., & Cherry, J. A. (1979). Groundwater, 604 pp.

Gordon, N., Adams, J., & Garcia-Rodriguez, F. (2011). Water quality status and phytoplankton composition in soetendalvlei, voëlvlei and waskraalsvlei, three shallow wetlands on the agulhas plain, south africa. *African Journal of Aquatic Science, 36*(1), 19-33.

Graham, M., Ball, D., Dochartaigh, B. Ó., & MacDonald, A. (2009). Using transmissivity, specific capacity and borehole yield data to assess the productivity of scottish aquifers. *Quarterly Journal of Engineering Geology and Hydrogeology, 42*(2), 227-235.

Heath, R. C. (1983). *Basic ground-water hydrology* US Geological Survey.

Holland, M. (2012). Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the limpopo province. *Water SA, 38*(3), 379-390.

Hubbard, S. S., & Rubin, Y. (2000). Hydrogeological parameter estimation using geophysical data: A review of selected techniques. *Journal of Contaminant Hydrology, 45*(1), 3-34.

Kalbus, E., Reinstorf, F., & Schirmer, M. (2006). Measuring methods for groundwater? surface water interactions: A review. *Hydrology and Earth System Sciences Discussions, 10*(6), 873-887.

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,*

Le Maitre, D., Colvin, C., & Maherry, A. (2009). Water resources in the klein karoo: The challenge of sustainable development in a water-scarce area. *South African Journal of Science, 105*(1-2), 39-48.

Leketa, K. C. (2011). *Flow Characteristics of Groundwater Systems: An Investigation of Hydraulic Parameters,*

Liling, Z., Wenjuan, X., & Zhihua, H. (2011). Groundwater evaluation in KeKeYa groundwater source: Comparison of water balance method and numerical simulation method. *International Journal of Geomatics and Geosciences, 2*(2), 580.

Lin, L., & Xu, Y. (2006). A tensor approach to the estimation of hydraulic conductivities in table mountain group aquifers of south africa. *Water SA, 32*(3), 371-378.

MacDonald, A., Barker, J., & Davies, J. (2008). The bailer test: A simple effective pumping test for assessing borehole success. *Hydrogeology Journal, 16*(6), 1065-1075.

MacDonald, A., Bonsor, H., Dochartaigh, B. É. Ó., & Taylor, R. (2012). Quantitative maps of groundwater resources in africa. *Environmental Research Letters, 7*(2), 024009.

Nyende, J., Van, T., & Vermeulen, D. (2013). Conceptual and numerical model development for groundwater resources management in a regolith-fractured-basement aquifer system. *J Earth Sci Clim Change, 4*(156), 2.

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

Palacky, G. (1988). Resistivity characteristics of geologic targets. Seg, 1, 53-129.

Parsons, R. (2009). Is groenvlei really fed by groundwater discharged from the table mountain group (TMG) aquifer? *Water SA, 35*(5), 657-662.

Pauw, T. (2012). *Assessment of SPOT 5 and ERS-2 OBIA for Mapping Wetlands,*

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

Post, V. (2005). Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? *Hydrogeology Journal, 13*(1), 120-123.

Post, V., & Abarca, E. (2010). Preface: Saltwater and freshwater interactions in coastal aquifers. *Hydrogeology Journal, 18*(1), 1-4..

Price, M. (2013). *Introducing groundwater* Routledge.

Roets, W., Xu, Y., Raitt, L., El-Kahloun, M., Meire, P., Calitz, F., et al. (2008). Determining discharges from the table mountain group (TMG) aquifer to wetlands in the southern cape, south africa. *Hydrobiologia, 607*(1), 175-186.

Shao, J., Li, L., Cui, Y., & Zhang, Z. (2013). Groundwater flow simulation and its applieation in groundwater resouree evaluation in the north china plain, china. *Acta Geologica Sinica (English Edition), 87*, 243-253.

Silliman, S. E., Borum, B. I., Boukari, M., Yalo, N., Orou-Pete, S., McInnis, D., et al. (2010). Issues of sustainability of coastal groundwater resources: Benin, west africa. *Sustainability, 2*(8), 2652-2675.

Sundaram, B., Feitz, A., de Caritat, P., Plazinska, A., Brodie, R., Coram, J., et al. (2009). Groundwater sampling and analysis–a field guide. *Geoscience Australia, Record, 27*, 95.

Tadesse, N., Bheemalingeswara, K., & Abdulaziz, M. (2010). Hydrogeological investigation and groundwater potential assessment in haromaya watershed, eastern ethiopia. *Momona Ethiopian Journal of Science, 2*(1)

Taylor, C. J., & Greene, E. A. (2008). Hydrogeologic characterization and methods used in the investigation of karst hydrology. *Field Techniques for Estimating Water Fluxes between Surface Water and Ground Water, Edited by: Rosenberry, DO and LaBaugh, JW, US Geological Survey, Reston, Virginia (EUA),* , 71-114.

Toens, P. (2001). The Eastern Overberg Catchment Management Draft Status.

Toens, P. (1996). Proposed Multi-Disciplinary Investigation Covering The Wetlands and Vleis Between Elim and De Mond In The District of Bredasdorp, Western Cape.

Toens, P., Visser, D., Van Der Westhuizen, C., Stander, W., & Rasmussen, J. (1998). Report on the overberg coastal groundwater resources, volume II. *T&P Report,* (980148)

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.

Tsang, C., & Doughty, C. (2003). Multirate flowing fluid electric conductivity logging method. *Water Resources Research, 39*(12)

Tse, A.C., & Amadi, P. A. (2008). Hydraulic properties from pumping tests data of aquifers in azare area, north eastern nigeria.

Vereecken, H., Kemna, A., Münch, H., Tillmann, A., & Verweerd, A. (2005). Aquifer characterization by geophysical methods. *Encyclopedia of Hydrological Sciences,*

Vouillamoz, J., Chatenoux, B., Mathieu, F., Baltassat, J., & 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., 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*, 4387-4400.

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., et al. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources, 51*, 3-26.

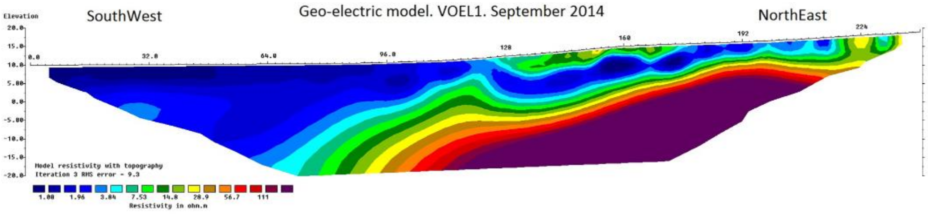
Xu, Y., Lin, L., & Jia, H. (2009). *Groundwater flow conceptualization and storage determination of the table mountain group (TMG) aquifers: Report to the water research commission* Water Research Commission.

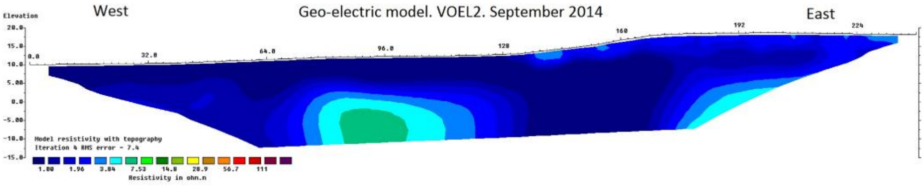
Zhou, Y. (2009). A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology, 370*(1), 207-213.

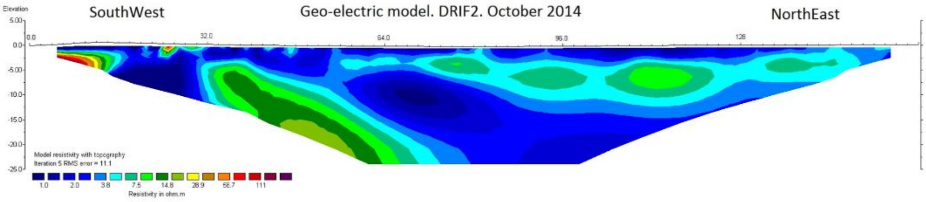
Zhou, Y., & Li, W. (2011). A review of regional groundwater flow modeling. *Geoscience Frontiers, 2*(2), 205-214.

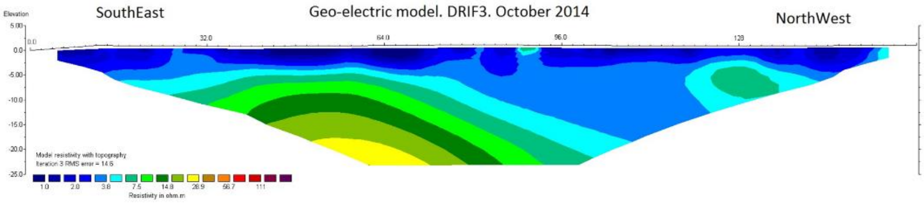
APPENDIX

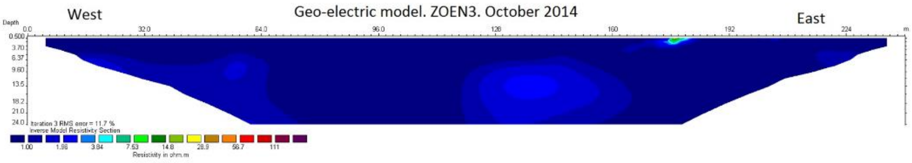
Appendix 1: Additional, electrical resistivity models for Site 1: Voelvlei, Site 2: Eilandsdrift –Wiesdrif, Site 4: Soetendalsvlei.

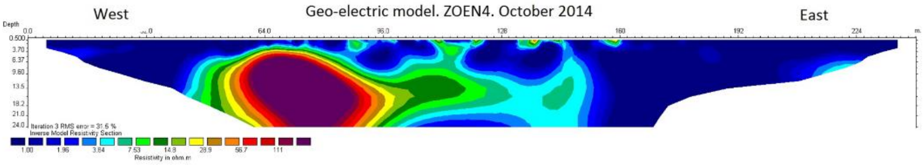


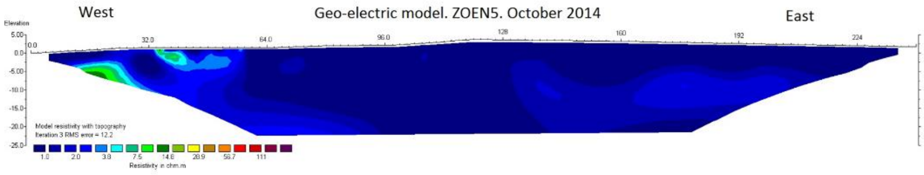




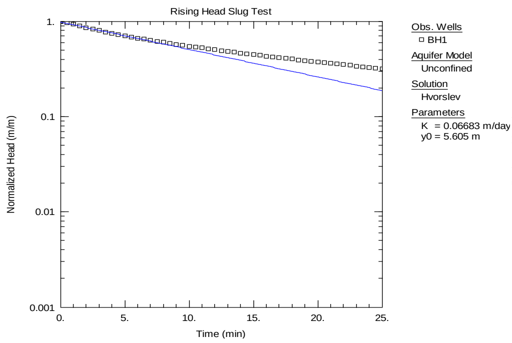


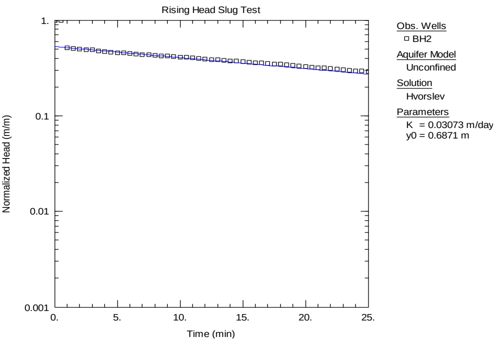


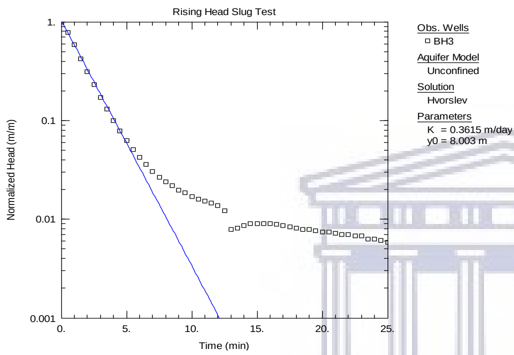


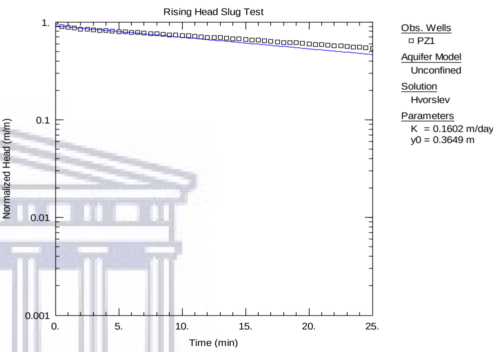


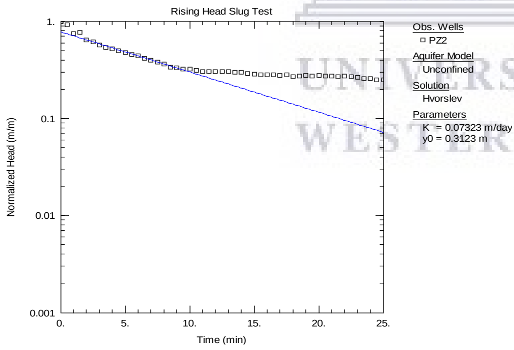
Appendix 2: Indicates normalized head vs time plots for the Hvorslve solution for estimating hydraulic conductivity or slug test data analysis. The pattern of the plots is similar to that of the Bouwer and Rice solution for partial or fully penetration well.

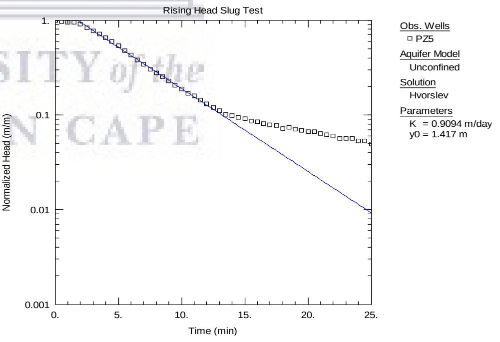


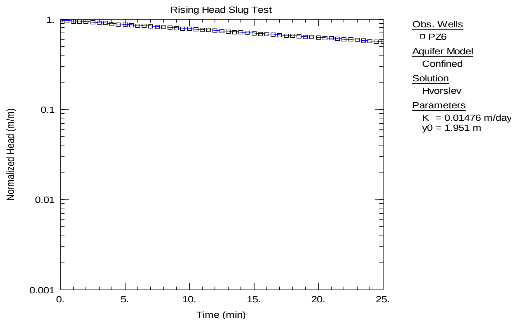


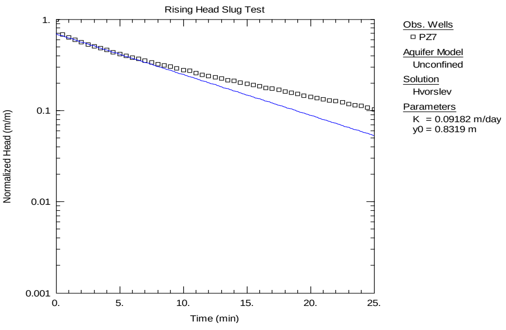


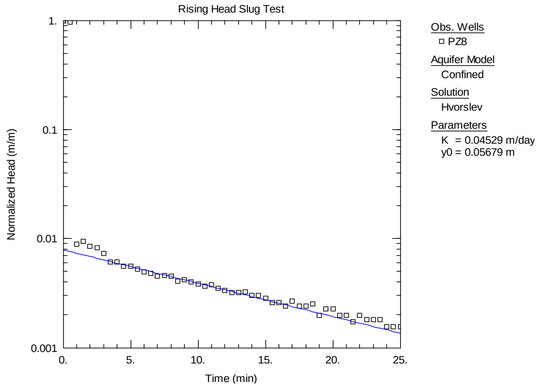


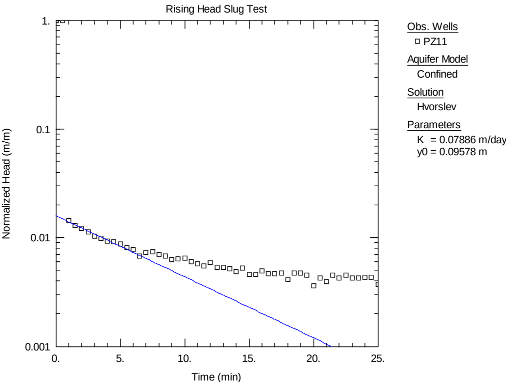









Rising Head Slug Test
Normalized Head (m/m)
1.
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ8
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 0.04529 m/day
y0 = 0.05679 m


Rising Head Slug Test
Normalized Head (m/m)
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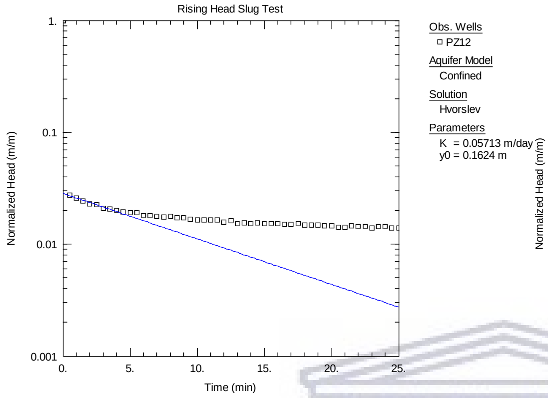
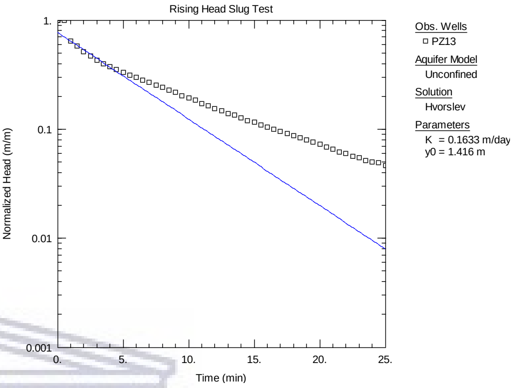
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ11
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 0.07886 m/day
y0 = 0.09578 m


Rising Head Slug Test
Normalized Head (m/m)
1.
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ12
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 0.05713 m/day
y0 = 0.1624 m


Rising Head Slug Test
Normalized Head (m/m)
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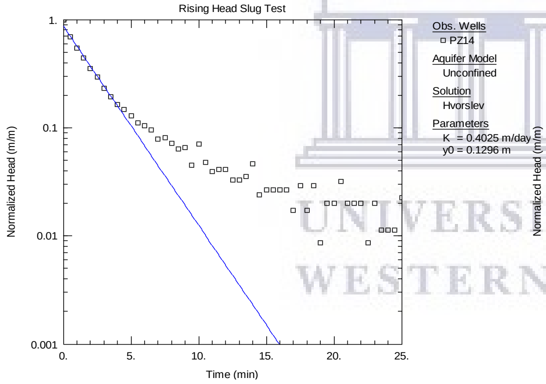
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ13
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.1633 m/day
y0 = 1.416 m


Rising Head Slug Test
Normalized Head (m/m)
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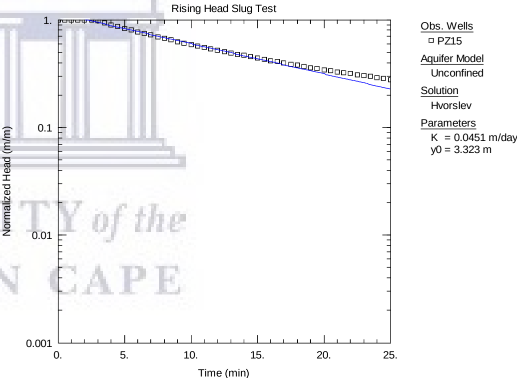
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ14
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.4025 m/day
y0 = 0.1296 m


Rising Head Slug Test
Normalized Head (m/m)
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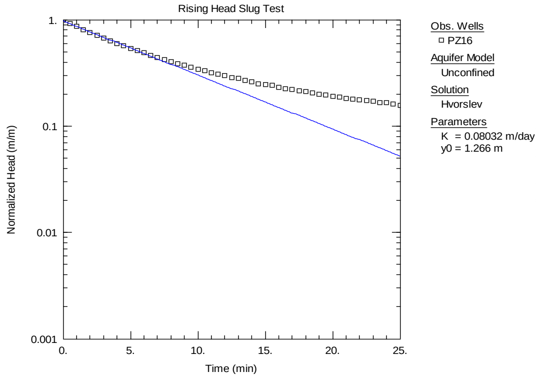
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ15
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.0451 m/day
y0 = 3.323 m


Rising Head Slug Test
Normalized Head (m/m)
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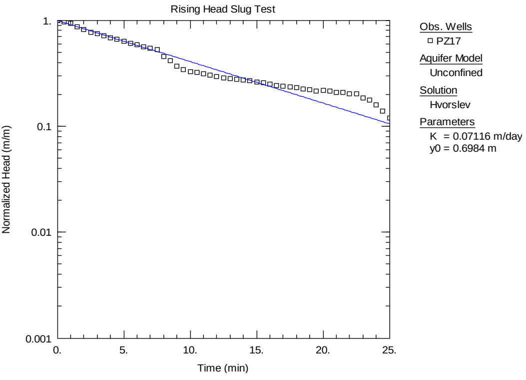
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ16
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.08032 m/day
y0 = 1.266 m


Rising Head Slug Test
Normalized Head (m/m)
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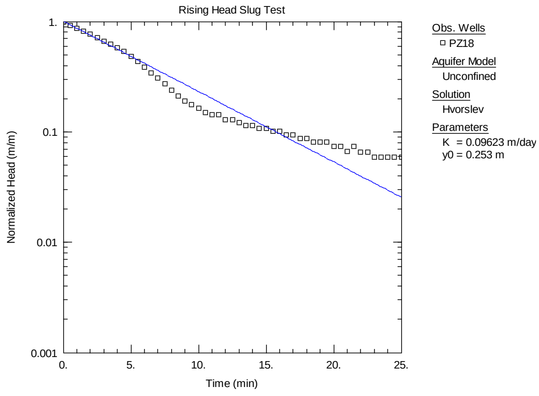
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ17
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.07116 m/day
y0 = 0.6984 m


Rising Head Slug Test
Normalized Head (m/m)
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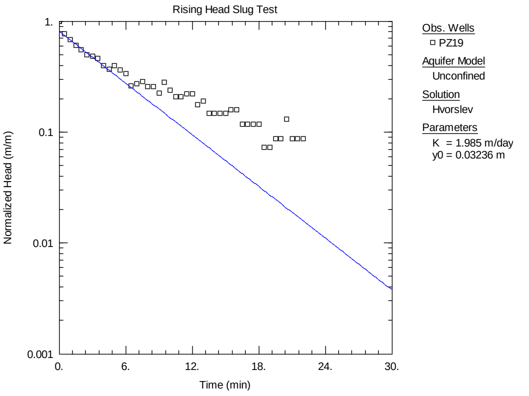
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ18
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.09623 m/day
y0 = 0.253 m


Rising Head Slug Test
Normalized Head (m/m)
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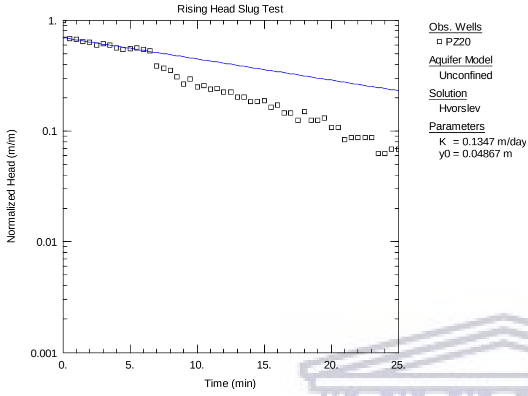
0.01
0.001
0.
6.
12.
18.
24.
30.
Time (min)
Obs. Wells
PZ19
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 1.985 m/day
y0 = 0.03236 m


Rising Head Slug Test
Normalized Head (m/m)
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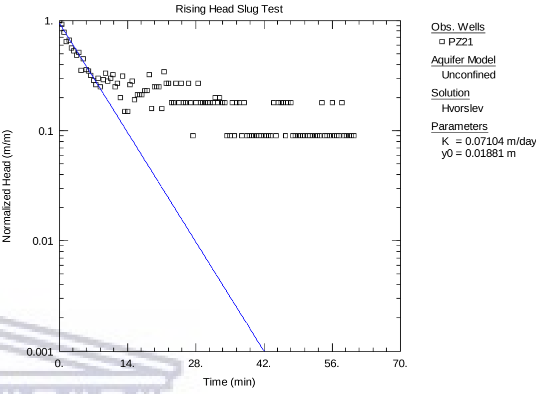
0.1
0.01
0.001
0.
5.
10.
15.
20.
25.
Time (min)
Obs. Wells
PZ20
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.1347 m/day
y0 = 0.04867 m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Normalized Head (m/m)
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0.01
0.001
0.
14.
28.
42.
56.
70.
Time (min)
Obs. Wells
PZ21
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
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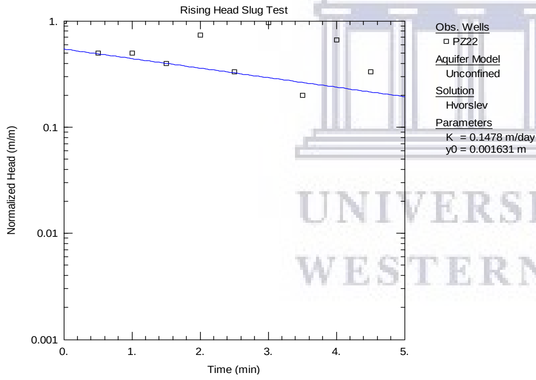
y0 = 0.01881 m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Normalized Head (m/m)
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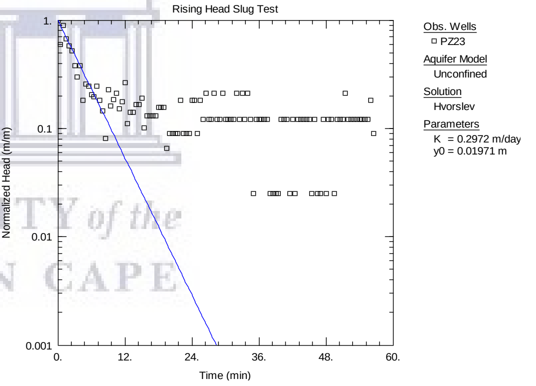
0.01
0.001
0.
1.
2.
3.
4.
5.
Time (min)
Obs. Wells
PZ22
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.1478 m/day
y0 = 0.001631 m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Normalized Head (m/m)
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0.01
0.001
0.
12.
24.
36.
48.
60.
Time (min)
Obs. Wells
PZ23
Aquifer Model
Unconfined
Solution
Hvorslev
Parameters
K = 0.2972 m/day
y0 = 0.01971 m