Assessing the surface water - groundwater interaction and its influence on the water quality from headwaters to lowlands.

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Abstract

Assessing the surface water - groundwater interaction and its influence on the water quality from headwaters to lowlands.

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The connections between surface water and groundwater systems remain poorly understood in many catchments throughout the world and yet they are fundamental in effectively managing water resources. Managing water resources in an integrated manner is not straightforward, particularly if both resources are being utilised. Groundwater-surface water interactions are difficult to observe, measure, and have commonly been ignored in water management considerations and policies. Thus, it is important to understand the interaction between the two water bodies as it can have significant impacts on both water quantity and quality. The current study assessed groundwater – surface water interaction in order to understand how the interaction influences the available water resource in the Nuwejaars Catchment. This study provides evidence of the spatial-temporal variations caused by groundwater – surface water interaction from headwaters to lowlands. To support this argument the study has three objectives: i) To characterize each study site from highland to lowlands using a multi-methodological approach using physical methods; ii.)To determine the spatial – temporal variations of the water quality changes at the groundwater and/or surface water sites; and iii) To characterize surface water and groundwater systems in terms of their connectivity within the catchment.

Water samples were taken from groundwater, surface water and rainfall during both dry and wet periods. Hydrogeological fieldwork were conducted to collect data with the addition of previous data that was collected in the catchment was reviewed. Analytical and laboratory-based methods were used for analysis and interpretation of geophysics, lithology logs , down-hole EC, pH and Temperature logs, groundwater level, river/borehole elevation, aquifer test (including slug test), hydro-chemical and environmental stable isotopic data sets. The use of a combination of methods for the characterization of such interactions is often recommended to provide a comprehensive assessment of the processes involved.

Six sites were considered for this study. Groundwater and surface water monitoring took place at these sites. Analyses were performed, the data was coupled with an addition of historical data collected at the same sites. The six sites include: Tussenberge, Boskloof, Spanjaardskloof, Jan Swartskraal, and Sandfontein and Moddervlei. Two of the sites (Sandfontein and Tussenberge) were in the headwaters, two sites on hillslopes (Spanjaardskloof, Boskloof), one site in the mid-slope region (Jan Swartskraal), and the Moddervlei site in the lowlands.

Insights from geophysics results showed that groundwater occurrence is characterized by multiple layers of varying depths inferred to be caused by different levels of weathering, geology and fractures. Electrical resistivity cross sections varied from highland to lowland. At the Tussenberge site Resistivity values increased to > 3000 Ω m at depths greater than 30m which suggest the existence of unweathered sandstone and the gravity transect showed no significant anomalies along the transect which suggest that no fractures and major changes in underlying formation occur at this site. The general trend shows a decline in gravity between 150 - 230 m along the transect, suggesting a less dense subsurface lithology. The Sandfontein site cross sections show slight variability in the resistivity cross section, with predominantly high resistivity, portraying a thick layer of bedrock. Whilst profiles from the Spanjaardskloof site suggest the occurrence of weathered sandstone with water. The boreholes drilled at the Jan Swartskraal intersect different weathering profiles with depth consisting of sandstone on the surface , overlying shale. A zone of low resistivity values was observed at the location where gravity anomalies suggested the existence of a fracture at Boskloof. These relatively low resistivity values are due to weathering along the fracture zone that increase permeability and the occurrence of water. At the lowland site, Moddervlei, very low resistivity values, < 10 Ω m, occurred along the western side up to a depth of 20 m. Such low resistivity values are likely due to sand material or weathered sandstone with saline water. Overall, the gravity and resistivity profiles from highland to lowlands showed high variability.

The borehole downhole sedimentary logs confirmed what was seen on the cross sections developed from both gravity and resistivity geophysical data, in terms of the lithological make up of the boreholes drilled at each site.

The elevation of nearby streams was used to assess the potential for GW-SW Interactions. With data collected it is evident the following streams in the uplands are mainly gaining streams and most of them are perennial: Tussenberge, Sandfontein, and Boskloof. This is assumed as the water table showed the groundwater table above the river bed, suggesting gaining stream hydraulic connectivity exists. The mid-slope region (Jan Swartskraal) had no evidence of

groundwater discharge. The water table was found to be below the river bed at the site in the riparian zone of Jan Swartskraal River with one of the shallow boreholes drying up.

The relationship between the water table and river bed is variable in the lowlands. The seasonal variations yields interesting findings too. The data suggests during the dry season groundwater does not make a contribution to the flows in the rivers. However the stable isotope signatures suggest a dominant groundwater contributes to the river water quality. Groundwater also contributes to river flows during the wet season, but it is masked by river runoff as part of the flow. The flow recession typically expected from groundwater, seems to be influenced by the wide floodplain and off-channel pools which contributes to the lowland flow.

Surface water – groundwater interactions are spatially and temporally variable within the lowlands. At the Moddervlei site, the potential exists for groundwater discharge into the river during the wet season. However, during the dry season, the water table is below the river bed. The existence of clay and very low gradient may limit any significant surface water-groundwater interactions along some river stretches.

Plotting of trilinear piper diagrams using data from groundwater (both deep and shallow), surface water from the catchment showed all matrices plot in the Na-Cl quadrant of the piper diagram. This implies that all the water samples may originate from a similar geological environment based on the ionic ratios in the samples. This also suggests the occurrence of groundwater – surface water interactions within the study area.

It was found that hydrochemical characteristics of surface water are influenced by groundwater discharge into streams in the uplands, while this is reduced in the lowlands. Stable isotopes revealed rainfall being the major source of groundwater recharge. In the uplands isotopic signatures of surface water and groundwater are similar indicating groundwater discharge.

The following streams in the uplands are mainly gaining streams: Tussenberge, Spanjaardskloof, and Boskloof. The mid-slope region (Jan Swartskraal) had no evidence of groundwater discharge. The water table was found to be below the river bed at the site in the riparian zone of Jan Swartskraal River with one of the shallow boreholes drying up. Surface water – groundwater interactions at the Moddervlei site have a seasonal behaviour based on the water level data and elevation data collected at the site.

With all this evidence gathered it is evident that at sites where interaction is present has significant change on the spatial and temporal variation of the available water resource in terms of the chemistry of the water. Additionally, these variations are distinct spatially in both highland and lowlands; and seasonally. It can be concluded from the data that there are localized processes happening within the catchment at each site. There is not just one regional system that this catchment is confined to.

Based on the findings in this study, the following recommendations can be made:

- The sites without automated water level loggers get loggers installed, in order to make comprehensive conclusions of all the sites;
- Hydraulic test need to be done at all the sites for longer periods in order to understand the extent of connectivity and hydraulic properties of each site, and
- Full scope of water quality parameters should be consistently monitored at sites in order to gain more conclusive evidence on the extent of the spatial – temporal variation of water quality within the study area.

Overall, this study proved the usefulness of investigating catchments from mountain headwater to coastal lowlands using a multi-methodological approach in order to understand the nature of surface water groundwater interaction. Based on the findings, it was not practical to study the site at catchment scale.

Declaration

I, Aneeqah Cornelius, declare that project title *"Assessing the surface water - groundwater interaction and its influence on the water quality from headwaters to lowlands."* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Aneeqah Cornelius

Signature:

Date: June 2023

Dedication

This Thesis is dedicated to my parents. To my mom Ruwayda Cornelius and my Father Sheraai Cornelius, thank you for sacrifices you made to ensure my success. Thank you for always believing in me and supporting me throughout my life. It is because of your continuous love and support that kept me going. I will forever be grateful.

The Quran, Surat Al-'Isrā' 17:24

وَقُل رَّبِّ ٱرْحَمْهُمَا كَمَا رَبَّيَانِى صَغِيرًا

“My Lord, have mercy upon them as they brought me up [when I was] small.”

Acknowledgments

I would like to first thank the Almighty Allah for providing me with the strength and the patience that was required for the completion of my Master's Thesis.

The Quran 11:88 (Surah Hud):- He said:

وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ ۚ عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ

"My success can only come from Allah. In him I trust, and unto Him I turn"

I would also like to thank my supervisors Dr Jaco Nel, Dr Sumaya Clarke and Dr Brigitte Melly respectively for their assistance throughout formulation and execution of this research. To Water Research Commission (WRC) and National Research Foundation (NRF) for their financial assistance, which made this research possible. I am grateful for the assistance of my peers in the Earth Sciences department that assisted me in the field.

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Chapter 1 Introduction

1.1 Overview

Groundwater and surface water have historically been isolated in research and management, despite the fact that they interact over a variety of physiographical environments (Sophocleous, 2002). According to Madlala (2019), the lack of integration between groundwater and surface water, particularly in South Africa, is due to the Water Act 54 of 1956 that saw groundwater and surface water as separate bodies; their use and allocation would happen separately. The National Water Act 36 of 1998 requires integrated water resources management that takes into account the impacts of development on interactions between groundwater and overlaying surface water bodies, such as lakes, dams, rivers, wetlands and estuaries. Despite this act being gazetted over 20 years ago, there is still a culture regarding these systems separately in South Africa.

The connections between surface water and groundwater systems remain poorly understood in many catchments throughout the world and yet they are fundamental in effectively managing water resources. Managing water resources in an integrated manner is not straightforward, particularly if both resources are being utilised. Groundwater-surface water interactions are difficult to observe and measure and have commonly been ignored in water management considerations and policies (Winter et. al., 1998, Brodie, 2007; Evans, 2010; Cantor, 2018; Chen et al., 2018; Joo et al., 2018; Madlala et al., 2019). Thus, it is important to understand the interaction between the two water bodies as it can have significant impacts on both water quantity and quality (Annan, 2006; Gordon, 2013; Saha et al., 2017; Madlala et al., 2019).

In past projects catchment management plans tend to focus on surface water, which is the most visible form, without considering the interlinkages between it and groundwater. There was no consideration of an integrated approach to the management of all elements of the hydrological cycle, such as Surface Water and Groundwater which is globally accepted as a fundamental basis for sustainable water resource management (Saha et al., 2017).

Similarly, previous research in the Nuwejaars catchment has shown the same tendency to separate ground and surface water research, while very little is currently known about the interaction between groundwater and surface (Manyama, 2017; Seaton, 2019). Thus, understanding groundwater-surface water interaction can assist with sustainable decision-making as the major source of water in this area is groundwater and it is mainly used for agricultural and domestic use.

In the last decade, recognition of the importance of groundwater-surface water interaction has expanded (Langhoff et al. 2006), and today it is widely known that to better manage these water issues, there is a necessity to manage groundwater and surface water together as linked resources (Saha et al., 2017; Zhao et al., 2018).

This study assesses the influence of surface water – groundwater interaction on the water quality from highland to lowlands of the Nuwejaars catchment employing combinations of hydraulic and hydrochemical techniques (Vandersteen et al., 2015; González-Pinzón et al., 2015; Li et al., 2016; Banda, 2019; Madlala et al., 2019).

1.2 Research problem

A criterion for sustainable water resources management is an understanding of how surface water and groundwater interact and affect the availability and quality of these resources (Banks et al., 2011; Saha et al., 2017) at the catchment scale, from the mountain headwaters to the river mouth. There is however inadequate understanding of the nature of these interactions and how they affect the spatio-temporal dynamics and; quality of water resources at the catchment scale, since most studies of groundwater - surface water interaction have focused on specific sites or river reaches (Banks et al., 2011).

It is also common for surface water–groundwater interaction assessments to investigate river reaches at a local scale and as discrete individual systems, which are generally classified as connected (gaining and losing type systems) or disconnected (transitional or completely disconnected type systems). While these classifications are valid at any point in space and time, studies often fail to consider how individual river reaches function in the context of the entire regional river system and what implications this can have on water quantity and quality.

In this study, spatial and temporal assessments are made in a regional catchment using hydrogeological, hydrological and hydro chemical techniques to determine the source and loss terms of the river and groundwater system and how their relative magnitude changes along the river from the catchment mountain headwaters towards the coastal lowlands.

Previous projects such as Parsons (2004) and Hughes et al., (2007) have established that the addition of surface water – groundwater interactions in models used for water resources assessments are problematic due to inadequate information about spatio -temporal variations of these interactions. Hence, there is a need to improve the understanding of, and the capacity to predict spatial and temporal variations in surface water and groundwater interactions, and their influence on available water resources at the catchment scale, in order to sustainably manage the water resource, with regards to the water quality and quantity.

Additionally, Banda (2019) established that there is a need for improving the groundwater monitoring sites both in highland and lowlands areas of the catchment to have a better distribution of groundwater level patterns and aquifer hydraulic parameters that may be influenced by the sub-surface heterogeneities in the Nuwejaars catchment. Banda (2019) also mentions that water sampling for both hydro chemical and isotopic samples need to be done during a period of average or high rainfall which would help describe the average dry and wet periods for the Nuwejaars catchment in order to make better conclusions. Furthermore, the author reiterated that it would be useful to monitor environmental isotopes from rainfall, groundwater and surface water more frequently in both highland and lowlands areas.

1.3 Study aims and objectives

1.3.1 Aim

The aim of this study is to establish the nature of groundwater - surface water interaction from mountain headwaters to coastal lowlands and to determine how these interactions influence the spatio-temporal variations of available water resources in terms quality at the catchment scale.

In order to achieve these aims, the current study will address the objectives stated below.

1.3.2 Objectives

- **a.** To characterise each study site from highland to lowland using a multi-methodological approach using physical i.e geophysics, down-hole logging, borehole logs, water level, temperature data and rainfall data .
- **b.** To determine the spatial – temporal variations of the water quality changes at the groundwater and/or surface water study sites; and
- **c.** To characterise the nature of groundwater – surface water interaction connectivity within the catchment.

1.4 Significance of study

An integrated approach to the management of all elements of the hydrological cycle, such as surface water and groundwater is globally accepted as a fundamental basis for sustainable water resources management (Banks et al., 2011; Saha et al., 2017). This is one of the cardinal and founding principles of the National Water Act of South Africa as well. It is also found that elements of the water cycle support and are part of ecosystems, and interactions between these elements affect ecosystems, thus it is important to understand how these resources vary over space and time. Furthermore, legislation in South Africa and elsewhere requires that the use of surface water and groundwater should take into account the need for reserving some water to support ecosystems and basic human needs.

Interactions between surface water and groundwater affect the availability of water to support ecosystems and basic human needs (Conant et al., 2019; Boulton and Hancock, 2006; Sophocleous, 2002). Thus understanding how surface water groundwater interacts is important. A prerequisite for sustainable water resources management is an understanding of how surface water and groundwater interact and affect the availability of this resource at the catchment scale, from the mountain headwaters to the river mouth. There is however inadequate understanding of the nature of these interactions and how they affect the spatio-temporal dynamics and quality of water resources at the catchment scale, since most studies of groundwater - surface water interaction have focused on specific sites or river reaches.

This research helps to sustainably manage the water resources that is available in the surrounding areas of the Nuwejaars Catchment for basic human needs and ecosystems. In the surrounding areas farmers mostly depend on groundwater for their farming practices and if the water resource is not managed properly these farmers will not be able to continue with their crop production and dairy farming. These practices are their form of income as they sell these products to businesses. For example, there is a protea farm in the area using groundwater as its main source for watering the plantation. Once proteas are ready, they are marketed throughout South Africa and even outside the country. In addition, promoting sustainable management of the resource will help protect ecosystems. If groundwater is over abstracted it can have implications on the ecosystem. Over abstraction can also cause contamination of surface water. Hence, this research will contribute to socio -economic status of South Africa. The ongoing changes in water management policy are also driving the interest in groundwater–surface water interactions to improve policies around how to sustainably manage available water resources (Keery et al., 2007).

1.5 Scope and Thesis structure

This thesis comprises of 7 chapters. **Chapter 1** provides a brief introduction of the present study including the aims and objectives. **Chapter 2** gives a review on the conceptual model (Hydrological cycle) and the theoretical background of different methods and techniques used when studying surface water – groundwater interaction. **Chapter 3** describes the study area concerning location, drainage patterns, climate, rainfall, topography, geology, vegetation and geo-hydrology. In addition, descriptions of transects and its location. **Chapter 4** description of materials and methods used to obtain results. **Chapter 5,** provides results and interpretations to answer objective 1 and 2 extensively .This chapter concludes with a chapter summary of main findings. Finally, **Chapter 6** provides insight into objective 3 including conceptual models for each site for the current study. Additionally this chapter synthesises the main findings from this study including recommendation for future research work to be done in this area.

1.6 Study conceptualization

This study forms part of a bigger project that is funded by the Water Research Commission (WRC Project No. K5/2855/1and2). The project aims to improve the understanding of surface water – groundwater interactions from headwater to lowlands for catchment scale sustainable water resources management. This project builds on previous projects that have been done by Parsons (2004); Hughes et al., (2007) and; Tanner and Hughes (2005).

Existing living laboratory infrastructure and research done in the Nuwejaars catchment, Western Cape area, was used during the course of this study. Other equipment such as installation of additional boreholes, water level loggers and rainfall samplers forms part of this MSc research project as well as the bigger project and other researchers.

Additionally, this study is a continuation of studies that has been done by Banda (2019) which focused on assessing hydrogeological characteristics to establish the influence of aquifer-river interaction in non-perennial river systems in Nuwejaars catchment. Banda (2019) did this by characterising the spatial and temporal variation in aquifer-river interaction and by conceptualizing the groundwater flow system of the Nuwejaars catchment. The present study will however improve on the shortcomings of this study of Banda (2019).

This study will improve groundwater monitoring sites in both highland and lowlands areas. High frequency sampling for both hydrochemical and isotopic samples will be done during a period of average or high rainfall which describes the average dry and wet periods for the study area. This is done in order to make better conclusions, as the study by Banda, (2019) has a low frequency data collection of water samples. Additionally, the present study conducts a more extensive monitoring of environmental isotopes from precipitation and groundwater in both highland and lowlands areas to add to the existing water level monitoring system.

Figures, and Tables used in some sections of this thesis were developed in parallel to deliverable reports for the Water Research Commission (WRC) progress reports, which are currently unpublished. The data used for all the figures and tables were collected for the current study and to integrate into the objectives of the bigger WRC Project.

Chapter 2 Literature Review

2.1 Introduction

This chapter provides a review on:

- The conceptual framework i.e. hydrological cycle and types of surface water – groundwater interactions systems
- Overview of different methods used to assess surface water – groundwater interaction with emphasis on
    - physical methods: geophysical methods;
    - Chemical Methods: stable isotope and physio-chemical constituents as that is the prominent methods/techniques used in this research project.

2.2 General conceptualization of groundwater- surface water interaction

When doing a study regarding flow of water it is found that Darcy's Law is the theoretical concept in order to understand the flow process. It also compliments the gradient flow. Darcy's Law governs fluid flow though porous medium. It states that there is a direct proportionality between the porous bed medium and the difference in heights of the fluid. Additionally Freeze and Cherry (1979) mentioned the inverse proportion to the length of the flow path. Darcy's Law also refers to the fact that the flow quantity is also directly proportional to the coefficient K (Hydraulic conductivity) which is dependent on the nature of the porous medium. The Law is used in many studies to evaluate the flow in aquifers, the following variables is measured in order to understand the water flow between matrices. See the Darcy equation below:

$$q = -K \frac{\partial h}{\partial h}$$

q =Specific discharge (L/T)

K = hydraulic conductivity (L/T)

h = Hydraulic head

l = distance (L)

The method involves the installation of piezometers at different depths along the surface body to determine the vertical hydraulic gradient beneath the surface water. The difference between the water levels measured from the piezometers and surface water bodies is recorded as the vertical hydraulic gradient (Oxtobee and Novakowski 2003).

Additionally the general conceptualization of groundwater – surface-water interaction can be examined using a borehole or boreholes that are located near a stream/river to assess whether the stream is gaining or losing water to the water table /groundwater (Figure 1). There are two commonly used types of streams : Gaining and Losing streams. For a stream to be characterised as a gaining stream, the elevation of the water table in the vicinity of the stream must be higher than the elevation of the stream water surface which will allow for groundwater to discharge into the stream channel. A losing stream is when the elevation of the water table in the vicinity of the stream must be lower than the elevation of the stream water surface, which will enable for surface water to seep to groundwater.

In the first scenario the stream gains water from inflow of groundwater through the streambed and into the river itself (gaining stream). The second scenario the stream loses water to groundwater resource due to the outflow through the streambed (losing stream). The second scenario is where the stream loses water to groundwater resource due to the outflow through streambed (i.e. a losing stream).

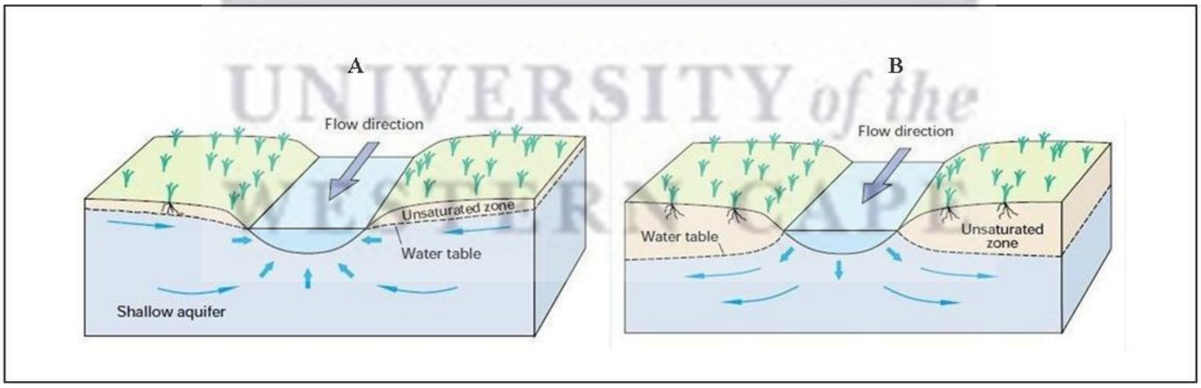


Figure 1: Gaining (A) and (B) losing stream (Winter et al., 1998)

There is a third scenario, where one stream can be a gaining and losing stream in different reaches of the stream and at different times of the year, depending on the water table.

The stream is disconnected from the groundwater system (see Figure 2 A) by an unsaturated zone. The water table may have a visible mound below the stream if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral groundwater flow away from the water table mound (Winter et al., 1998). However, in some environments, streamflow loss or gain can continue, which might result in a stream always gaining water from the aquifer or it might always lose water to aquifers (see Figure 2 B). However, the flow direction can differ a great deal along a stream in other environments, where some reaches receive groundwater from aquifer and other reaches loses water to groundwater.

Furthermore, in very short timeframes flow directions can change as a result of storm which in turn can cause temporary flood peaks moving down the channel, resulting in focused recharge near stream banks or transpiration of groundwater by riparian vegetation (Ala-aho, 2015; Biyela, 2015. Lasagna et al., 2016).

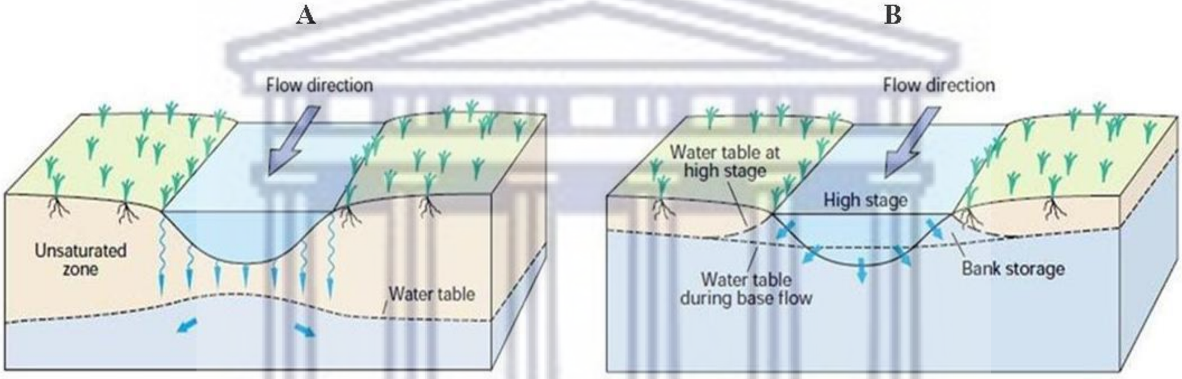


Figure 2: Gaining (A) and (B) losing stream (taken from Winter et al., 1998).

Extracting water from shallow aquifer that is directly connected to surface water bodies can have a major effect on the movement of the water between these two water bodies. The effects of pumping a single well or a small group of wells on the hydrological regime are local in scale and the effect of many wells extracting water from an aquifer over large areas may be regional in scale.

Additionally, abstraction from shallow groundwater can influence nearby streams or surface water bodies. The analysis of the sources of water to a pumping well in a shallow aquifer that discharges to a stream is provided here to gain an understanding into how a pumping well can change the quantity and direction of the flow between shallow aquifer and the stream. The changes in the direction of the flow between two water bodies can affect transport of contaminants linked with the movement of water. Even though a stream is used in the example, these results are applicable to all surface water bodies, including wetlands and lakes (Winter et al., 1998; Ala-aho, 2015; Biyela, 2015. Lasagna et al., 2016)

2.3 Approaches for investigating surface water – groundwater interactions

This section reviews the literature which is associated with the aim of the current study. The intention to include the literature is to have the knowledge about studies that has assessed surface water – groundwater interaction using multi methodological approach. Literature suggests that when assessing groundwater-surface water interaction, it is pertinent to use a multi-methodological approach.

2.3.1 Previous Studies

As the knowledge pool of groundwater and surface water is increasing the significance of the interaction between the two resources are recognised as being connected. This recognition allowed the development of different methods to assess the interaction between ground water and surface water. The methods however are still in the developmental stage, selecting the most suitable one can be challenging according to Anna (2006).

Previous WRC-funded projects (Parsons, 2004; Hughes, et. al., 2007; Tanner and Hughes, 2005)) have established that the inclusion of SW-GW interactions in models used for water resources assessments is problematic, due to limited information about spatio-temporal variations in these interactions. There is thus a need to improve an understanding of, and the capacity to predict spatial and temporal variations in SW-GW interactions, and their influence on available water resources at the catchment scale. Inter annual and seasonal variations of rainfall are known to affect SW-GW interactions. However, there is a low predictive capacity of how these variations influence these interactions. It may be that these interactions reduce adverse effects of inter-annual and seasonal variability.

There are various different approaches used in order to quantify and/or characterize groundwater - surface water interaction. Commonly these approaches follows four principle approaches i.e. hydrometric measurements, direct measurements of seepage, the use of tracer approaches, and direct measurements of stream flow (Madlala et al., 2019).

Many studies were done using different techniques that include:

- Hydrogeological mapping (Chu et al., 2017);
- Hydrograph analysis (Donelan, 2018 and Killian et al., 2019);

- Temperature studies (Irvine et al., 2015, Yao et al., 2015 and Tirado-Conde et al., 2019)
- Seepage measurements (Tirado-Conde et al., 2019);
- Salinity surveys (Pai et al., 2015); and
- Field observations and water budgeting (Brannen et al., 2015) which are an addition to those that were mentioned above earlier in this chapter.

Many scientists have their own importance of why they study the interactions of the two water bodies (Kalbus et al., 2006). Here are some examples to show how different techniques was used to study surface water – groundwater interaction:

- Langhoff et al. (2006) considered stream– aquifer interactions from a hydrological, geophysical and geomorphological point of view;
- Nemeth and Solo-Gabriele (2003) evaluated a method to quantify water exchange based on the reach transmissivity concept;
- Keery et al. (2007) explored a method of utilizing temperature time series to calculate vertical water fluxes across riverbed sediments;
- Oxtobee and Novakowski (2002) analysed groundwater–surface water interactions by considering mainly electrical conductivity, temperature surveys, isotopic analysis and mixing calculations, together with hydraulic head and discharge measurements;
- Criss and Davisson (1996), Ne´grel et al. (2003), and Soulsby et al., (2007) analysed these interactions from a hydrochemical and/or isotopic point of view;
- Chekirbane et al., (2016) analysed groundwater – surface water interaction using combination of Multivariate Statistical Analysis and Geophysical Method. The interaction between these water bodies can be studied from different angles. However it can contribute to the same objective which is to sustainably manage the water resources for future use;
- Brodie, et al., (2007) categorised the various types of methods into 12 categories based on the type of method. These methods are classified into 1) seepage measurements, 2) field observations, 3) ecological indicators, 4) hydrogeological mapping, 5) geophysics and remote sensing, 6) hydrographic analysis, 7) hydrometric analysis, 8) hydro chemical and environmental tracer analysis, 9) artificial tracers, 10) temperature studies, 11) water budgets and 12) hydrogeological modelling. Overall these approaches categorized by Brodie, et al., (2007) involves the quantification of the water balance, estimation of differences in water level or the identification of interaction areas

grounded on the variances in aquatic biota, temperatures, isotopic or physico-chemical constituents; and

- Banks (2011) provides a description of the different approaches used to characterise groundwater - surface water interaction.

a. The role of geochemistry in understanding groundwater – surface water interactions.

According to Brodie *et al.* (2007), hydrochemistry can be used to provide important information on catchment-scale connectivity as well as on targeted areas for detailed investigation. The chemical composition of groundwater is mainly influenced by its origin and the rock type hosting the water, as well as hydrogeological characteristics of the area under study (Appelo and Postma, 2005). Usually, higher concentrations of dissolved constituents are expected in groundwater than in surface water since groundwater is exposed to soluble materials in the rocks in which it is situated. This is mostly applicable when the surface water body is not contaminated. However, it is that difference between the groundwater and surface water characteristics or concentrations that is used as an indicator of groundwater discharge or recharge, especially at a local scale and provided that the differences are sufficiently large (Kalbus *et al.* 2006). Some chemical constituents or isotopic properties of water can therefore be used to assess interactions between groundwater and surface water (Levy and Xu, 2012).

Surface water bodies (rivers, wetlands and lakes or vleis) are hydraulically connected to groundwater in most types of landscapes. As a result, in these cases the surface waters are essential parts of groundwater flow systems. Even if a surface water body is separated from the groundwater system by an unsaturated zone, seepage from the surface may recharge groundwater. Because of the interchange of water between these two components of the hydrologic system, exploitation or contamination of one commonly affects the other (Winter and Dlugosz 2000).

The movement of surface and groundwater is controlled to a large extent by the physiography (land-surface form and geology) of an area. In addition, climate, through the effects of precipitation and evapotranspiration, affects the distribution of water to and from a landscape (Winter and Dlugosz 2000).

An array of methods are used for assessing the interactions between groundwater and surface water. These methods include seepage measurements, field observations, hydrochemistry, ecological indicators, hydrographic analysis, environmental and artificial tracers, and hydrometric analysis. Each method has its own advantages and limitations, mostly depending on the purpose of the study.

One tool that has been increasingly used to improve investigations of groundwater/surface-water interactions has been the analysis of stable isotopes of oxygen and hydrogen. The ratio of deuterium to ^{18}O has great potential for delineating groundwater discharge areas and even for quantification of groundwater discharge in any kind of geologic setting, including fractured bedrock aquifers. Deuterium and ^{18}O have been used to locate and confirm groundwater discharge locations, quantify groundwater discharge to surface water, and confirm the recharge of groundwater systems from surface-water impoundments (Levy and Xu 2012).

As seen in previous studies, Banda (2019) conceptualizes and explains the role of hydrogeological characteristics in rivers, using the Heuningnes catchment.This was done answering three objectives to determine the aquifer characteristics, to characterise the aquifer-river interaction and to conceptualize the groundwater flow system, similarly to Manyama (2017). This study done by Banda (2019) reasons that comprehensive characterization of aquifers is crucial in order to adequately establish the degree of groundwater- surface water interaction and how groundwater influences the flow and water quality of the rivers.

Banda (2019) concluded that on a catchment scale, highland areas have high groundwater recharge rates and the lowlands areas are discharge zone. The groundwater recharge was established to be mainly due to rainwater infiltration with no evidence of river seepage. It was also concluded that the Heuningnes Catchment has a shallow water table which is less than 10 m, both in highland and lowlands areas thereby encouraging a rather quick discharge to the rivers.

Additionally a water quality study done by Malijani (2020) aimed at characterizing the water chemistry of rivers and associated aquifers in the Nuwejaars Catchment by providing information about the quality of water and factors that influence the chemistry of water resources in river systems in order to assist with management of the river running through this catchment . The objectives of this study was to firstly, assess a number of physico-chemical variables of groundwater and surface water to establish temporal and spatial variations in water quality, secondly to identify hydrogeochemical processes that influence groundwater chemistry and lastly to use isotope signatures to establish interactions between groundwater and surface water in the Heuningnes catchment.

The studies done by Banda (2019) and Malijani (2020) plays a significant role in the information yield for this catchment. However, it is evident that the studies had limitation, which included short data sets, different study sites and different objectives to the current study. Additionally, Malijani (2020) did not put emphasis on the groundwater component.

2.4 Characterisation of groundwater – surface water interactions

2.4.1 Methods for characterisation

There are many different approaches that can be applied to assess aquifer hydrogeological properties. These methods include aquifer characterisation, numerical and analytical simulations, and application of tracers and isotope hydrology. Most studies as discussed in previous sections use a multidisciplinary approach. However, it is suggested by many authors that reviewed this topic, that the integration of hydrogeological and hydrogeophysical is best suited as it allows for more insight about the groundwater systems compared to other individual approaches.

Speculation have been made that limitations and uncertainties of various methods and the measurement scale effects should be taken into considerations when selecting suitable methods and materials (Kalbus et al., 2006). The multi-scale approaches, whereby different techniques are combined can significantly reduce uncertainties. It is recommended in studies regarding groundwater and surface water interactions.

According to Manyama (2017) the characterisation of aquifers is crucial for proper sustainable management of the groundwater resource. This provides a hydrogeological framework to develop knowledge and understanding about aquifer hydrogeology and properties using different methods.

2.4.2 Physical methods

In order to understanding the nature of groundwater resource, knowledge of the hydrogeological setting is essential. 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. The physical properties of interest include among others geological units, groundwater zones, stratigraphy, rock type, dykes, faults and fractures. The hydraulic properties include hydraulic conductivity, borehole parameters and borehole yields. These properties of the aquifer help in explaining the occurrence, movement and discharge of groundwater in the nearby rivers or streams. 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. While Leketa (2011) used pumping tests (both step and constant discharge method for determining borehole performance and aquifer transmissivity) and slug tests for determining aquifer parameters of an unconfined aquifer. Though methods have their benefits and limitations in terms of spatial representation, data quality and quantity, cost of application and technicality, use of standard methods in aquifer characterization is essential as these methods are widely used as an acceptable practice and standard.

2.4.2.1 Geophysical Methods

The objective of geophysics is to attain information about geophysical properties of the subsurface to deduce information about the geological, hydrological and biogeochemical properties (McLachlan *et al.,* 2017 and Binley et al., 2015). There are various types of geophysical methods that exist. These methods are used for different rock types and water characteristics. On many occasions various geophysical methods are coupled together when doing a study.

According to Freeze and Cherry (1979) geophysical methods cannot replace test drilling, but can give more in depth information about selection of the test-hole drilling which may lead to the lessening in the amount of drilling required. Thus, the data collected from the surveys being done will be used in order to characterise the subsurface of the sites/ catchment as a whole and to assist with deciding on where to drill boreholes.

Geophysical tools have a clear purpose to reveal geological, hydrological and biogeochemical heterogeneity at the groundwater – surface water interface. In addition, geophysical tools are complementary to traditional tools used to characterise subsurface. The majority of geophysical applications have focused on characterising subsurface structures, revealing spatial variability in groundwater- surface water interactions and imaging hydrological processes (McLachlan et al., 2017)

The Geophysical techniques considered in this study include Electrical resistivity and Gravitational Survey which is discussed in detail below.

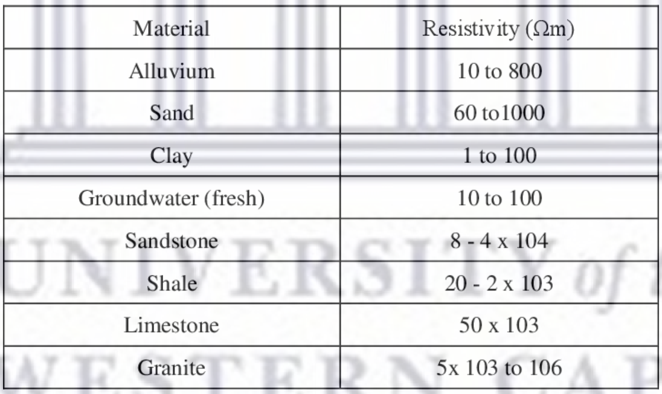
Electrical Resistivity survey is used to determine subsurface geological structures, aquifer properties and contamination plumes, as well as buried underground tanks, pipes and landfill boundaries (Lasher, 2011). Additionally, it is used to map the variation in hydrogeological parameters, such as vertical and lateral extent of aquifers and groundwater salinity. Furthermore, electrical resistivity method can be used in a wide range of geophysical investigations, such as exploration for minerals, engineering investigation, geothermal studies, archaeological surveys and geological mapping (Anomohanran, 2015). This method has been used widely in Nigeria and in other parts of the world to study the subsurface. According to Anomohanran (2015) this method was used it to estimate the aquifer properties of Sagar Island Region in India, where they observed that the results correlated significantly with borehole data from the area.

To perform this method, low frequency (<1 kHz) electrical currents are injected into the ground with two current electrodes and measuring the resultant of the voltage between two or more potential electrodes (McLachlan et al., 2017). This method is subtle as it commonly consist of placing stainless steel “rods” which are the electrodes a few centimetres into the subsurface (McLachlan et al., 2017), however in some cases boreholes electrical resistivity method is used for further characterisation (Slater et al., 1997; Coscia et al., 2011, 2012). The electrical resistivity of geological materials is mainly dependent on variations in water content, composition of rock and dissolved ions found in the groundwater. Therefore, resistivity investigations are used to detect zones with different electrical properties. These variations in resistivity within the rock will reflect variations in the geo-electrical properties. Surface geophysics generates information on both a regional and a site specific scale.

This method was done following the Schlumberger sounding protocol which was first applied by Conrad Schlumberger in 1912. It has been used widely and successfully over decades for detection and delineation of geothermal systems, location of aquifers, etc. The basic principle of the Schlumberger sounding method is to inject a current into the ground through current electrodes at the surface. This current creates a potential field in the ground. The subsurface resistivity can be inferred by measuring the resulting potential difference (Hung, 1997).

Assumptions have been drawn that restrictions and uncertainties of different methods and the measurement scale effects should be taken into considerations when decide on appropriate methods and materials (Kalbus et al., 2006). Therefore, the multi-scale approaches merging different techniques that can considerably reduce uncertainties is vastly suggested in studies on surface water-groundwater interactions (Zhao et al., 2018; Manyama, 2017, Anomohanran, 2015; Madlala et al., 2019, Banks et al., 2011). According to Anomohanran (2015) this method was used it to estimate the aquifer properties of Sagar Island Region in India, where they observed that the results correlated significantly with borehole data from the area. McLachlan et al., (2017), used Geophysics alongside hydrological and biogeochemical methods to provide additional information about the subsurface and groundwater- surface water interaction. Conclusions can be made using Table 1 adopted from Adeeko & Nordiana (2018) which provides common rocks and soil materials and different Resistivity value used as indicators. This information along with borehole downhole logs can confirm the sediments collected in the field used to create the logs.

Table 1 : Resistivity values of common rocks and soil materials in survey area. (Adeeko, & Nordiana, 2018)



Material	Resistivity (Ωm)
Alluvium	10 to 800
Sand	60 to1000
Clay	1 to 100
Groundwater (fresh)	10 to 100
Sandstone	8 - 4 x 104
Shale	20 - 2 x 103
Limestone	50 x 103
Granite	5x 103 to 106

Gravity Survey provide measurements of variations in the earth's gravity at different locations in a region (Fairhead, 2020 and Downey, 2014). It is an indirect method used to calculate the density properties of the subsurface. The higher the values are of gravity the denser the rock is of the subsurface. It is key to understand that the gravity field on the surface of the Earth is not uniform. The gravity field varies with the distribution of the mass materials underground. According to Fairhead (2020) and Halder (2018) gravity surveys are used either alone or in combination with magnetotelluric, magnetic, and induced polarization and electrical resistivity surveys to determine the location and size of the major source structures which may contain accumulations of hydrocarbons, massive base metal deposits, iron ore, salt domes, and hydrogeological aquifers. Combining gravity surveys with another type of geophyisical method improves the resolution the data (Fairhead, 2020)

Previous studies pointed out by Halder (2018) expressed the value gravity surveys has brought to science. Using this type of geophysics multimetal sulfide orebodies was discovered and exploration drilling was renewed due to convincing Bouguer anomalies calculated using the data collected. Many more orebody discoveries were made in South Africa, India, and Russia using the gravimetric surveys (Halder, 2018). Whilst many of these discoveries was based on surface geophysics, borehole geophysics is another technique used to provide a high-resolution measurement of the acceleration due to gravity – along the well path in boreholes (Kennedy, 2015). Borehole gravity surveys have two main applications: To relate the surface gravity survey to the vertical variations of acceleration due to gravity and to provide a deep-reading density log of the boreholes (Kennedy, 2015). Whether the gravity survey is conducted at the surface or along a borehole, it both involves measuring acceleration due to gravity at different points.

Overall studies prove that gravity surveys non-invasive remote sensing method, which is a cost effective, and yield good resolution data to understand spatial variations of the subsurface (Fairhead, 2020, Halder, 2018, Kennedy, 2015 and Fairhead, 2012)

2.4.2.2 Drilling and Sampling of rock materials

Borehole drilling is one of the most traditional methods and most used method in hydrogeological studies for determining aquifer characteristics. This method helps establish subsurface material and physical properties of the aquifer (Freeze and Cherry 1979, Price 2013). However, this method is expensive and does not provide effective characterisation when used without other methods. Another disadvantage of this method is that it does not provide spatial differences of the subsurface materials and this method is based on point measurements.

Despite limitation, borehole drilling is the most common method used and is useful method for establishing aquifer parameters. This method is also useful as it provides lithology logs as the drilling progresses. Usually for every 1 meter during drilling samples of the aquifer materials are taken to establish properties such as rock type, fracturing, faulting, texture, composition and weathering. Borehole drilling method involves making a hole in the ground vertically using different drilling methods depending on the geology in the area being drilled.

2.4.2.3 Hydraulic Methods

Hydraulic tests are methods commonly used for determining hydraulic properties. These include pumping tests and recovery tests, slug/infiltration test, bailer test (Freeze and Cherry, 1979). Both slug and bailer tests offer point measurement or less spatial coverage of hydraulic properties of the aquifer and thus fail to account for both heterogeneity and anisotropy.

Aquifer hydraulic test forms one of the most common large-scale field activities carried out by ground water specialist (Brassington, 1998). Aquifer hydraulic tests can provide reliable data which, if interpreted in the context of the geological and hydrogeological setting, can give insight to borehole yields, aquifer properties and groundwater flows. For these reasons pumping test are often an important part of hydrogeological field investigations.

Aquifer hydraulic tests form part of aquifer characterisation by providing quantitative data on aquifer hydraulic parameters, such as transmissivity of the water bearing formation. Aquifer hydraulic tests involves pumping the aquifer at a known rate (pumping test) or through rapid introduction or removal of water from the well (slug tests). In all the tests, the corresponding changes in the water level is monitored and results are interpreted (Vincent, 2019).

2.4.3 Chemical Methods

The chemical characteristics of a natural surface water body or of a groundwater flow system can record information about the source of chemical constituents in the water body and about the interactions of the water body with other parts of the hydrological cycle (Guo et al., 2019).

A suitable method of analysing groundwater - surface water interaction is through an extensive hydro chemical study. Especially when investigating the degree of fractionation of stable isotopes of deuterium and oxygen in the water existent in these systems. This type of isotopic analysis is an effective way to study the degree of interaction between precipitation, evapotranspiration surface water and groundwater (Guo et al., 2019; Zhang et al., 2016 and Zhang et al., 2006). Additional, when using isotopic analysis, it can assist with investigation of mixing of waters from different sources, the effects of specific hydrologic processes and to determine water movement (Guo et al., 2019 and Zhang et al., 2016).

Surface water and groundwater interactions can be investigated using different methods which would generally be subject to the type and scale of study catchments. It is found that environmental tracers such as the stable isotopes of water, radioisotope ^{222}Rn, and water chemical constituents, have been applied to many hydro geochemical and hydrogeological problems particularly studies regarding groundwater – surface water interactions (Xu et al., 2017). Guo et al., 2019 used Kuye River located in China as a case study, to investigate groundwater-surface water interactions using hydro chemical and isotopic techniques. This river, just like the current study is located in an arid to semi-arid climate with vulnerable ecological environment. In this study descriptive statistical method, stable isotope measurements and Piper trilinear diagram were utilised to analyse the interaction between the groundwater and surface water. Similarly, a study done by Du et al., (2019), environmental isotopic signatures such as ^{18}O and ^{222}Rn in surface water and groundwater to understand groundwater-surface water interaction.

In this current study, environmental tracers are one of the techniques used to understand groundwater –surface water interaction. Interpretation of the chemical constituents of rain, runoff and groundwater provide understanding into surface water – groundwater connectivity. Dissolved constituents are used as environmental tracers to track the movement of water. Some of the universally used environmental tracers comprise of field parameters such as electrical conductivity or pH; major anions and cations such as calcium, magnesium, sodium, chloride and bicarbonate; stable isotopes in the water molecule of oxygen-18 (^{18}O) and deuterium (2H). According to Laar (2018) hydrogeochemical assessments improves understanding of possible causes or changes in the water chemistry (Glynn and Plumber 2005 in Laar, 2018). As water moves from the surface of the groundwater into the ground, it reacts with various components of the rock materials. Hence, the use of hydrogeochemical analysis requires assessment of the physicochemical parameters of the water in relation to the surrounding geology and land uses activities in the catchment

2.4.3.1 Stable Isotope Techniques

Understanding the interaction between groundwater and surface water is of utmost importance for the sustainably managing water resources in arid and semi-arid areas (Zhao *et al* ., 2018). Various methods and techniques have been developed, generally focusing on areas such as sources identification, hydrologic dynamics of interchanges, and exchange characteristics of water quality and quantity (Stellato et al., 2008, Xu et al., 2017, Liao et al., 2018). These studies made worthy contributions to promoting advances in current studies. The most frequently used approaches include the environmental isotopic tracers (hydrogen and oxygen, chemical components).

It is seen quite often in literature that surface water groundwater interaction is being investigated by using stable isotopes along with other hydrochemical tracers. In a study done by Zhao et al., (2018) surface water – groundwater interaction was investigated by using hydrochemical and isotopic tracers such as ^{222}Rn, deuterium, oxygen-18; another study done by Li et al., (2017) about surface water –groundwater interaction at catchment scale was studied by using electrical conductivity, chloride concentrations, and stable water isotope data (δD and δ18O).

According to literature, stable isotopes of water provide an important environmental tracer for understanding vadose zone hydrology, groundwater recharge, mixing processes, stream flow generation, subsurface storage, and catchment yield (Thomas et al., 2013). Additionally, stable isotopes can provide information of both water movement patterns and geochemical processes (Guo et al., 2019; Zhang et al., 2016) and Younger, 2007). The main stable isotopes used to infer physical processes affecting groundwater flow patterns are oxygen 18 and deuterium as both these isotopes are found in the water molecule (Younger, 2007), thus it is used in this study as this study aims to understand the water movement / flow patterns from surface water and groundwater (Guo et al., 2019 and Zhang et al., 2016).

Chapter 3 Study Area

3.1 Introduction

The current chapter provides a description of the study area where the study is conducted. The physiographic characteristics at regional and local scales of the study area is described. Furthermore, this chapter is centred on describing features such as climate, structural geology, geology, hydrogeological setting, soils, vegetation and land use. Overall all the features described in this chapter has an influence on the interaction between groundwater and surface water

3.2 Study area: Heuningnes catchment

The Heuningnes Catchment with an area of 1401 km2 and located in the Cape Agulhas in the Western Cape Province of South Africa, it covers five quaternary catchments; G50B, G50C, G50D, G50E and G50F. The Heuningnes has two major tributaries, which are namely the Karsriver and the Nuwejaars River.

The Nuwejaars River flows through Zoetendalsvlei. In the lower reaches of Nuwejaars River, the topography is very flat and low-lying and with several pans and vleis which drains to this river. The vleis are Voevlei and Soutpan, the Nuwejaars River flows into Zoetendalsvlei, which is approximately 5 km long and 3 km wide at the middle.

This catchment starts in the Bredasdorp Mountains, along the northern border and continues through a low-lying coastal plain known as the Agulhas Plain. There are several temporary ponds and lakes with the largest being Soetendalsvlei Lake (approximately 3 km wide and 8 km long) and is one of the largest freshwater lakes in South Africa.

3.2.1 Climate

This region typically has a Mediterranean type of climate, with hot and dry summers and cool wet winters. The rainfall in this area is mainly cyclonic with some orographic rainfall occurring in the higher reaches of the Heuningnes catchment, and a mean annual runoff of about 37.6 x 106m3. Historical rainfall data indicates that the mean annual rainfall in this catchment is 452mm per annum with a coefficient of 24%. Majority of the rain falls in winter with levels ranging from 450 mm per annum and along the coast 650 mm per annum. Most of the rainfall received in this area is during the winter season, which occurs mid-May to late August. The maximum temperatures occur in January and the minimum temperatures take place in July and

August. The mean temperature is approximately 17°C, January is the hottest month whereas July is the coldest and wettest month.

3.2.2 Geology

The Nuwejaars catchment is largely dominated by the following main geological formations: The Cape Granite Suite, Malmesbury, Table Mountain, Bokkeveld and Bredasdorp Groups (Figure 3). Malmesbury and Cape Granite are basement rocks, which are overlaid by the Table Mountain and Bokkeveld Groups. The geology of the upper catchment of the Nuwejaars River is dominated by Malmesbury and the Peninsula Group, whereas the low lying areas of the catchment where the major lakes occur is underlain by Bredasdorp beds displayed on Figure 5.

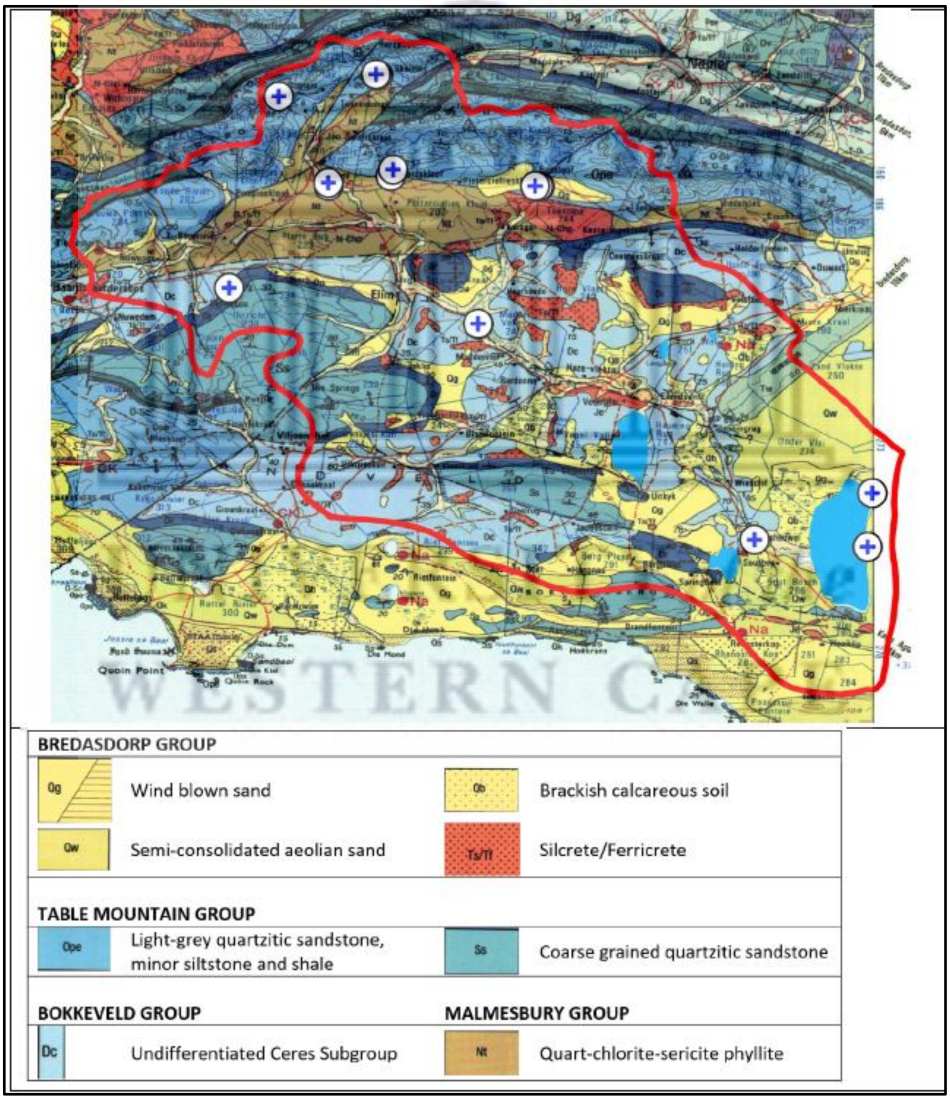


Figure 3: Geology of the Nuwejaars Catchment. White circles with blue crosses indicate locations of the monitoring boreholes. Source: 3319 Worcester 1:250, 000 Geological Series, Geological Survey of South Arica, Pretoria.

Within the catchment, there are outcrops of the intrusive Cape Granite Suite and Malmesbury Group that are present. 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.

3.2.3 Faulting in the geology

In the Heuningnes catchment, faulting is widespread, with fault lines running in a more or less east-west direction. There are also two major fault lines that run southeast to northwest. Faults are essential when doing groundwater studies as it can act as a groundwater boundary, which can assist or limit the movement of the groundwater in aquifer. The sites situated in the upper to midslopes of the catchment (Tussenberge, Sandfontein and Jan Swartskraal) is along faults (see Figure 4).

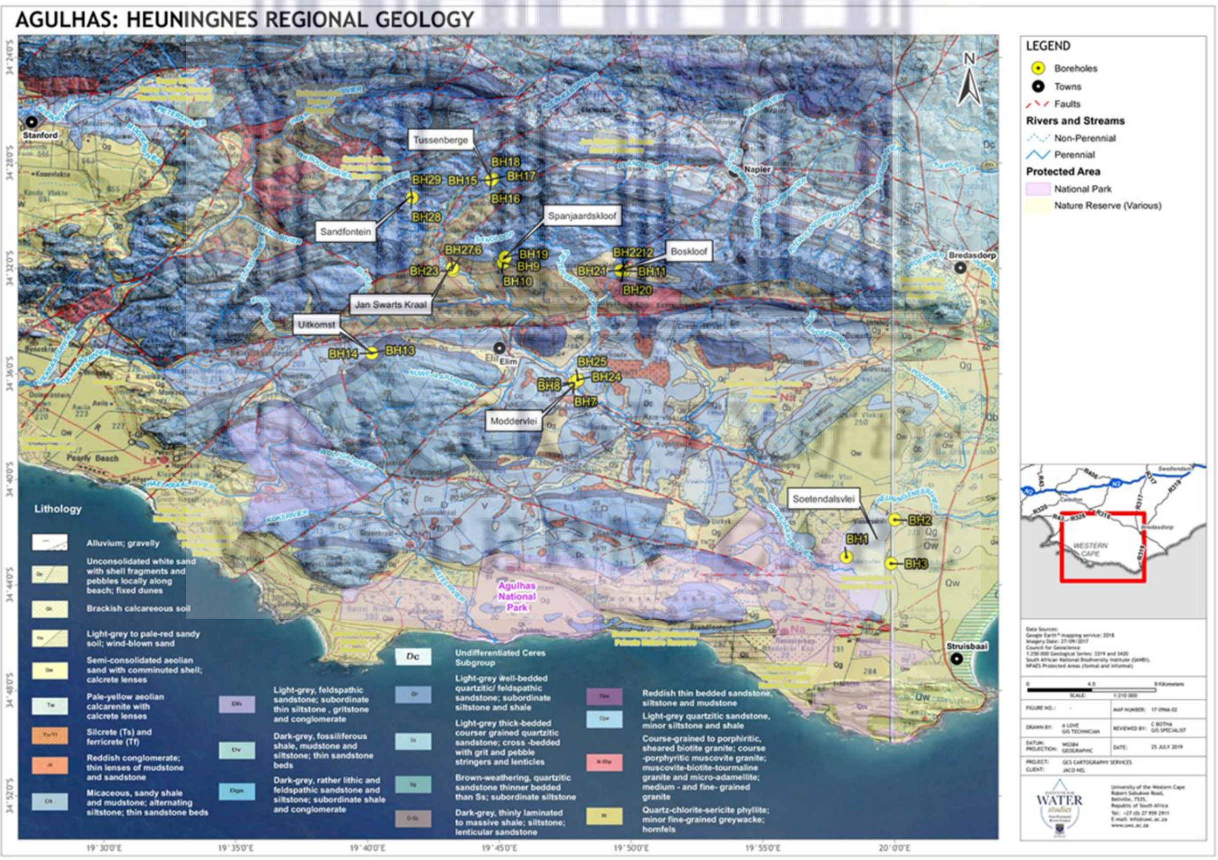


Figure 4: Positions of boreholes in Nuwejaars catchment relative to geology and geological structures (Faults)

2.3.4 Hydrogeological setting

The catchment has both primary and secondary aquifer. According to Price (2013) Primary aquifers are made up from unconsolidated sediments which has been deposited as alluvium in floodplains of major river systems. This type of aquifer usually occur in low rainfall areas and primarily recharged in the course of high flows and in flooding in wet period.

Alternatively, Secondary aquifers are most widespread and extensive (Manyama, 2017), which include the Table Mountain Group quartzite and the Bokkeveld Group shales. The water in this type of aquifer is stored in and flows through fractures and fault systems. The primary groundwater system within the Heuningnes Catchment is of the Table Mountain Group.

The Table Mountain Group aquifer is high yielding as a result of the faulting and fracturing, also the water quality is generally good, and of low Total Dissolved Salts (TDS). However, the Bokkeveld aquifers are low yielding as a result of it being representative of a lesser degree of faulting, and the water quality is generally poor, with high TDS, usually natural from the rock formation through which groundwater flows (Manyama, 2017). Aquifers of the Bokkeveld Group has groundwater of moderately to highly salinity levels and generally contains shale materials.

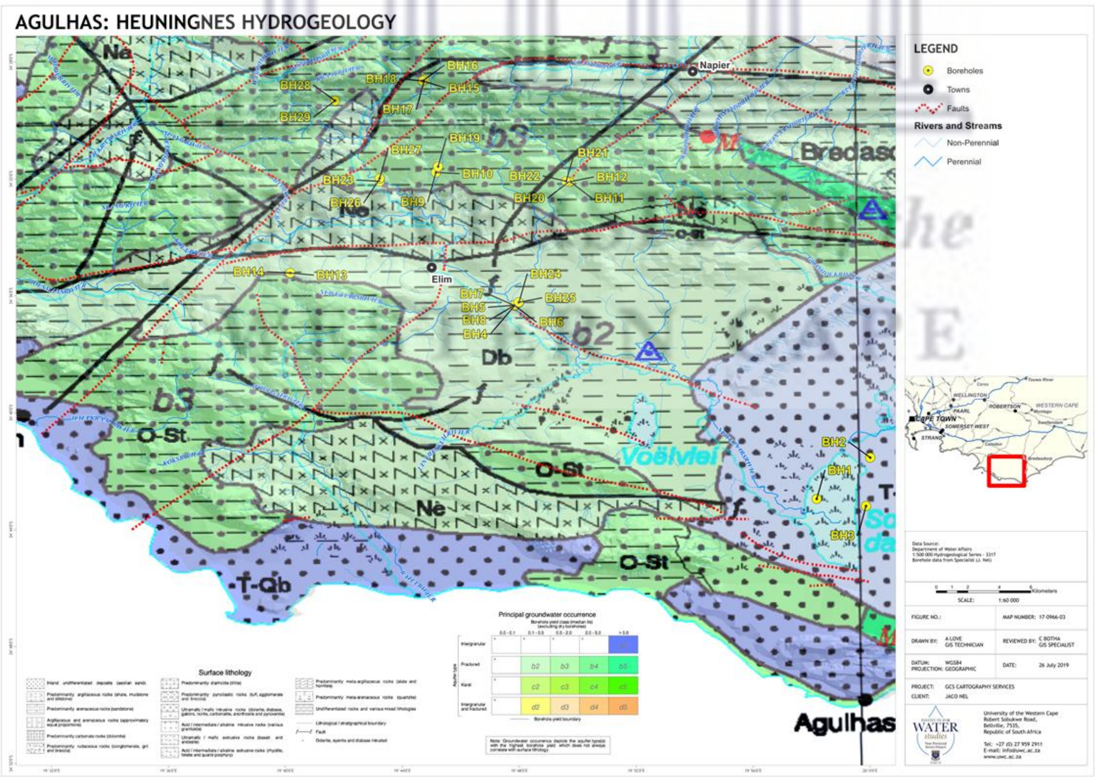


Figure 5: Hydrogeological map showing yield classes across the catchment.

3.2.5 Vegetation

The Cape Agulhas region has an array of indigenous vegetation types. There are more than 1 750 plant species that are present in this catchment (Nowell, 2011). According to Fourie et al., (2012) Mountain Fynbos, Proteoid Fynbos, Restioid Fynbos and Asteraceous Fynbos are the groups that these plant species are clustered into. Along with other factors, the on-going rapid dispersion of invasive alien plants in the area is considered a major threat to the both faunal and floral biodiversity as well as the surrounding water resources. Common alien veg species include black wottel and Acacias. Mkunyana (2018) stated that numerous species that grow in semi-arid to arid areas have shallow, spreading root systems that are used to scavenge water for plants. These plants grow rapidly where there is an abundance of water. Example Mkunyana (2017) found that riparian *A. longifolia* invasions transpired 596 mm/year, which was 146% more than the volume used by hillslope invasions (242 mm/year). In hydrology, the impacts of invasive vegetation include reductions of stream flows, lowering of groundwater levels (Mkunyana, 2018 and Dzikiti et al., 2013).

3.2.6 Landuse

The main land uses are rain fed production of wheat and barley, and livestock production. There are a few vineyards and pine plantations. Most of the Nuwejaars catchment consists of privately owned farm areas. According to land use mapping it shows that 36% of the area shows cultivated land and 10% of the land use mapping shows wetland that are present. Additionally, it was identified and categorised by Heydenrych (1999) that there are different types of farming taking place in the Cape Agulhas region namely livestock, mixed, fynbos and conservation farms and agricultural farming.

3.2.7 Monitoring network and available data

Initially in the living laboratory that has been set up by previous researchers, there were weather stations, boreholes, rain gauges, piezometers and level loggers installed already. For the present study, 15 additional boreholes were drilled at 6 different sites with the addition of 7 piezometers at 3 of the sites where the river is passing through.

3.2.8 Selection of study sites: Nuwejaars Catchment

Selecting the study sites involved several inspection visits and assessments of the sites in the catchment. This inspection resulted in sites along the river from headwater to lowlands, at these sites there will be defined as transects where certain objectives will be made in order to yield necessary results. The selection criteria of these sites included sites that are:

i. Available water resources , with flow
ii. Sites were spatially distributed throughout the catchment from highlands to lowlands
iii. Sites with different geological units
iv. There were supporting infrastructure such as weather statins nearby
v. Areas with invasive alien plants present for other components of the study to be met i.e. Tree evaporation
vi. Accessibility – permission had to be granted from the landowners to install and frequently visit the sites during/after the period of this project.
vii. Clear pathway/road- for easy access for big drilling trucks to enter and 4x4 vehicles
viii. Safe for equipment, to ensure no of vandalism or theft

Table 2: Study sites selected with description.

Location	Code	GPS co ordinates		Elevation (mamsl)	Borehole Depth (mbcl)	Screen length (m)	
		Longitude	Latitude				
Tussenberge	BH15	-34.477446	19.74491	205	50	24	Highland
	BH16	-34.477418	19.744954	212	12	6	Highland
	BH17	-34.47683	19.74601	212	30	6	Highland
Spanjaardskloof	BH9	-34.52958	19.75255	149	60	11.2	Highland
	BH10	-34.52961	19.75252	149	20	11.2	Highland
	BH19	-34.477418	19.744954	205	12	6	Highland
Boskloof	BH11	-34.53489	19.82909	135	60	14	Highland
	BH12	-34.53485	19.8291	134	20	11.2	Highland
	BH20	-34.534917	19.828389	125	100	18	Highland
	BH21						Highland
	BH22	-34.534661	19.826799	115	60	9	Highland
	BH23	-34.534655	19.826733	115	20	6	Highland
Moddervlei	BH4	-34.60535	19.79761	21	50	11.2	Lowlands
	BH5	-34.60535	19.79758	21	20	11.2	Lowlands
	BH6	-34.60561	19.79758	21	50	8.4	Lowlands
	BH7	-34.60561	19.79753	21	20	11.2	Lowlands
	BH8	-34.60531	19.79741	21	8	5.6	Lowlands

	BH24	-34.603750	19.799861	19	60	60	Lowlands
	BH25	-34.603705	19.799722	21	7	7	Lowlands
Sandfontein	BH26	-34.488722	19.695000	231	50	9	Highland
	BH27	-34.488722	19.694972	231	11	6	Highland
JanSwartskraal	BH28	-34.533078	19.720556	150	50	15	Lowlands
	BH29	-34.53302	19.72043	150	7	3	Lowlands

3.2.9 Borehole information

There is a potential for the existence of shallow and deep groundwater at the selected sites. Shallow groundwater is likely to be affected by local recharge processes, while deep groundwater may be influenced by regional flow systems including fractures. At each of the selected sites (Figure 3, 4 and 5), a minimum of two monitoring boreholes tapping into shallow and deep groundwater have to be established (Figure 6). The borehole nests at each site have to be oriented in an upslope to downslope direction to enable monitoring of effects of possible downslope groundwater flow. Table 3 provides the details of the monitoring boreholes existing and new ones to be developed at each of the sites to form the borehole nests

Table 3: Number of existing and new monitoring boreholes to be developed at the selected sites.

Location	Number of Existing boreholes	Number of new boreholes
Tussenberg	None	3
Sandsfontein	None	2
Jan Swartskraal	None	2
Spanjaardskloof	2	2
Boskloof	2	4
Moddervlei	5	2

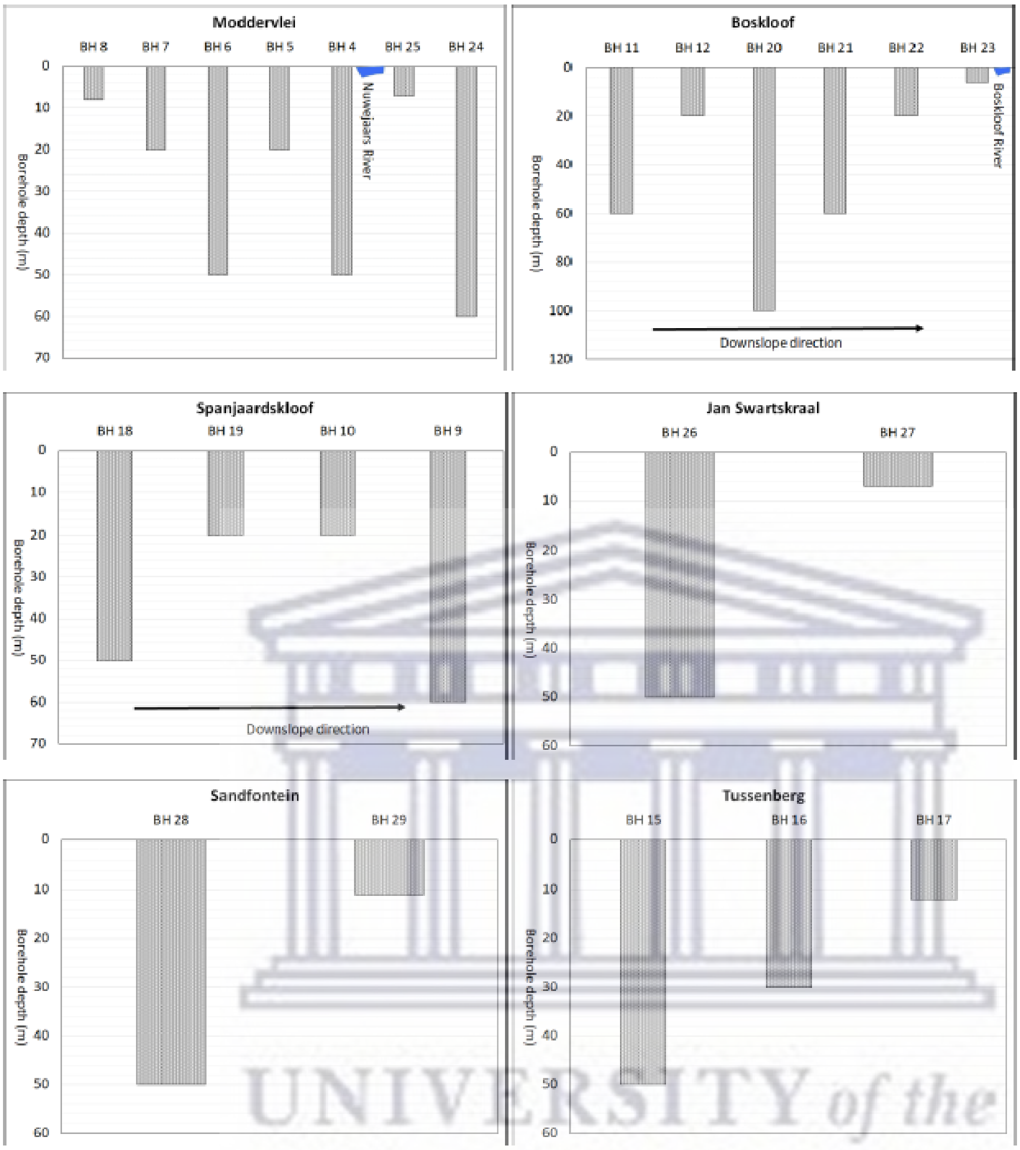


Figure 6: Nests of Boreholes established in the Nuwejaars catchment. The horizontal axis is not to scale and does not reflect the distance and exact configuration of boreholes on the ground.

Chapter 4 Materials and Methods

4.1 Introduction

This chapter presents and discusses the materials and methods, which was used to achieve the current study. The present study followed a combination sampling design approaches which includes deliberate and random sampling design.

Firstly, a site scouting visit was done in early 2018. The main purpose of the field scouting visit was to get to know the area and to identify possible study sites. Thereafter middle of 2018 a second field scouting visit followed, the objective of this trip was merely to do site selection for the present study and the bigger project for which this study feeds into.

Before going out to the field, possible monitoring sites were selected on Google Earth mainly on the basis of having a good spread of sites in the catchment but also taking into consideration how accessible the sites are. From the possible monitoring sites that were selected before going on the field trip some of the sites were removed and new sites was added, the sites that were removed were mainly because it was not going to yield sufficient information for the present study or permission of farm owners were not granted.

The sites that were selected, was selected for various purposes. All the sites were easily accessible, a few of the sites were good for geophysics and borehole drilling, other sites where selected mainly to put up weather station and isotope samplers, and some of the sites had good flowing water to take stream flow measurements from (see sub-sub section 3.2.8 – Table 2).

Once sites were finalized, the geophysical surveys were performed at the specific sites where borehole drilling took place exactly a month after. The geophysics was done approximately 1km at each site using gravitational transects and electrical resistivity surveys, however distances vary due to accessibility, as some sites were surrounded by dense vegetation. See chapter 5 for discussion of geophysical cross sections of each site.

The sampling methods used in this study is classified into 2 groups namely: Physical and chemical methods. For the purpose of this study physical methods refers to geophysics, borehole lithology logs, borehole EC and temperature profile logs, water levels, hydraulic tests and collections of weather and river flow data. While the chemical methods refers to the collection of water samples from groundwater, surface water and rainfall for major ion and environmental stable isotope analysis.

4.2 Physical Methods

4.2.1 Geophysical Methods

Two types of geophysical surveys were done namely Electrical Resistivity; and Gravity. **Electrical Resistivity** data was collected at each site using 10 m peg spacing technique which followed the Schlumberger protocol (explained in depth Chapter 2, sub-sub section 2.4.2.1). **Gravity** was done every +-25m along the profile lines. Both Geophysical Surveys took place on the same lines at all the sites however every line differed in length from site to site as some sites were not accessible or was too saturated to use equipment at.

The geophysical survey was done at each study site, electrical resistivity and gravity survey yielded information necessary to map variation in hydrogeological parameters such as the vertical and lateral extent of aquifers, groundwater salinity, it also provided information to identify geological features that control seepage flux and thereafter borehole pumping test.

These surveys are well known to be used as a method of understanding what the subsurface looks like, the results were used to establish good BH sites and to situate faults in the system.

The results that one gets look like typical excel spreadsheets, those results gets analysed using specific anomalies and then presented as cross-sections to better understand the subsurface. Borehole drilling followed geophysical surveys. At each site the aim was to drill a pair of boreholes (shallow and deep), some of the sites had existing boreholes others were completely new sites see table below (Table 4)

Table 4: Number of existing and new monitoring boreholes developed at the selected sites.

Location	Number of Existing boreholes	Number of new boreholes
Tussenberg	None	3
Sandsfontein	None	2
Jan Swartskraal	None	2
Spanjaardskloof	2	2
Boskloof	2	4
Moddervlei	5	2
Total	**9**	**15**

4.2.2 Borehole lithology logs

Due to the poor distribution of groundwater monitoring points, new boreholes were drilled at four (4) of the six (6) sites within the study area, Tussenberge, Boskloof and Sandfontein site located highland of the catchments and Jan Swartskraal located lowlands.

A total of fifteen (15) boreholes were drilled within the Nuwejaars catchment from October to November 2018. The 15 new boreholes comprised of only monitoring boreholes no production boreholes, which were 7 shallow (1 – 20 m) and 8 deep (30 – 100 m) boreholes. These borehole location was determined by assessing geophysical surveys that was done prior to the drilling period.

Once the location of the boreholes was selected. Borehole drilling period then started where the boreholes was drilled using the Air percussion method and all geological logs were captured and are presented in Chapter 5 respective to each site.

These 15 boreholes are used with an addition of nine (9) existing boreholes in the catchment, which were previously drilled in May 2017.

Lithological logs are used to delineate the subsurface layer and for identifying aquifers. This can assist with determining the depth and thickness of aquifer unit in the different geological units.

Table 5: Description of boreholes and when boreholes were drilled.

Code	Longitude	Latitude	Elevation (mamsl)	Borehole Depth (mbcl)		Year when drilled
BH15	-34.477446	19.74491	205	50	Highland	2018
BH17	-34.477418	19.744954	212	12	Highland	2018
BH16	-34.47683	19.74601	212	30	Highland	2018
BH9	-34.52958	19.75255	149	60	Highland	2017
BH10	-34.52961	19.75252	149	20	Highland	2017
BH19	-34.477418	19.744954	205	12	Highland	2018
BH11	-34.53489	19.82909	135	60	Highland	2017
BH12	-34.53485	19.8291	134	20	Highland	2017
BH20	-34.534917	19.828389	125	100	Highland	2018
BH21					Highland	2018
BH22	-34.534661	19.826799	115	60	Highland	2018
BH23	-34.534655	19.826733	115	20	Highland	2018
BH4	-34.60535	19.79761	21	50	Lowlands	2017
BH5	-34.60535	19.79758	21	20	Lowlands	2017
BH6	-34.60561	19.79758	21	50	Lowlands	2017
BH7	-34.60561	19.79753	21	20	Lowlands	2017

BH8	-34.60531	19.79741	21	8	Lowlands	2017
BH24	-34.603750	19.799861	19	60	Lowlands	2018
BH25	-34.603705	19.799722	21	7	Lowlands	2018
BH26	-34.488722	19.695000	231	50	Highland	2018
BH27	-34.488722	19.694972	231	11	Highland	2018
BH28	-34.533078	19.720556	150	50	Lowlands	2018
BH29	-34.53302	19.72043	150	7	Lowlands	2018

4.2.3 Borehole logging

This technique is also known as downhole-logging or well logging which provides in-situ information in addition to the direct geological information. Common borehole logging techniques are video, resistivity, natural gamma, electromagnetic induction, 3-arm caliper, spontaneous potential, borehole deviation, and temperature which can be deployed and interpreted quickly and cost effectively. Thus for the present study temperature technique was deployed using YSI multiprobe system at 3 sec intervals. This system collected data for parameters such as temperature pH and EC in relation to depth.

The borehole logging was done in all the Boreholes post and pre pump test and in wet and dry season for temporal comparison.

The general theory for temperature profiles suggest that the temperature profile will only deviate from the regional cooling trend to the surface due to water movement. This water movement can include fractures or recharge. Cooler temperatures on the regional scale would suggest better recharge areas, while vertical profiles would indicate areas where groundwater is moving.

The EC profile on the other hand can be influenced by changes in geology or flow conditions. But do not necessarily indicate flow. Measuring the EC before and after a pumping test supplies information regarding the origin of the water relative to the borehole profile.

The down the hole logs provide evidence of groundwater flow under natural conditions. These conditions change with the wet and dry cycles as seen in the graphs below.

4.2.3 Water level and elevation data

For the monitoring of groundwater and surface water levels, Solinist Level loggers (LTC/LT) was installed in the boreholes for monitoring of the water levels, temperatures and in some boreholes EC as well. These transducers were shortly installed after drilling of boreholes was completed. These transducers took a reading every 60 minutes (1 hour). At sites with no level loggers monthly water levels was taken, a procedure discussed by Weaver et al., (2007) was followed, where the sensor of dip meter was lowered down in each borehole until the buzzer went on notifying the researcher that it had reached the water. The measurements were then taken using the datum point which was marked by the top of borehole casing. This measurement was rechecked and recorded to improve the accuracy of the data collected. Existing data that was collected in 2017/2018 will be added to the present study, for a more comprehensive analysis.

Additionally, to the Level loggers an addition of a Barrologger has been installed in the catchment which collects atmospheric pressure data. The water level data with the data collected from Barrologger was used together with static water level to compensate data on Level logger 4.3.0, Wizard tool, to yield depth to water results, see Data in Results and sections of this study.

The exact elevations of monitoring boreholes and the river bed adjacent to nest of boreholes were surveyed using a Trimble R7 and R2 Global Navigation Satellite System (GNSS) receivers, and post processing kinematic survey method. A Trimble S3 total station for surveying features near/under vegetation was used since GNSS receivers are limited by these features. The precision of the survey was +/- 4 cm for the horizontal position, and +/- 8cm for the vertical position

4.2.4 Weather data

Weather data were collected from five automatic weather stations within the catchment (Figure 2.1). Three of these stations (Spanjaardskloof, Tiersfontein, Visserdrift) were established in December 2015, while Moddervlei was established in June 2016, and Tussenberge in May 2019. The altitude above sea level of these stations are as following;

- Vissersdrift 7 m,
- Moddervlei 25 m
- Spanjaardskloof 85 m
- Tiesfontein 200 m
- Tussenberg 230 m

All the weather stations store hourly data for air temperature, relative humidity, atmospheric pressure, solar radiation, wind speed and direction, and rainfall. Weather data were used to estimate catchment rainfall and evapotranspiration rates. The 2015 - 2020 annual actual evapotranspiration (ETa) estimates based on the MOD16A3GF (Running, et. al., 2019) downloaded from https://lpdaacsvc.cr.usgs.gov/appeears/ were used to provide an indication of the spatial variation of evapotranspiration throughout the Nuwejaars Catchmen

River water level data loggers were installed at 11 sites. These are equipped with either a HOBO U20L-01 water level logger which measures up to 9 m water depth with a +/- 0.1 cm accuracy, or Solinst loggers (Model 3001). River water level measuring stations on the Nuwejaars River at Elandsdrift, and Soetendalsvlei were established in May-June 2015, and May 2016 for the other stations. All the stations capture hourly river water level data.

4.2.5 Borehole pumping test

4.2.5.1 Estimation of Aquifer Parameters

A range of aquifers tests which are carried out to collected data for aquifer characterization exist. These include Slug tests, Bailer test, step down tests and constant rate pumping tests amongst other as discussed in Chapter 2. These tests work for the different purposes but the common purpose is that they all collect data used when estimating aquifer parameters. Slug tests are conducted in geological formations that display low hydraulic conductivity and these involves the rapid removal of a certain volume of water and observation of the subsequent changes in water levels as the equilibrium conditions return. Bailer test is the removal of water from the well using a bailer. Step down test is used to assess the performance of a particular well under different controlled discharge rate to establish the relationship between the well being pumped and other wells in proximity to the well being pumped. The test involves increasing the discharge rate from an initially low constant rate through a sequence of pumping intervals of gradually higher constant rates. The intervals are of equal duration (Kruseman and Ridder, 1991). Constant rate test involves the pumping of water out from the aquifer at a constant discharge rate and measuring the response from the neighbouring observation wells (Gxokwe, 2018).

For the current study a 3-hour step down, constant discharge rate hydraulic test and Slug test was used for the estimation of aquifer parameters at each study site. The boreholes were tested with a submersible pump (Pump specifications: KW-0.37; RPM-2850).

A Solinst-data logger was installed prior to the testing of the boreholes to monitor water levels hourly. This water level data logger was not only utilised to electronically record water level hourly but was also used to monitor the drawdown during the pumping test and recovery. Post pumping test data loggers that were already installed in the boreholes was reset to take readings every minute (60 seconds) during the aquifer test.

A step test was conducted on the boreholes to obtain an optimal pumping rate for the constant rate test. A Constant discharge test was completed during which each borehole was pumped at a constant rate (based on results from the Step test) and the drawdown in the pumping borehole was recorded for the duration of the test. Discharge measurements were taken at least once every hour to ensure that the constant discharge rate was maintained throughout the test period.

Manual measurements were also taken using an electrical contact water level meter. This was done in order to monitor water level drawdown, ensuring physical, comparable measurements to that of the pressure transducer data logger and to make sure that drawdown does not exceed the pump inlet. Also it is recommended by Kruseman and Ridder (1991).

The beginning of the step test discharge was estimated using the protocol described by Kruseman and Ridder (1991) as "Container', this method for measuring discharge rate is fairly accurate and simple follow through, this method requires you to measure the time it takes to fill a container of known capacity. This method is most appropriate for low discharge rates (Kruseman and Ridder, 1991).

On completion of the test, water level recovery was measured in the production borehole until approximately 80% recovery (relative to the initial water level) was reached. The recovery test provides an indication of the ability of a groundwater system to recover from the stress of abstraction.

The pumping test was interpreted and analysed using suitable analytical solutions in the Aqtesolve software to arrive at the following parameters: Transmissivity of the aquifer; and Recommended yield of the borehole. This will further be discussed in the data analysis section below.

The following **parameters** were measured prior or during these hydraulic testing:

Static water levels- measurement before pumping started in both the pumping well and observation well. This variable was used calculating drawdown during pumping and recovery for each hydraulic testing.

Well location, Depths and elevations- measured before pumping for both the pumping and observation well in each site.

Discharge rate- The variable was measured during the pumping period for both hydraulic tests. It was used when estimating Transmissivity for each hydraulic testing.

Depth to water level- This was measured at intervals during pumping and recovery for both hydraulic testing. The parameter was used when calculating the drawdown for pumping and recovery period in each hydraulic testing.

A pumping test can be conducted to determine hydraulic conductivity, and requires the existence of a pumping borehole and at least one observation borehole (piezometer) in the influence zone. The borehole is pumped at a constant rate and drawdown in the observation borehole/piezometer is measured as a function of time. The hydraulic properties of the subsurface are determined using one of several available methods, e.g. the methods of Theis (1935), Cooper and Jacob (1946) or special cases of these formulas. All the different interpretation methods have assumptions inherently part of the individual analytical equations that need to be considered.

Pumping tests that are conducted sufficiently long provide hydraulic conductivity values that are averaged over a large subsurface volume. Best practice seems to suggest that at least 2 hours of pumping data is required for hydraulic properties. Longer tests are required if boundaries to the system and sustainable yield is important. The results from pumping tests are more representative for the entire subsurface body than conductivities obtained by point measurements, e.g. Slug tests and infiltration tests. Pumping tests results are also less sensitive to heterogeneities in the subsurface material and preferential flow paths.

For this study the aquifer testing of the boreholes will provide an estimate of the aquifer characteristics of the zone around the screened intersection of the boreholes. These zones are not dewatered during the testing period, honouring the constant aquifer thickness Theis and Cooper Jacob Assumptions. The pumping tests were conducted for about 4 hours in most cases allowing for good sets of late time data representative of the matrix contribution to the borehole and the data not influenced from any preferential pathways or well storage effects.

Additionally, previous studies in the catchment included some hydraulic testing reported by Manyana (2017) and Banda (2019). Manyana (2017) and Banda (2019) conducted testing on 3 boreholes each. The data from previous studies will form part of the conclusion and conceptual understanding of the current study.

A total of seven (7) aquifer tests were conducted between April 2019 and May 2019 on the newly drilled monitoring boreholes. These tests consisted of a series of step drawdown, constant discharge rate (4 hours), recovery tests and slug tests.

A Solinst-data logger was installed March 2019 prior to the testing of the boreholes to monitor water levels hourly. This water level data logger was not only utilised to electronically record water level hourly but was also used to monitor the drawdown during the pumping test. Data loggers that were already installed in the boreholes was reset to take readings every minute (60 seconds) during the aquifer test. The first aquifer test on BH 26 (Jan Swartskraal, 50m depth) was conducted on the 23th of April 2019. The test on BH 29 (Sandfontein, 11m depth) was conducted on 26th of April 2019 and the aquifer test on BH 15 (Tussenberge, 50m depth) was conducted on 2 May 2019.

Additional to the pump test, slug tests were conducted in boreholes where the available water were less than 30cm in a borehole (i.e. a SWL of 6.77m and a borehole depth of 7m). A slug test on BH 27 (Jan Swartskraal, borehole 7m deep) was conducted 25th of April 2019, as well as on BH 19, BH 24 and a test on BH 25 was on the 2nd of May 2019.

Slug tests are based on introducing/removing a known volume of water (or a solid object) into/from a borehole (or piezometer), and as the water level recovers, the head is measured as a function of time. Slug tests are quick and easy to perform with inexpensive equipment. In contrast to pumping tests, only one borehole or piezometer is needed to perform a slug test. This method provides point measurements of hydraulic conductivity and is also appropriate for process studies or for investigating heterogeneities.

The Bouwer and Rice method indicates that the hydraulic conductivity of an aquifer near a well can be calculated from the rise of the water level in the well after a slug of water is suddenly added. The calculation is based on the Thiem equation, using an effective radius Re for the distance over which the head difference between the equilibrium water table in the aquifer and the water level in the well is dissipated. Values of Re were evaluated by electrical resistance network analogue. An empirical equation was then developed to relate Re to the geometry of the system. This equation is accurate to within 10-25%, depending on how much of the well below the water table is perforated or otherwise open. The technique is applicable to partially or completely penetrating wells in unconfined aquifers but also can be used in confined aquifers that receive water from the upper confining layer (Bouwer and Rice, 1976).Thus, slug tests were done on some of the boreholes where it was possible to conduct a pump-out test.

The aquifer characteristics were assessed by plotting aquifer test data on linear and log graphs and interpreting the data with the AqteSolve software. Basic principles were applied to log diagnostic plots to determine aquifer parameters.

4.3 Chemical Methods

The data obtained using passive and grab sampling techniques, which required continuously collection of water samples upon fieldwork excursions which ran from April 2019 to November 2019. With addition of existing sampling data from 2017 -2018.

With the help of Principal aquifer setting method, groundwater sampling points were identified for the assessment of groundwater – surface water interaction and surface water sampling points were randomly selected based on their closeness to the groundwater sampling points/Boreholes. A total of 23 groundwater points were identified and 3 surface water points were selected.

Overall, this chapter aims to highlight the methodology and literature associated with the acquisition, preparation, interpretation, and validation of the collected data. The research methodology being used to data to address research question is a Quantitative methodology. Quantitative methodology uses measurable data to formulate facts and uncover patterns in research.

4.3.1 Collection of Water samples

With the help of Principal aquifer setting method, groundwater sampling points were identified for the assessment of groundwater – surface water interaction and surface water sampling points were randomly selected based on their closeness to the groundwater sampling points/Boreholes. A total of 23 groundwater points were identified and 3 surface water points were selected along the Nuwejaars River. An additional 2 (one is upper catchment and one lowlands) rainfall samples were collected for isotope analysis.

The 23 groundwater and 3 surface water sample points were collected for three different analyses: major and minor ions, chemical and isotope signatures. These samples were collected post and pre- pumping test; and during wet and dry season. However, the rainfall samples were collected on a monthly basis. The isotopic data collected can be used to characterise groundwater recharge.

The data collected for the present study formed as a continuation of data collected in 2017/2018 which will also be used in this study.

Groundwater, river and rainfall samples were collected between the year 2017 and 2021. Samples for isotopic analysis were collected in 50 ml double capped HDPE plastic bottles, that limit evaporation. Samples were filled completely to the top, avoiding the generation of any bubbles, before sealing as per standard procedure. Samples for major ion analysis were stored in both 250 ml polypropylene and HDPE plastic bottles and filtered through a 0.45-μm Munktell and nylon syringes prior to analysis. Samples were properly labelled and kept cool in the field using a cooler box and stored in a refrigerator at a temperature of 4°C before they could be analysed.

4.3.2 Preparation of sample

The groundwater and surface water samples were obtained based on the hypothesis that the different chemical concentrations of the constituents will provide information that could be used to assess the quality of the groundwater and surface water in the study area as well as help with the main aim of this study to assess surface water groundwater interaction. The investigation of these constituents' similarity, variability and interactions between each other and the lithology is expected to give an insight to the quality of the groundwater and surface water. It could also be used with other data such as flow paths to answer the objectives of this study.

Parameters (such as pH, EC and Temperature) of groundwater and surface water were measured on site for the following reasons (Weaver et al., 2007):

- To check the efficiency of purging

- To obtain reliable values of those determinants that will change in the bottles during transport to the laboratory

- To obtain some values that may be needed to decide on the procedure or sampling sequence immediately during the sampling run

Hence, on site measurements of pH, EC (mS/m) and Temperature (°C) were taken for Groundwater and surface water samples. For groundwater sampling a pressurized bailer was used and dropped 1m into the screen. Pressure was determined by depth the bailer was at, for every 10 m 1 bar of pressure was pumped into the bailer. At each site 2 250 ml samples were taken.

4.3.3 Analysis and representation of samples

4.3.3.1 Major ions

The one set of the groundwater and surface water samples were sent to the national Department of Agriculture laboratory in Elsenburg where Major ions were analysed using Inductively Coupled Plasma-Optical Emission Spectrometry (ICPOES). Analysis was performed using a high performance iCAP 7600 ICP-OES Radial Spectrometer, manufactured by Thermo Fisher Scientific. The detection limit and sensitivity of the instrument varies from element to element. Minimum detection limits provided for the instrument include calcium 0.02 µg/L, potassium 5.10 µg/L, magnesium 0.04 µg/L and Sodium 1.80 µg/L. (Information available on manufacturer's website: http://www.thermofisher.com).

According to Solomons (2013) hydrogeochemical or hydrochemical facies are generally studied and compared using various graphical depictions such as Stiff (Stiff Jr, 1951), trilinear (Piper, 1944) and Durov (1948) diagrams. These methods are useful for visual identification of hydochemical data for detecting particular patterns and trends. According to Hiscook (2009) grouping of chemical analysis results using these methods mentioned above helps in identifying hydrochemical facies and helps in understanding the hydrogeological and hydrological processed that effect the groundwater or surface water chemistry.

Trilinear diagrams are one of the most commonly and extensively used methods in representing or interpreting water quality trends (Henok, 2013). These graphical representations have contributed to understanding and interpreting groundwater and surface water flow and quality trends. To assess the hydrogeochemistry of the groundwater and the hydrochemistry of surface water for this study area, Piper diagram (Piper 1944) graphical representation method from Geochemist's workbench 12.0 was used.

The Piper diagram gives a graphical depiction which shows the concentration of individual water samples that are plotted as percentage of total cation and/or anions concentrations in meq/L. The samples with different total ionic concentrations can fit on the same position in the diagrams. Seven ions, $Ca^{2+,}$ $Mg^{2+,}$ Na^+ plus K^+, Cl^-, $SO_4{}^{2-}$ and HCO^{3-} were used for the analysis. According to Henok (2013) the Piper diagram depicts the relative abundance of the ions and is composed of two triangles and a diamond field. The two triangles represent meq percentages of three sets of components, totalling 100%. Typically, components of the one triangle are cations ($Ca^{2+,}$ $Mg^{2+,}$ Na^+ plus K^+) at each corner while components of the other are anions (Cl^-

, $SO_4{}^{2-}$ and $HCO^{3-)}$. Depending on where the samples are positioned on the diagram can give an indication of the type of water that samples is see Figure 9 below.

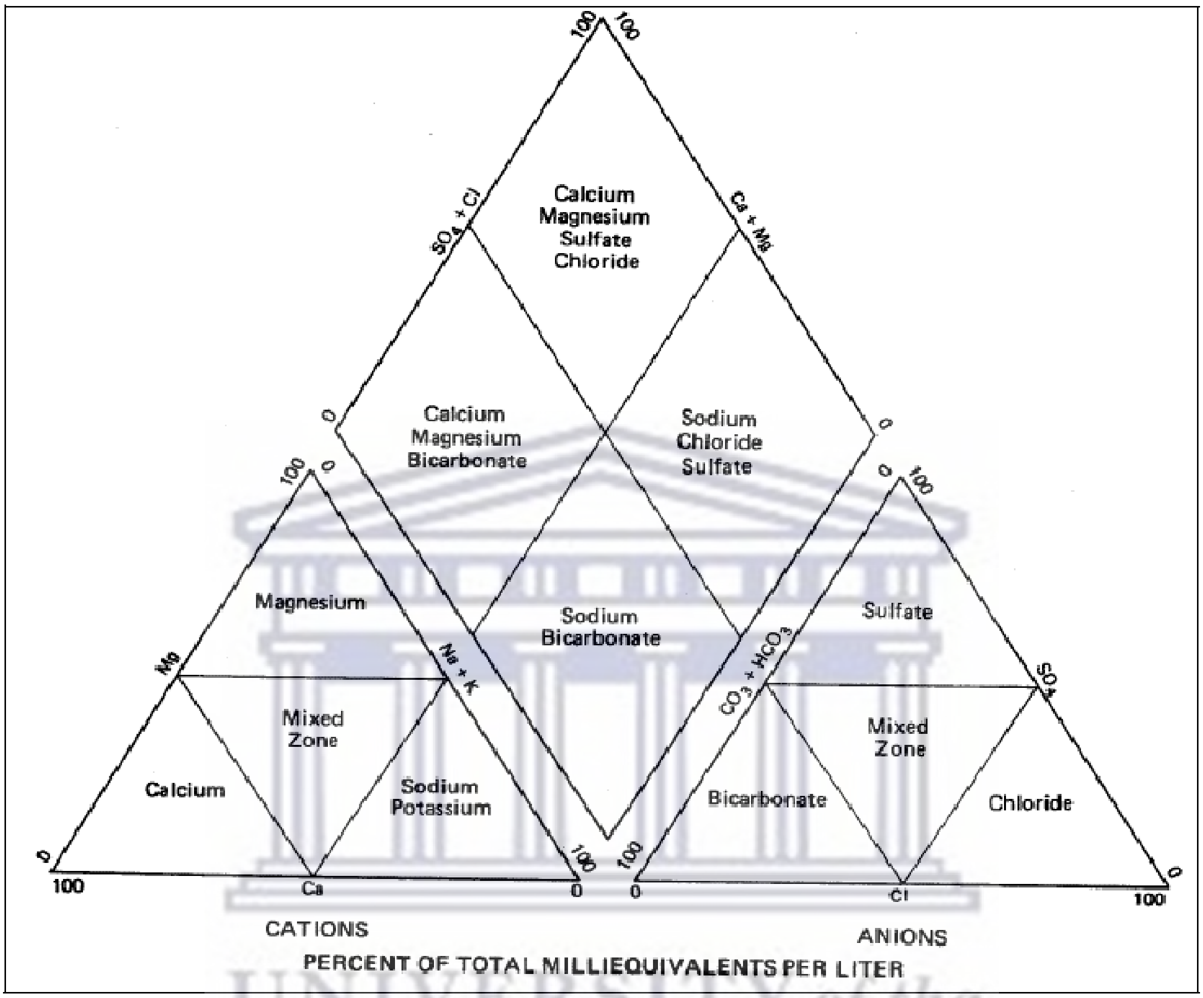


Figure 7: Trilinear diagram showing water type categories Chandel (2008)

4.3.3.2 Isotopes

The quantification of stable isotopes $^{18}O/^{16}O$ and $^{2}H/H$ was conducted in the Earth Sciences Department at the University of the Western Cape, Bellville, South Africa. The off-axis integrated cavity output spectroscopy (OA-ICOS) method was performed on a LGR DLT-100 liquid water isotope analyser (model 908-0008-2010) manufactured by Los Gatos Research Inc. (Mountain View, California, USA). The instrument was connected to a LC PAL liquid auto-sampler (model 908-0008-9001) manufactured by CTC Analytics, for the simultaneous measurement of $^{2}H/H$ and $^{18}O/^{16}O$ ratios in water samples. The auto-sampler was inserted with a SGE 5µl (model 5F-C/T-0.47/5C) syringe for the injection of water samples into a heated injector block (85□C). According to the manufacturer specifications (Los Gatos Research

Inc.), the model of the isotope analyser provides a 1-sigma precision below 0.6‰ and 0.2‰ for δ2H and δ18O, respectively. (Information available on company website: www.Igrinc.com)

Meanwhile, stable isotope analysis for water samples collected between February 2019 to December 2019 were analysed in the laboratory of the En-vironmental Isotope Laboratory (EIL) of iThemba LABS, Johannesburg. The equipment used for stable isotope analysis consists of a Los Gatos Research (LGR) Liquid Water Isotope Analyser. Laboratory standards, calibrated against international reference materials, are analysed with each batch of samples. The analytical precision is estimated at 0.5‰ for oxygen-18 and 1.5‰ for deuterium. All values reported on are expressed in the standard delta notation in per mill (‰).

Environmental Isotopes are used in this study to identify sites which potentially shows signs of groundwater – surface water interaction. The stable isotopes signatures can provide insight on whether interaction is taking place using δ2H and δ18O. For the purpose of this study it is important to compare bother the groundwater and surface water data to local meteoric water line (LMWL) which in this case Cape Towns LMWL is used as both the study catchment and Cape town is described as having a Mediterranean climate and both is situated at similar elevations ranges and within the same latitude. The results are also plotted against the global meteoric water line (GMWL) which has been defined in the method section of this study.

4.4 Quality assurance and quality control

Precaution was taken to safeguard the accurate labelling, packaging and transportation of collected water samples to prevent hydrochemical changes, spillages and/or misinterpretation of laboratory results due to incorrect labelling.

Every water sample was analysed in an accredited laboratory, in agreement with the international standards. The field water quality parameters which changes during transportation and storage, were measured on site immediately during the sampling. The multi – probe was calibrated daily in field trips, before measurement of water quality field parameters was taken.

The research methodology being used to address research question is a Quantitative methodology. Quantitative methodology uses measurable data to formulate facts and uncover patterns in research. With the aim of ensuring reliable results for this study, ion balance equation will be used to calculate the balance error of the water samples test, the total amount of anions and cations will be expressed in millequivalent per litre (meq/L). The total amount of cations must be equal to the total amount of anions; it can have a maximum difference of 10%. Below is the equation that will be used for quality assurance and control of the results.

Once data were generated for the relevant objectives, it had to be sorted out or in other words cleaned. This process involved the checking for any blank data areas, removal of duplicate data and backing up of data. In addition, sample bottles were pre-rinsed at least three times before collecting the sample for analysis.

4.5 Statement on ethical consideration

The autonomous principle (permission and procedure) was applied prior to doing any fieldwork for the installation of necessary equipment and for the collection of required data, it was necessary to acquire permission from landowners/farmers of the sites that was chosen. The sites were chosen after looking at google earth images as explained in Chapter 3. Once permission was granted from all farm owners and landowners a formal email was sent to them stating the main objective of the project and how we would like to utilise their property whether it was for doing geophysical surveys, drilling boreholes, installing weather stations etc. Furthermore, we informed each farmer 1 week prior to field visits and on the day just to be sure that the farmers are aware of what we will be doing on their farms.

4.6 Limitation of the study

This study does not include information about how the vegetation in this area influences the groundwater - surface water interaction and the water quality of the available water resources. Additionally, this study is site specific; however, it can be used as a guideline when doing a catchment scale study. During the period of data collection, there were shortfalls in terms of equipment needed to collect in-situ parameters such as EC, pH and temperatures on each field visit. Furthermore, funds were limited, which influenced the frequency of field visits, analysis of water samples collected and frequency of sampling trips. Another shortfall of this study is that it does not quantify the interaction at the sites.

Chapter 5: Aquifer and site characterisation

5.1 Introduction

This chapter provides results obtained for objective one and two of the current study, which is to characterise each study site and the aquifer. The characterisation of each site was done by using geophysical surveys, down-hole EC and Temperature profiles, borehole lithology logs and aquifer testing at the site. Additionally, using previous studies done at these to add to the characterisation of the study sites.

The six study sites that were used as case studies in this research are Boskloof, Tussenberge, Spanjaardskloof, Jan Swartskraal, Sandfontein and Moddervlei. The location of these sites can be found in Chapter 3, which provides overview of the site description as well.

Characterisation in this chapter is defined as providing description the study sites using multi-method/technique approach using geophysical methods to understand the subsurface, Lithological logs used to delineate the subsurface layer and for identifying aquifers, down-hole logging technique to understand the water columns in the boreholes and aquifer testing using constant test, step-down test and slug test, to understand aquifer properties at each site.

5.2 Results

5.2.1 Tussenberge

a. Geophysics results and interpretation

Gravity and electrical resistivity surveys were undertaken on a transect running SW-NE on an upland area with fynbos and underlain by sandstone. There were no significant gravity anomalies along the transect (Figure 8) which suggest that no fractures and major changes in underlying formation occur at this site. Resistivity values were less than 700 Ω m up to a depth of 20 m along the first 100 m on the south-western part of the transect. Resistivity values increased to > 3000 Ω m at depths greater than 30 m which suggest the existence of unweathered sandstone. The portion of the transect from 250 to 350 m from the south-west had generally high resistivity values, >2500 Ω m, even at shallow depth. Based on the electrical resistivity values, it was decided to drill monitoring boreholes to varying depths, 12, 30 and 50 m to establish if the occurrence and flow of groundwater varied with depths.

Gravimetric data at the Tussenberge site was collected over a distance of 865 m with a maximum elevation of 245 m. This data was analysed using the Bouguer Gravity 2.0 anomaly, which indicates a correlation between the subsurface density and topography over the transverse. The general trend shows a decline in gravity between 150 - 230 m along the transverse, suggesting a less dense subsurface lithology. This is followed by a gradual increase in gravity peaking at 515 m. In correlation with our borehole logs, lower densities are sandstone, whereas higher densities are clay (Figure 9).

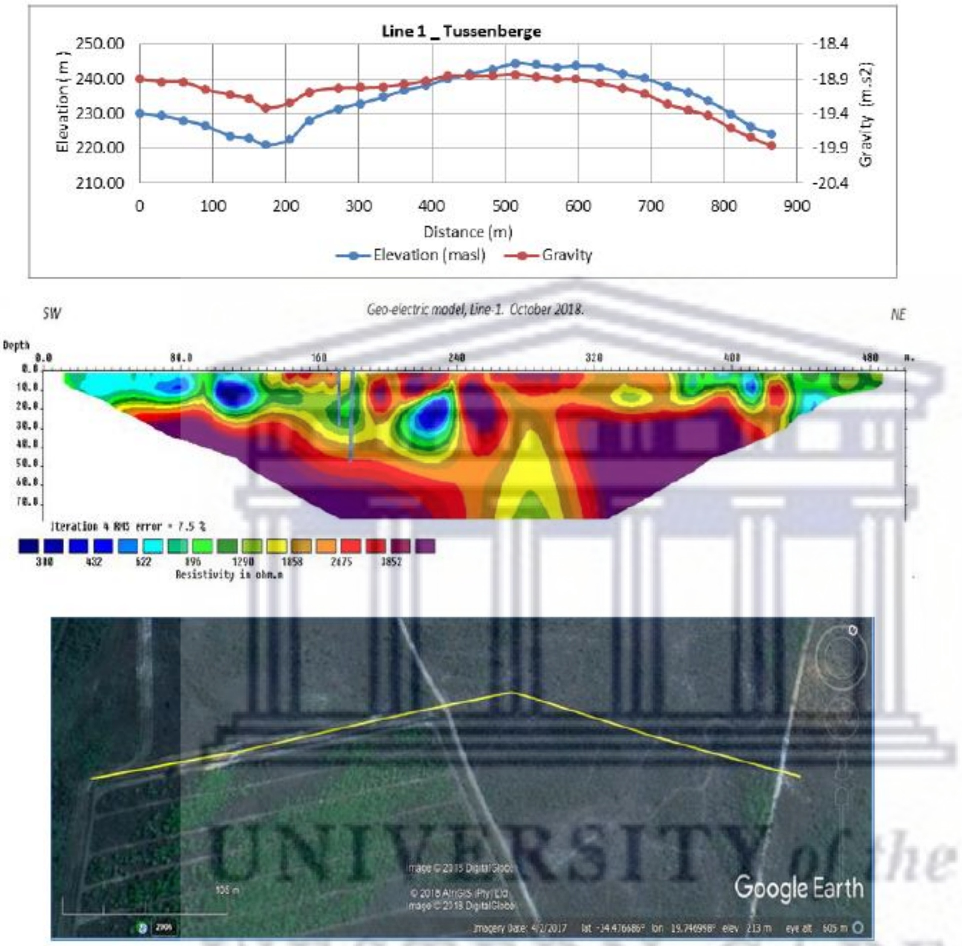


Figure 8: Gravity and electrical resistivity survey, and the location of the transect at Tussenberg. The resistivity survey transect and Google Earth image correspond with the 230 – 710 m part of the gravity survey transect

b. Borehole lithology logs

The boreholes drilled at Tussenberge site show lithology with very high hydraulic conductivity. Figure 9 show a dominance of sandstone, it is expected as Tussenberge site is situated in the TMG ground made up of sandstone and clay and shale. The deepest borehole (BH15 – 50m) was the only borehole out of the three showing a clay in closer to the bottom of the drilling borehole.

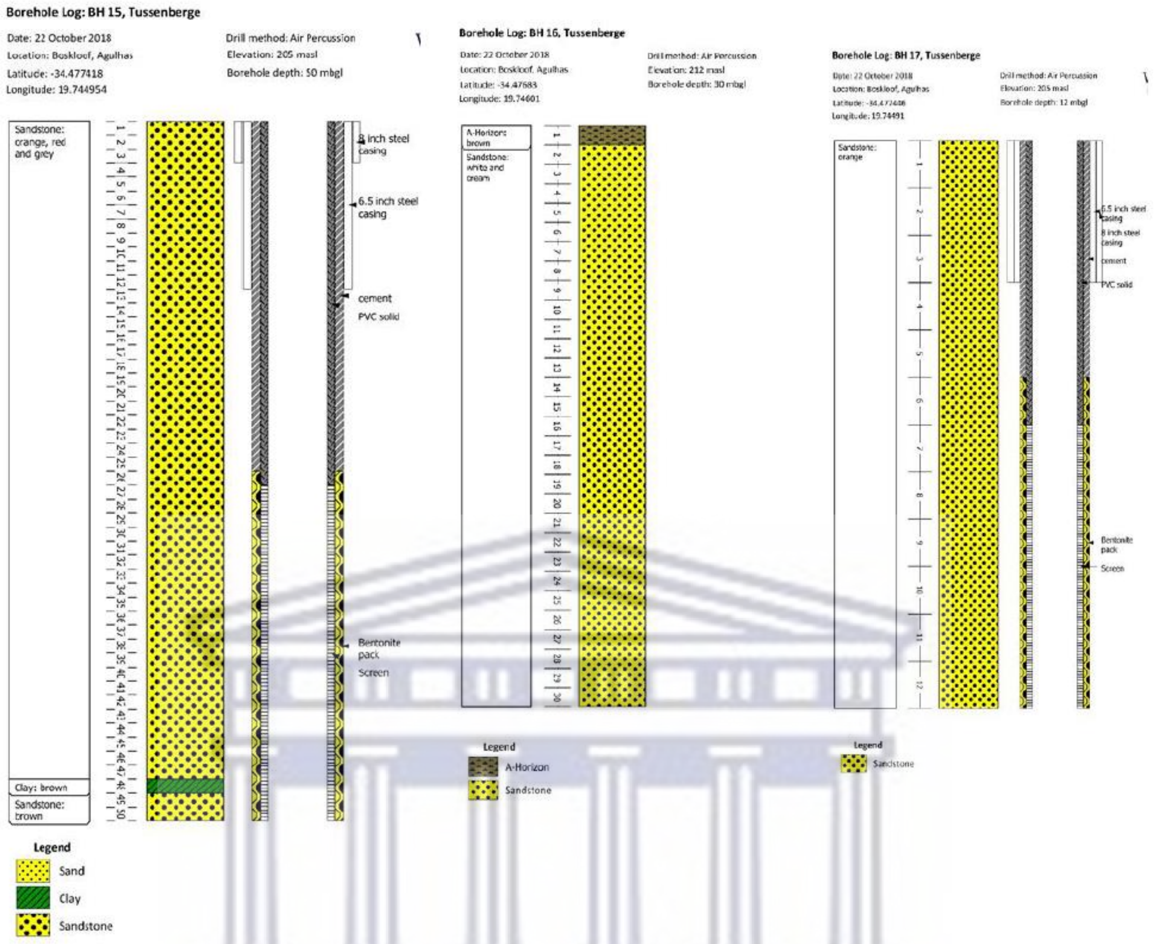


Figure 9: Drilling logs and construction of boreholes at Tussenberge

c. Hydraulic test (Pump test)

A constant discharge test was conducted on BH 15 during April 2019. The pump was lowered to a depth of 44 m, while the borehole depth is 50 m. The step drawdown test for BH 15 was conducted at respective hourly rates of 0.13 and 0.26 litres per second (l/s).

Based on the results of the step drawdown test, the constant discharge test for BH 15 was conducted at a rate of 0.11 l/s for a 4-hour period. The static groundwater level was 1.78 mbgl before the test commenced, and the total drawdown after completion of the test was 13.5 m.

The test results for BH 15 are illustrated Figure 13 while Figure 14 and Figure 15 show the pumping test analysis results from AqteSolve using Cooper Jacob and Theis solutions under confined aquifer conditions. The result yielded via Aqtesolve very low transmissivity results. With limited resources, only test was done on the deepest borehole at Tussenberge site using the other 2 boreholes as observation boreholes however after 4 hour pump test no changes were seen on both BH16 and BH17, this could possibly suggest no or little connectivity at the site.

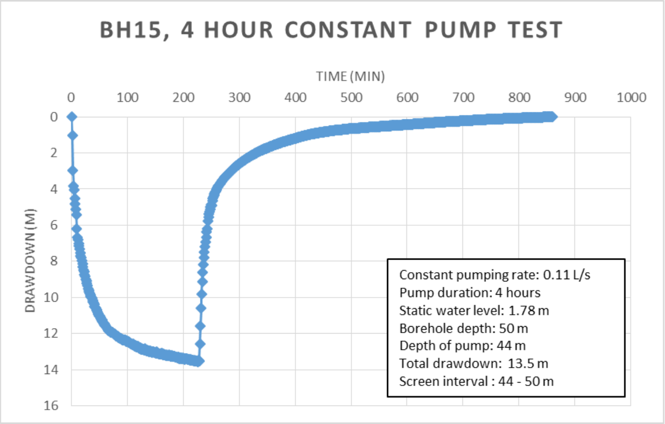
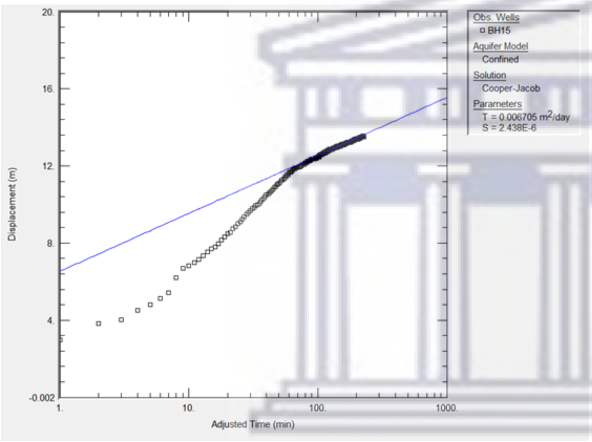


Figure 10: Drawdown and recovery from 4-hour pumping test for BH15



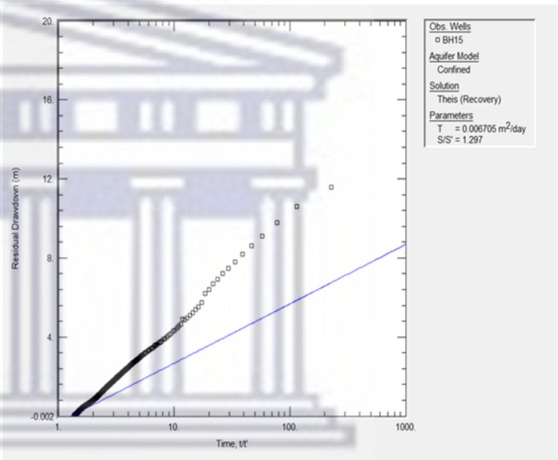


Figure 12: The 4-hour aquifer test at 0.11 l/s interpretation results using Cooper-Jacob method within Aqtesolve for BH15

Figure 11: The 4-hour aquifer test at 0.11 l/s interpretation results using Theis Recovery method for BH15

d.Downhole EC and Temperature logs

The EC is fairly stable down BH15, with slightly lower levels during the dry season (March 2019) than in the wet season (May 2019) (Figure 15). The temperature profiles show a shift in the shallow aquifer caused by changes in the movement of groundwater in the shallow aquifer. In the wet season (May), EC remained constant throughout the BH16 until about 15m, close to the bottom of the borehole, where there may be stagnant water that is more saline and slightly

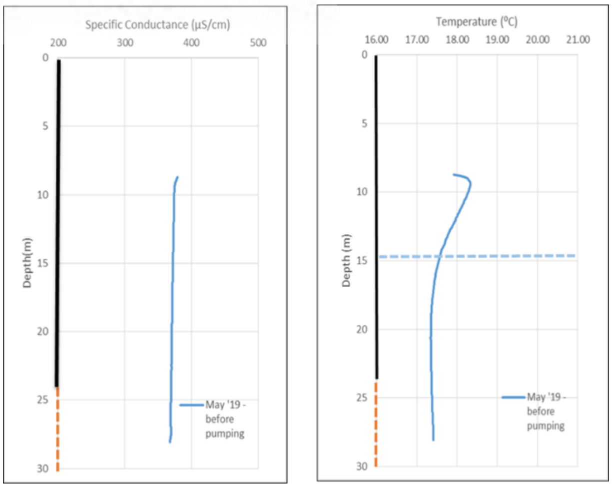


Figure 13: YSI down-the-hole logging results for BH 16, Tussenberge. Log prior to pumping.

warmer (Figure 13). The temperature shows a similar shallow aquifer groundwater flow signature compared to BH15. Whilst BH17 show evidence of possible fresh water inflow between 6 and 7m depth in both the dry season (March 2019) and the wet season (May 2019) (Figure 14). Temperature data shows vertical downward flow during the May 2019 log. It is also key to note that the shallow and deep boreholes seem to have similar EC values suggesting a linked system.

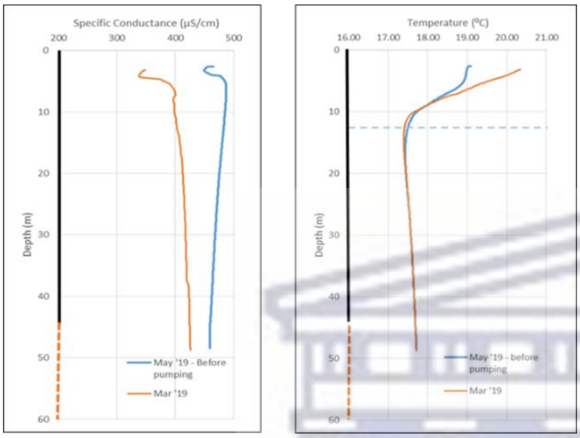


Figure 15: YSI down-the-hole logging results for BH 15, Tussenberge. Initial log prior to pumping test, in March 2019.

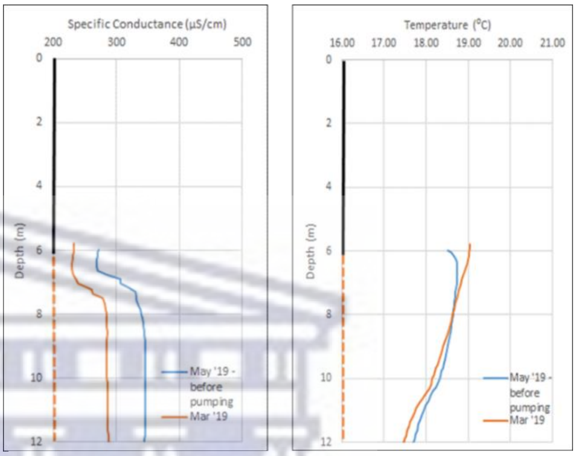


Figure 14: YSI down-the-hole logging results for BH 17, Tussenberge. Initial log prior to pumping test and May log pre-pumping.

d. Groundwater levels and temperature fluxes

The three boreholes located at the Tussenberge site is located in the upland area of the catchment with elevation between 205 to 212m above sea level and is 160 m away from nearby river. The groundwater level results from Tussenberge site with response to rainfall data is presented in Figure 16. From the figure, it is evident that the results from the boreholes show signs of connectivity as the groundwater levels for both shallow (BH16 and BH17) and deep boreholes (BH15) show a similar trend over time. During the rainy season, boreholes show a delayed response to rain, with the water table being almost close to the surface. The shallow well (BH17) has a sharper amplitude compared to the deeper holes (BH15 and BH16) and responds faster to precipitation. This may be due to the fact that BH16 is drilled at bedrock elevation compared to BH15 and BH17 which were drilled in a weathered deep zone. It can also be seen that the water table shows a significant response after more than 50mm of rainfall. However, over time, the water level gradually falls and flows into the lower reaches of the catchment until the next rain event, when the water level begins to rise again. The groundwater level of both the shallow and deep boreholes are always above the riverbed suggest that the river is potentially a gaining river. The shallow and the deep aquifer has a positive hydraulic head throughout the year, creating conditions conducive for groundwater discharge into the nearby stream. The adjacent stream is perennial confirming that this is a gaining stream.

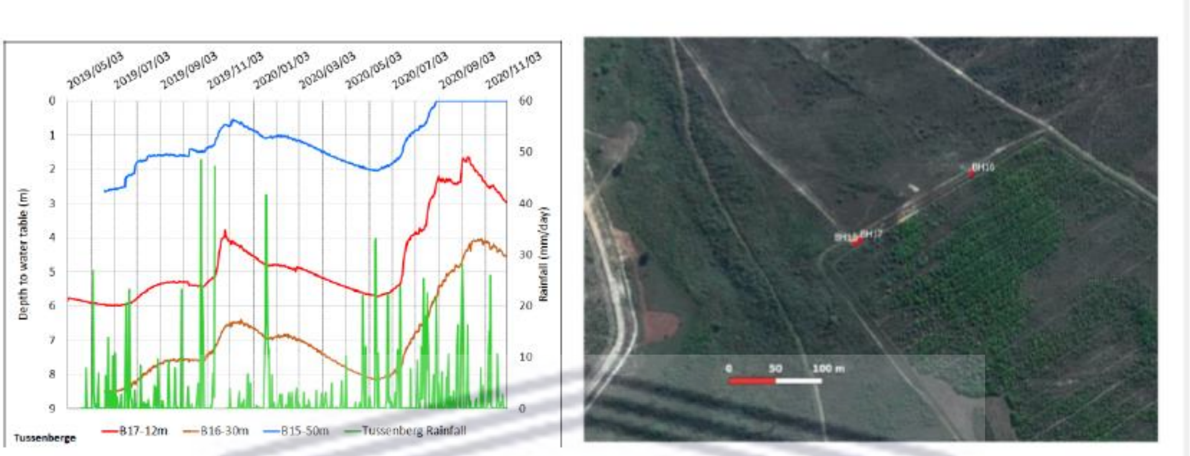


Figure 16: Variations of the depth below ground level of water tables in Tussenberg boreholes, and the layout of boreholes. The stream 100 m from BH15 on the south-western part. (Google Earth Image)

The deeper aquifer intersected by BH15 50m has a higher water table than the 12 and 30m deep well. This indicates that the deeper aquifer is confined by a recharge zone further up the slope. The water table of the deep aquifer was at ground level from September to December 2020, resulting in groundwater runoff at the surface. The deep aquifer (BH15 50 m) does not experience changes in groundwater temperature (17. 4 °C) which would be expected for a confined aquifer with a remote recharge zone uphill. The groundwater temperature in BH16 30m is similar to that in BH15 50m and varies between 17.3 and 17.4 °C. Water replenishing the shallow aquifer, BH17 12m, between May and September 2020 resulted in a reduction in the Groundwater temperature (Figure 17).

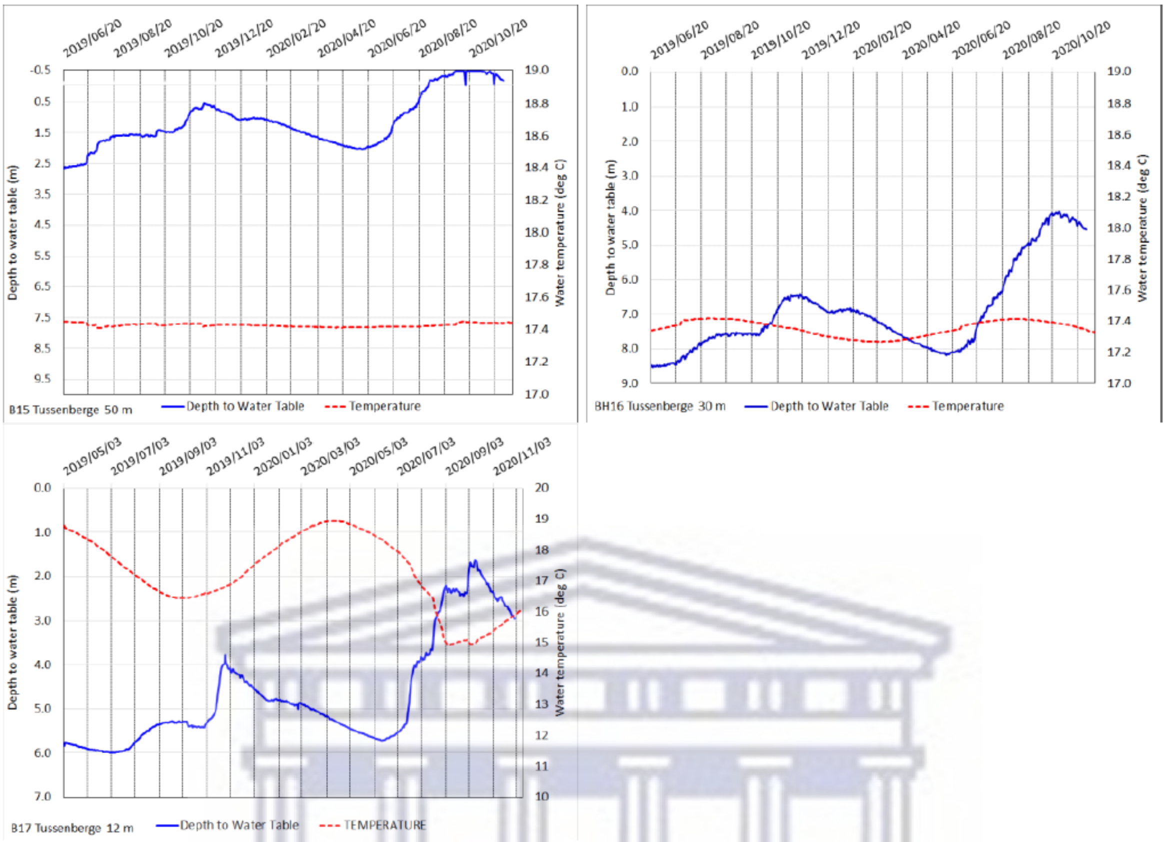


Figure 17: Temporal variations of groundwater temperature at Tussenberge.

d. Environmental stable Isotopes

The results indicate potential of interaction taking place between the boreholes representative of the groundwater and the surface water (Tussenberge River). Comparing the isotopic signatures from the river to the boreholes, it is evitable that shallow borehole (BH17 – 12m) display more isotopically similar to the river compared to the other 2 boreholes present (Appendix 2 _ Figure 59). With the very small dataset available, the information provided is limited because these boreholes are amongst the newly established networks in the catchment. Based on the results of shown by environmental isotopes, it is evident that the river at this site is most likely to be gaining from the shallow aquifer and not the deeper aquifer. With a longer set of data, better findings can be yielded. Meanwhile, the margin difference between the river and deeper boreholes (BH16 and BH15) was greater than 7 and 8 ‰ for δ2H, respectively during the October 2020 to December 2020 period. Based on the results, the river at Tussenberg is more likely to be gaining from the shallow aquifer as compared to the deeper aquifer. However, interactions between the river and deeper aquifer can still occur since isotopic signatures are still similar. River water isotope signatures were noticeably more different to the deeper aquifer in October 2020 as compared to the months that followed. It is possible, that the isotopic signature of the river and shallow aquifer might have been influenced by the rainfall received during October 2020, that exhibited significantly enriched values (-1.9 45 ‰ for δ2H and -3.06 ‰ for δ18O). Rainfall in this region is usually more depleted, with isotope values usually below -18 ‰ for δ2H.

5.2.2 Sandfontein

a. Geophysics results and interpretations

Electrical resistivity surveys were undertaken on a transect running W-N on an upland area underlain by thick layer of bedrock made up of primarily sandstone and shale. The electrical resistivity profile was collected over 200 m to display a subsurface profile at the Sandfontein site.

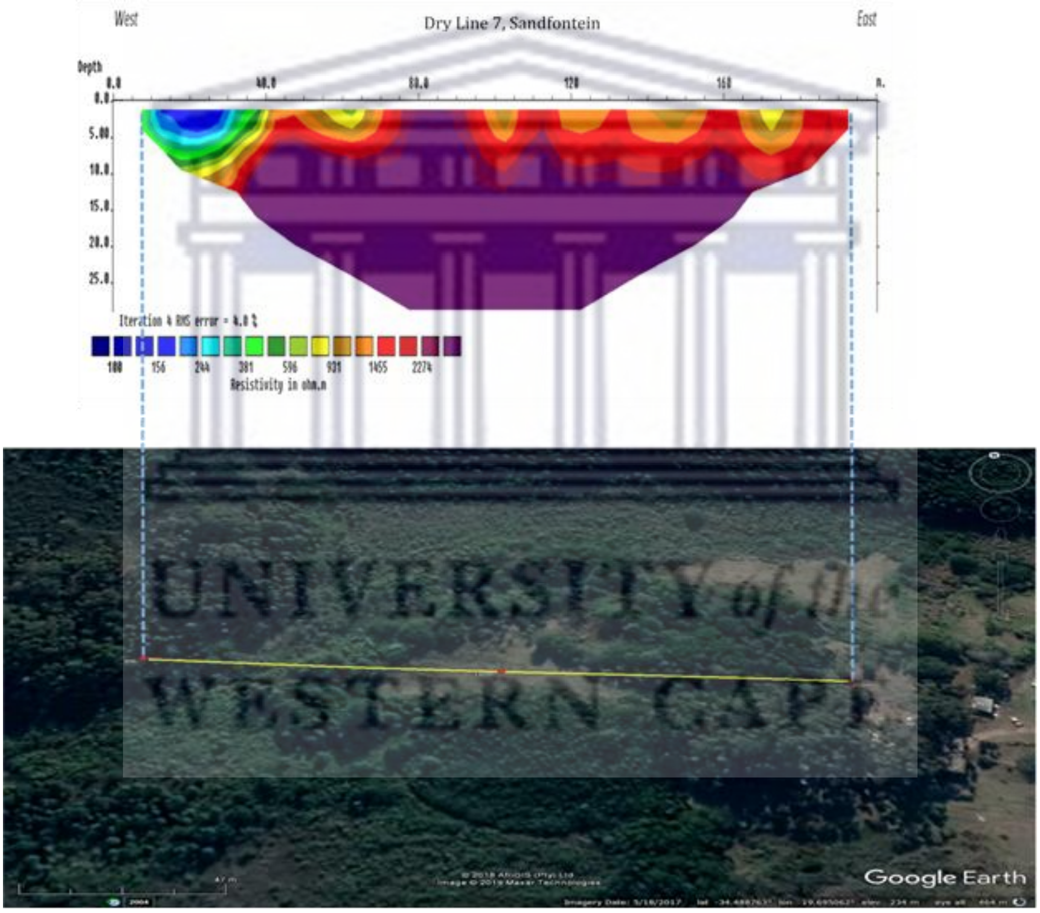


Figure 18: Electrical resistivity survey at Sandfontein. The transect for the electrical survey was from west to east, corresponding to location on Google Earth image.

This profile shows slight variability in the resistivity data in the top 10 m the 200 m profile. It is evident on the profile that there is a thick layer of bedrock, presented with very high values of resistivity (Figure 18). The resistivity value of >3000 Ω m at depths greater than 10 m across the profile. It is apparent that the profile resistivity is predominantly in the high resistivity range. Additionally, it is evident that with depth increasing resistivity increases. However, on the western part of this profile there is a river present, evidence of why the profile presents very low resistivity, with resistivity values range from 100 – 400 Ω m. According to the profile one can see that this profile was done on a thick layer of bedrock comprising of sandstone and shale according to resistivity values of common rocks (Adeeko & Nordiana, 2018) which made it difficult in the field to augar a piezometer in this area. The lithology logs (Figure 19) confirm this. Based on the resistivity profile, boreholes with the depths of 50 m and 11 m was drilled to monitor groundwater table relevant to the river at the site. With future studies done on water up take from the alien vegetation at the site.

b. Borehole lithology Logs

BH28 was drilled to a depth of 50m. The first 1 m showed brown type of sandy soil (moist), then the next 2 m (2-3 m depth) had fined weathered sandstone. Fractured sandstone occurred from 4 m up until 10 m. Water occurred at 11m where fractured and coarse red/brown sandstone existed. The lithology then continued to be sandstone from 12 m to 40 m. This is seen on both the resitivity and the gravimetric crossections. A change lithology then occurred at 41 m deep where shale was present up until 47 m deep and lastly the bottom 2m (49- 50 m) showed red and white hard sandstone (Figure 19). Similarly, to the Tussenberg site, which is classified as the highland areas in the catchment, within the TMG group, Sandfontein lithology presents high hydraulic conductivity property.

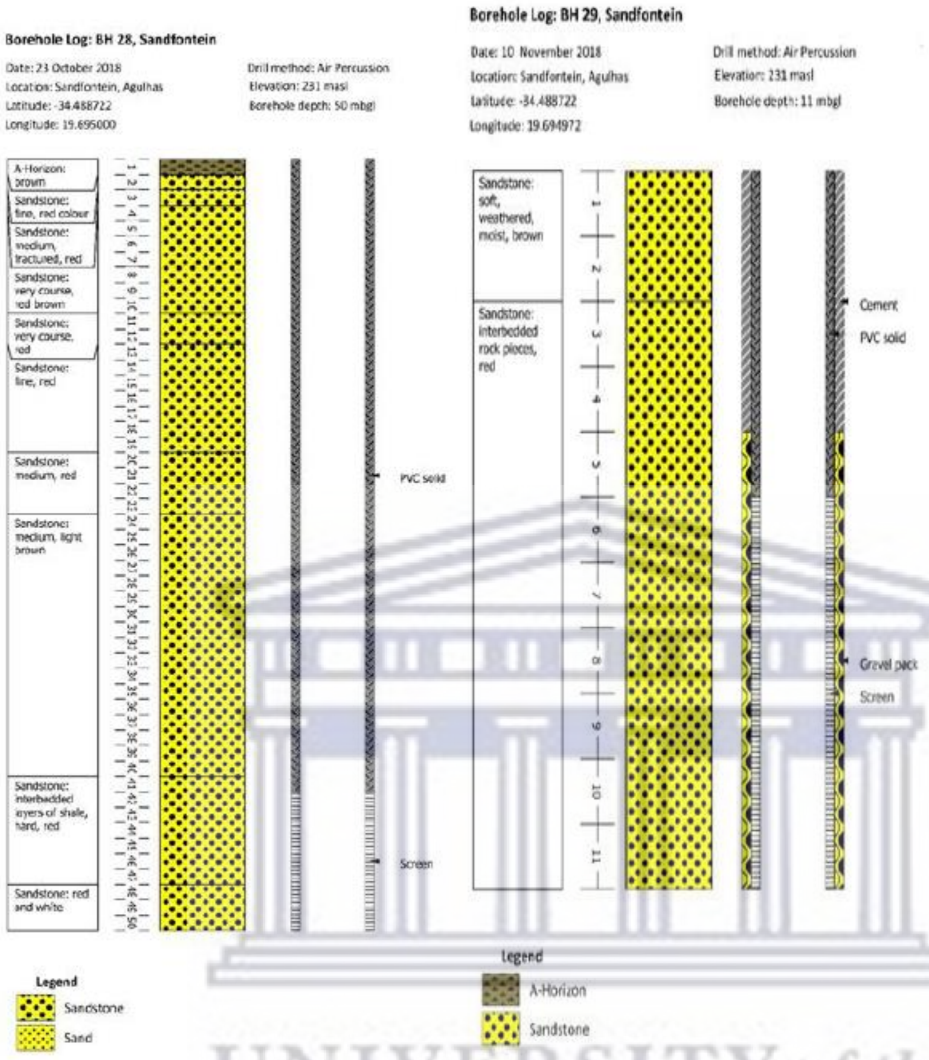


Figure 19: Drilling logs for the boreholes at Sandfontein

c. Hydraulic Test

A constant discharge test was conducted on BH 29 during April –May 2019 (Figure 20). The pump was lowered to a depth of 6 m, while the borehole depth is estimated at 11m.

The step drawdown test for BH 29 was conducted at respective rates of 0.1, 0.3 and 0.8 litres per second (l/s). Each rate increased respectively over hourly intervals for a total of 3 hours.

Based on the results of the step drawdown test, the constant discharge test for BH 29 was conducted at a rate of 0.6 l/s. The static groundwater level was 1.78 mbgl before the test commenced, and the total drawdown after completion of the test was 5.5 m.

After the pump was switched off, the water level showed relative moderate recovery with incomplete recovery. After a total of 6 hours of recovery, the water level only returned to 1.34 m below static with 75% recovery from static conditions (see Figure 23)

The test results for BH29 are illustrated in Figure 20, while Figure 21 and Figure 22 depicts the data analysis results from AqteSolve. The results was analysed using both Cooper-Jacob and Theis calculation yielding transmissivity results.

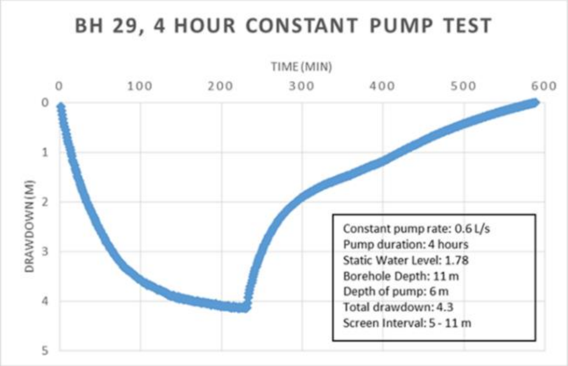


Figure 20: Drawdown and recovery from a 4-hour pumping test for BH29.

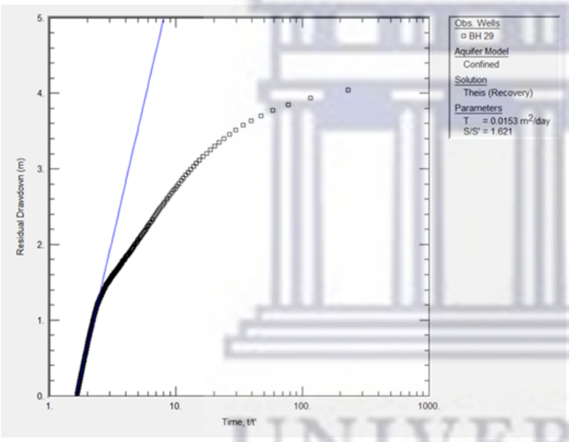


Figure 22: The 4-hour aquifer test at 0.6 l/s interpretation results using Theis Recovery method for BH29

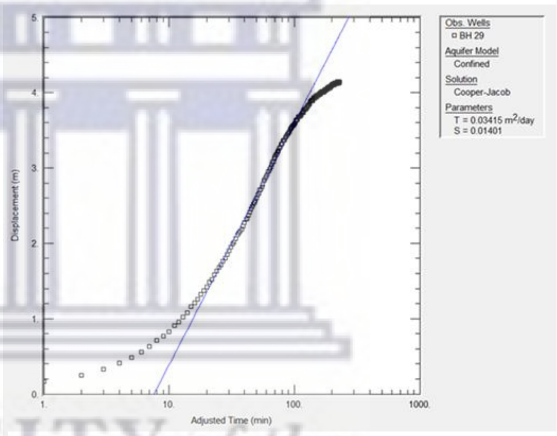


Figure 21: The 4-hour aquifer test at 0.6 l/s interpretation results using Cooper-Jacob method for BH29.

d. Downhole EC and temperature logs

EC and temperature are fairly constant throughout the BH 28 during the dry season (March 2019) and before and after pumping (Figure 2 3and Figure 24). The temperature profiles show changes in groundwater flow in the shallow aquifer, suggesting recharge of the shallow aquifer.

In BH 29 groundwater is less saline in the shallow aquifer, compared to the deeper aquifer section from BH28. There is a noticeable change in the temperature gradient at about 7m in BH 29, indicating an inflow of groundwater at that depth (Figure 25 and Figure 26).

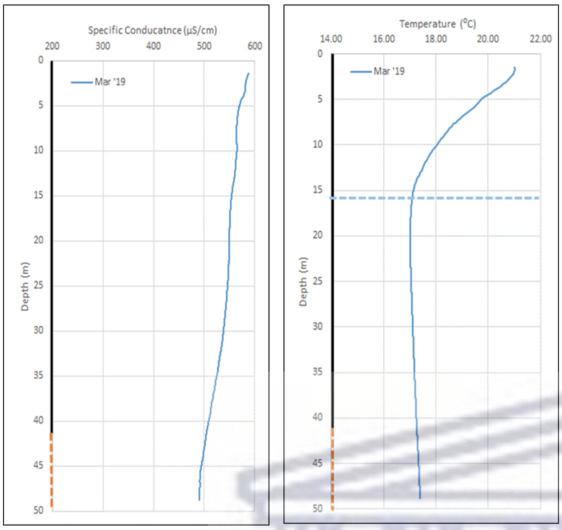


Figure 24: YSI down-the-hole logging results for BH 28, Sandfontein 50 m. Initial log March 2019, with pre- and post-pump Test in April 2019.

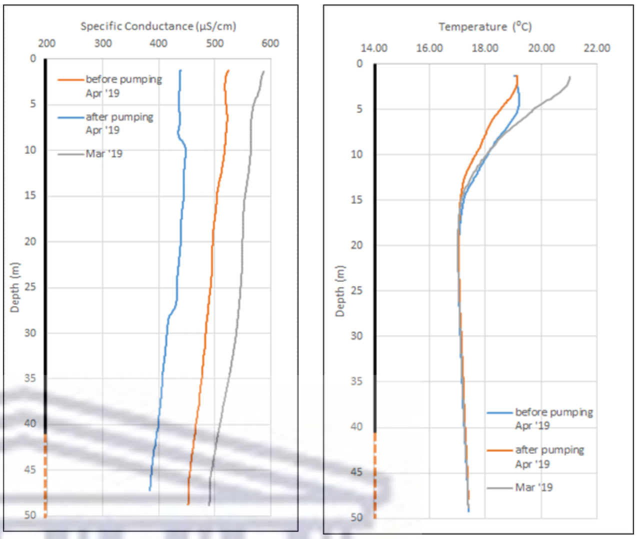


Figure 23: YSI down-the-hole logging results for BH 28, Sandfontein 50 m. Initial log March 2019, together with pre- and post-pump test in April 2019.

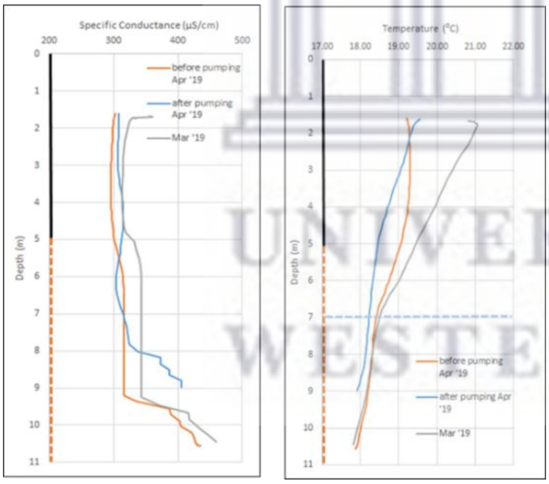


Figure 25: YSI down-the-hole logging results for BH 29, Sandfontein 11 m. Initial log in March 2019, pre- and post-pump test in April 2019.

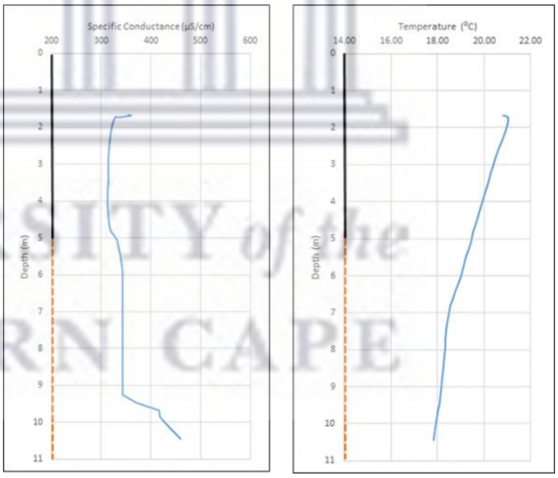


Figure 26: YSI down-the-hole logging results for BH 29, Sandfontein 11 m. Initial log prior to pumping test, in March 2019.

e. Groundwater levels and temperature fluxes

The boreholes at Sandfontein area is located in the upland area of the catchment with elevation of 231m above sea level for both shallow and deep borehole and is 60m away from the river which is at an elevation of 222 m. The water table in both the 11m and 50m borehole shown in Figure 27 is at the same depth. The pumping test data showed no connection between the deep and shallow aquifers, although the water tables responded in a similar way. The wells are located in the discharge zone lower part of the hillslope, hence the similarity in the water table responses see Figure 27. The groundwater level rise to the surface from September 2020, causing groundwater seepage. The landowner reported frequent swampy conditions at the well site, which is confirmed by the groundwater draining at the surface, especially during the wet season with low evaporation rate, can eventually reaching the nearby river.

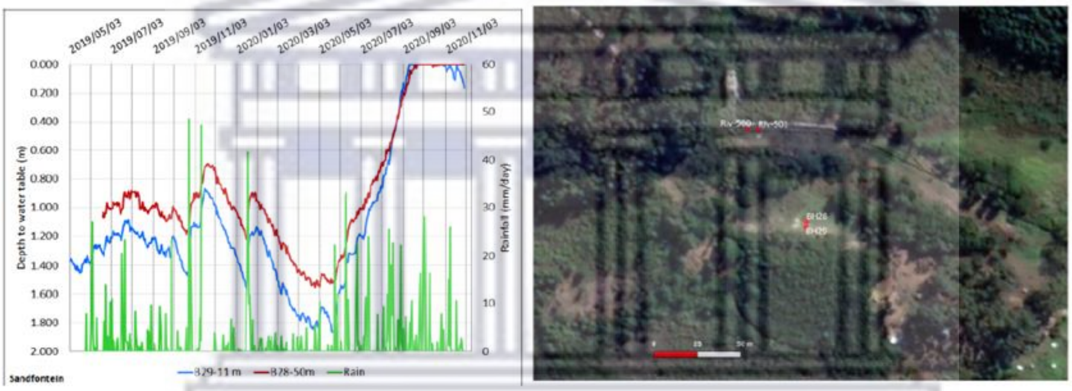


Figure 27: Temporal changes in the water table depth in Sandfontein boreholes, and the layout of boreholes with the stream (RIV-500, Riv-501) being at a distance of 55 m on the northern side. (Source Layout: Google Earth Image)

The groundwater temperature at Sandfontein shows similar trend as Tussenberg also located in the upland areas of the catchment. The groundwater in the 50 m deep aquifer (BH28) shows no temperature changes, while the shallow aquifer during May to September 2020 period show reduced temperature (Figure 28).

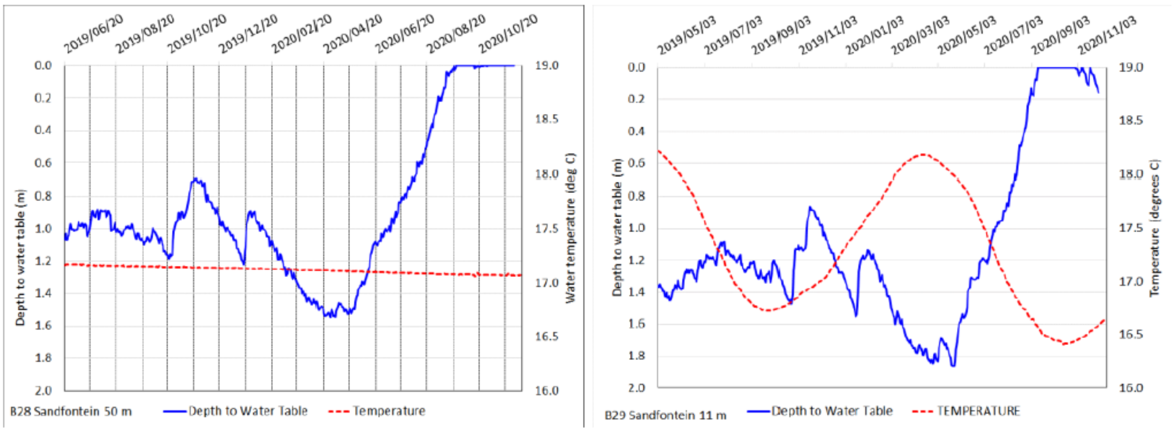


Figure 28: Water temperature in the Sandfontein boreholes.

f. Environmental stable isotopes

Sandfontein site is one of the sites that were recently established with a limited dataset. This site was established in 2018, with sampling only commencing in mid 2019. From the data presented in Appendix 2 – Figure 61, both δ2H and δ18O signatures form BH28 groundwater (deep 50m borehole) is mostly negative values, which means the samples taken is most depleted samples during the sample period. Such strong similarities between the river and shallow aquifer, although still present, were not as pronounced during the more recent October 2020 to December 2020 period. The river during 2019, measured very depleted values close to -24 ‰ for δ2H, which then increased to values above -17 ‰ for δ2H between October 2020 to December 2020. The isotopic signatures of the October 2020 rainfall were unusually much more enriched compared to signatures of rainfall received at any other period within the catchment. The effect of such a rainfall signature during this period could be the reason for a large marginal difference between the isotope signatures measured in river waters at this site during 2019 and 2020. The river at Sandfontein is therefore isotopically similar to both the deep and shallow aquifer, although usually much more similar to the shallow aquifer. As a result, the river at Sandfontein plotted much closer to BH 29 as compared to BH 28 on the dual isotope plot. This indicates that a stronger connectivity between the river and the shallow aquifer exists. However, due to similarities in the isotope signatures of the river with BH28 (50 m) as well, interactions between the river and deeper aquifer are also possible. Stable isotope results obtained at this site therefore suggest that the river at this site can possibly gain from both the shallow and deeper aquifer. Analysis of water tables also confirmed the potential for groundwater discharge.

5.2.3 Spanjaardskloof

a. Geophysics results and interpretation

A 400 m long S-N resistivity transect was located on a sloping ground with the southern and lower part having an elevation of 136 m and the northern and upper part at 164 m (Figure 29). Part of this area was a pine plantation which co-occurs with acacias. The first 180 m along this transect from the lower part and up to a depth of 30 m had resistivity values less than 800 ohm metres (Ω m) (Figure 29). This suggests the occurrence of weathered sandstone with water. A quartzite formation evident at the surface occurs from 200 to 350 m along the transect, and this had high resistivity values, > 2000 Ω m. Resistivity values decreased to less than 900 Ω m along the last 350 – 400 m of the transect which is likely due to sandstone, that is moist.

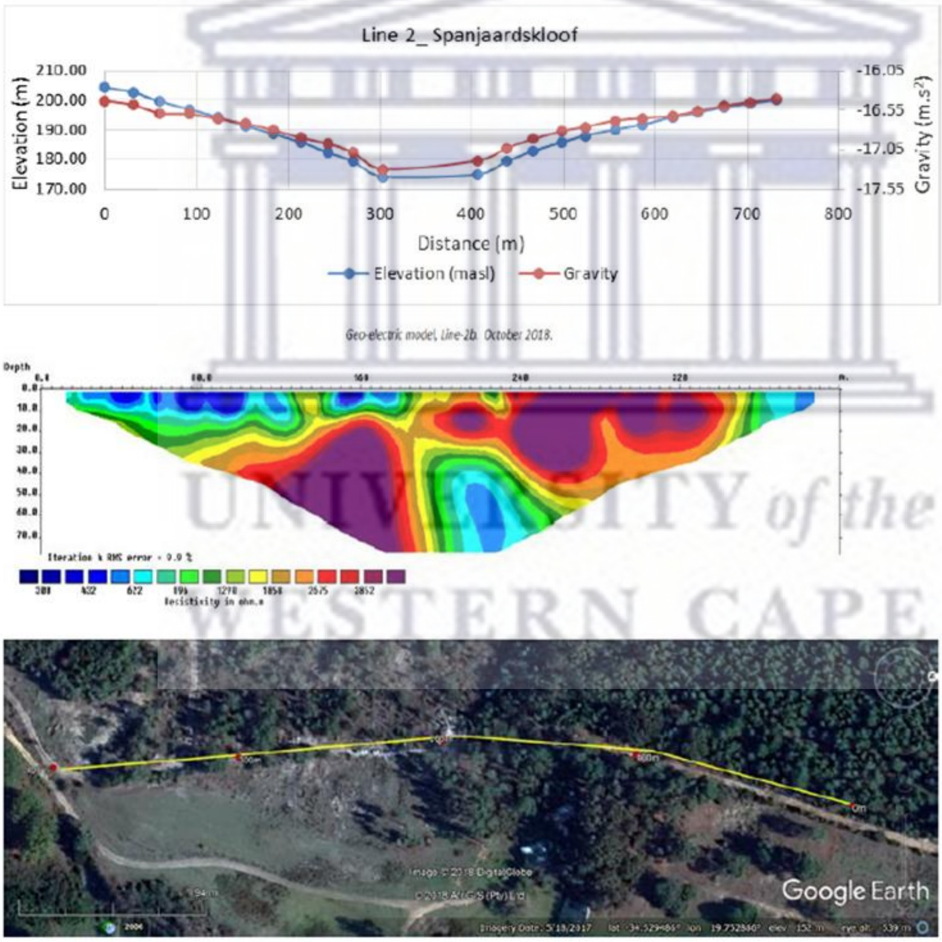


Figure 29: Gravity and electrical resistivity survey at Spanjaardskloof. The transect for the gravity survey was from west to east, while the electrical resistivity was done on a S-N transect corresponding to the Google Earth image

The gravimetric data at this site was collect over a distance of 750 m with a maximum elevation of 205 m. Gravity anomalies from S – N does not show any significant difference across the profile, with the exception of the significant change seen between 300 m and 400 m. The significant dip in gravity anomalies suggest existence of fracture present. Compared to the profile of resistivity which displays low resistivity values which is indicative of weathering along fractured zone, resulting in increased permeability and occurrence of water, this occurred at the along the same zone where gravity anomalies suggested presence of fractured zone.

b. Borehole Lithology logs

The boreholes drilled at this site was not only for aquifer characterisation but also to feed into possible research on the effects of invasive alien vegetation on different groundwater zones. The overall lithology of the boreholes found at Spajaardskloof is sandstone with variations in the colour of the sandstone in both the shallow (BH19 20m) and deep boreholes (BH18 50 m).

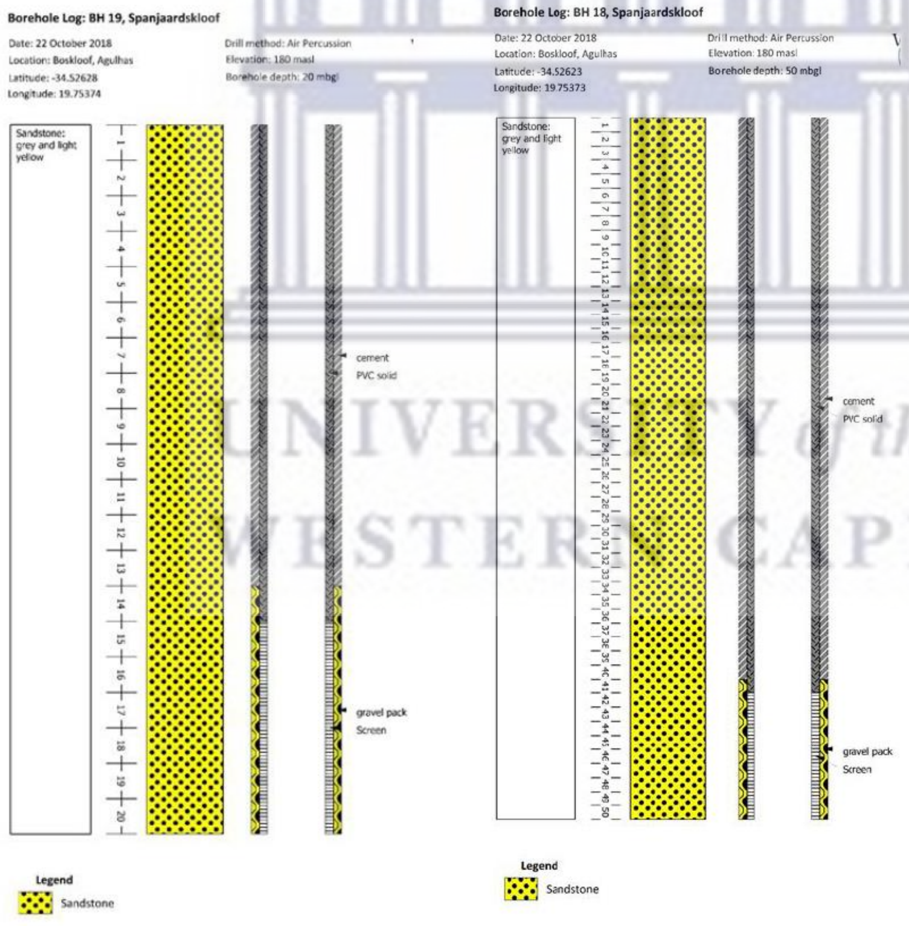


Figure 30: Drilling logs and borehole construction at Spanjaardskloof

The top 16 m of BH18 had white weathered sandstone, followed by white-grey weathered sandstone and moist white/yellow weathered sandstone (Figure 30). Whilst BH 19 had variation of red-orange sandstone in the first 1m followed yellow/grey sandstone, and the last 11m (10-20m) (Figure 33). The moist sandstone present at this sight is confirmed by the resitivity crossection, Figure 29.

c. Hydraulic test (slugtest)

A slug test was conducted on BH 19 in May 2019. The static water level (SWL) at this borehole was 6.77 m, while the total depth of the borehole is 7 m. It was therefore not possible to conduct a pump-out test at this borehole, given that not enough water was available for pumping. The slug test was repeated three (3) times to ensure saturation. The transducer that were installed in the borehole was set to 20 second time interval, and it was left in the borehole to take readings until water level was representative of the SWL reading prior to the slug test. However, it has not reached recovery even after leaving the transducer overnight. This can be evidence of a confined aquifer, or possible recharge only from rainfall.

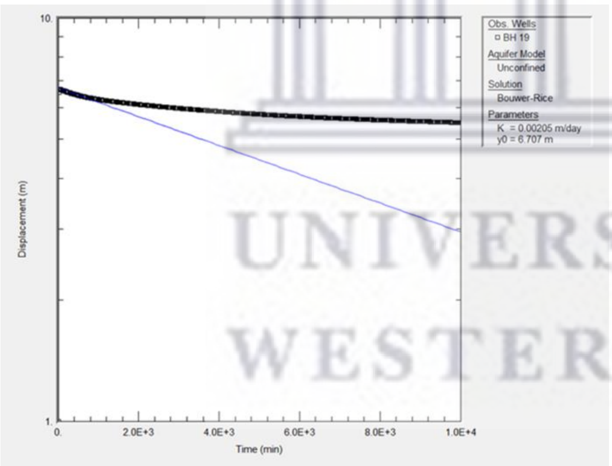


Figure 31: Interpretation of Slug test data results for BH19, Spanjaarskloof.

g. Downhole EC and temperature logs

The stagnant water in the solid casing section seems to have a higher EC, decreasing with borehole depth towards the screened section in BH 18. The temperature gradient in the shallow aquifer above 15m shows groundwater flow in this zone (Figure 33). The shallow borehole

(BH 19) (Figure 32), shows the same temperature profile, but with higher EC in the shallow aquifer compared to BH18 . This can be due to different aquifer conditions at the screened sections of the boreholes indicating 2 different aquifer qualities at the depths measured

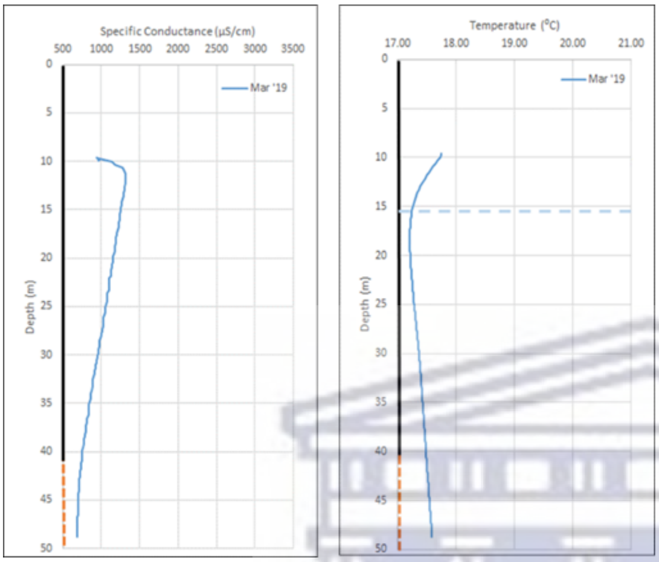


Figure 33: YSI down-the-hole logging results for BH 18, Spanjaardskloof. Initial log prior to pumping test, March 2019.

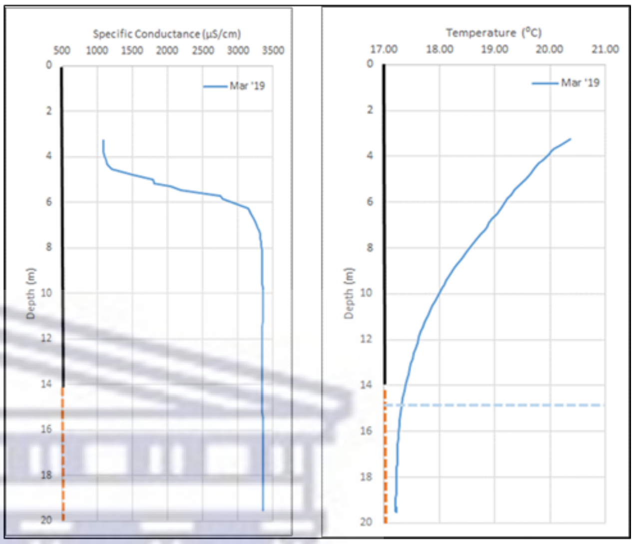


Figure 32: YSI down-the-hole logging results for BH 19, Spanjaardskloof.

d. Groundwater levels and temperature fluxes

The boreholes at Spanjaardskloof are located on a hillslope with elevation varying from 145 to 179 m above sea level. The two sets of boreholes are 385 m apart (Figure 34). This included the existing two boreholes (BH9 and BH10) and the newly added boreholes (BH18 and BH19).

Unfortunately, there is not water level data available for BH18 and BH19. Water logger in shallow borehole was faulty and the deeper borehole has a pump stuck in it that cannot be removed after trying different techniques. The pump got stuck during a pump test when the cable snapped and the pump dropped down 50m down. Recovery of pump was unsuccessful.

The water table in the deep borehole (BH9- 60m) at Spanjaardskloof responds after rainfall exceedance of 20 mm/day (Figure 34), while, the water table in in the shallow borehole (BH10 – 20 m) rises quicker in response to rainfall, which is likely due to quick downward preferential flow. After the water table has risen by 3 – 4 m it declines to the original level within 1 – 5 days (Figure 34).

There is no clear relationship between water temperature and the change in depth of the water table (Figure 35). From July 2018 to September 2018 the water temperature in the 60 m borehole decreased from 18.0° to 17.3°C and remained constant even though there is a increase in the depth to water table from June 2020 to November 2020.

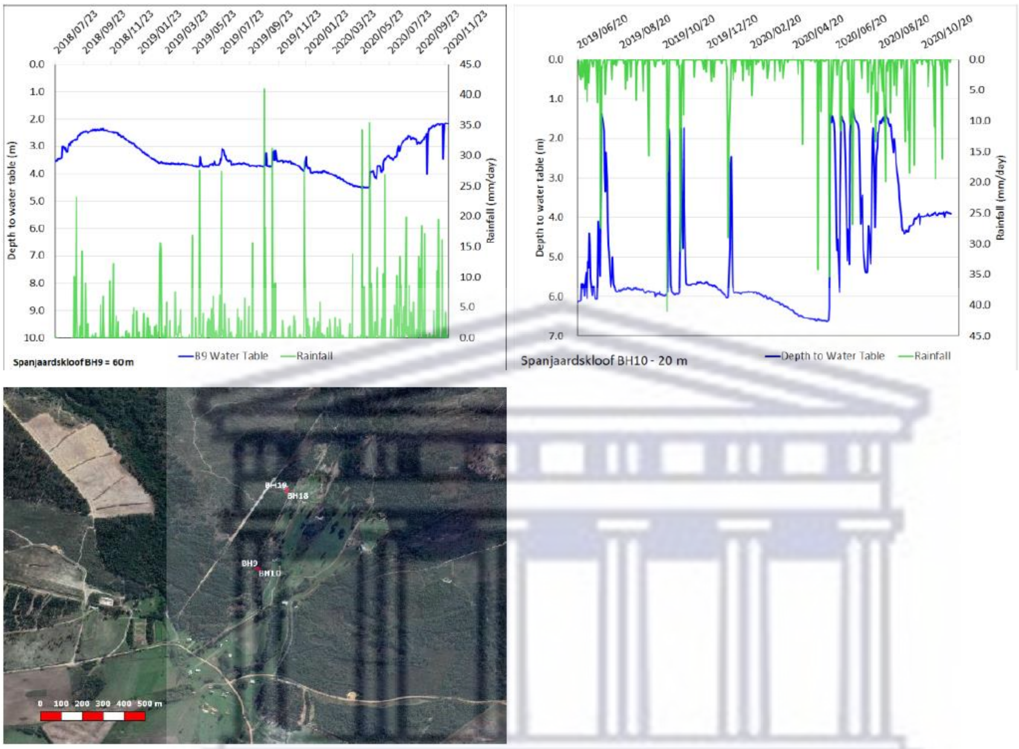


Figure 34: Temporal variations of depth to water table at Spanjaardskloof, and layout of boreholes. Boreholes at the southern part are at 145 m while northern boreholes are 179 masl. (Source Layout: Google Earth Image)

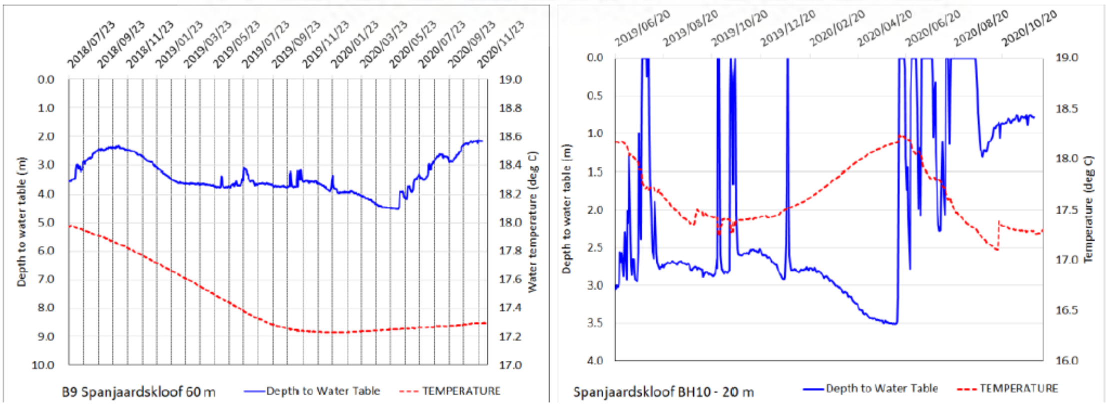


Figure 35: Water temperature in the Spandjaardskloof boreholes

5.2.4 Jan Swartskraal

a. Geophysics results and interpretation

Electrical Resistivity data was collected over 400 m to display a subsurface profile at the Jan Swartskraal site (Figure 36). This profile shows a high degree of variability in resistivity with uniform increase in resistivity deeper into the subsurface until it reaches a bedrock. The bedrock is represented by high resistivity from 40 m deep with high resistivity values ranging from 600 to > 1111 Ω m.

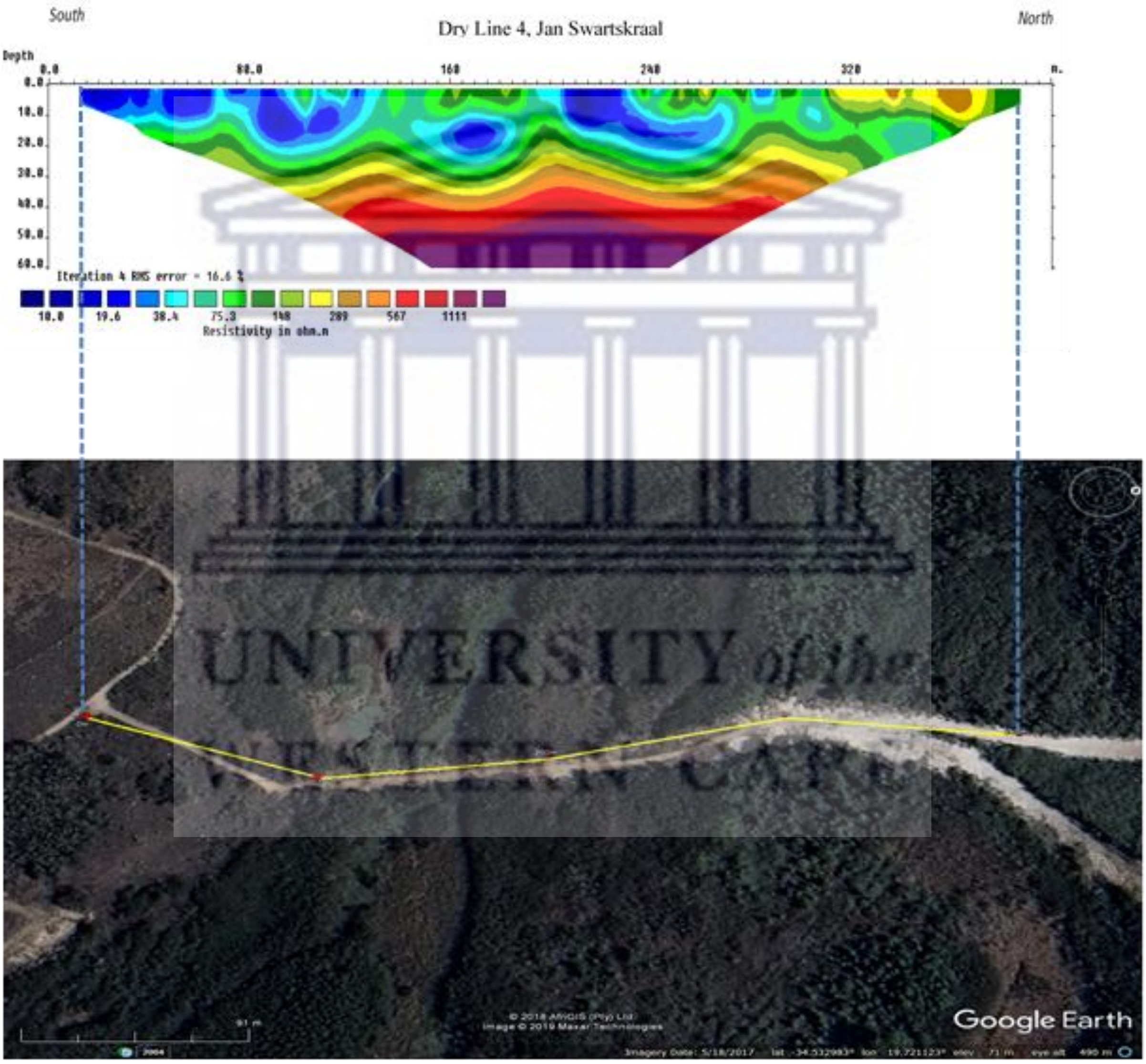


Figure 36: Electrical resistivity survey at Jan Swartskraal. The transect for the electrical resistivity was done on a S-N transect corresponding to the Google Earth image

Compared to the other profiles done in the catchment this profile shows a deeper weathered zoned that is about 30 m deep on the resistivity profile with low resistivity value of generally < 100 Ω m . Within the low resistivity zone, the data suggests presence shallow water table close to the surface. This is true compared to field observation done in the wetter period when this particular site is flooded after a rainfall event. In accordance to table created by Adeeko & Nordiana (2018), these low resistivity value indicate presence of clay and groundwater (fresh).

b. Borehole lithology logs

This site is situated in the midslopes of the catchment within the Malmesbusy group along a fault line. The site is newly established site with 2 boreholes BH26- 50m and BH27- 7m.

BH26 This borehole was drilled to a depth of 50 m. The first 1 m showed brown weathered coarse sandstone. Thereafter the lithology showed a thick layer of shale (2 – 29 m) with the first 4 m being weathered. A change of the lithology then occurred from shale to medium grained sandstone up until 50 m and this is when the water was struck at 30 m depth. Whilst, **BH27** 7 m shallow boreholes had coarse sandstone first 2m, followed by shale for the last 5 m.

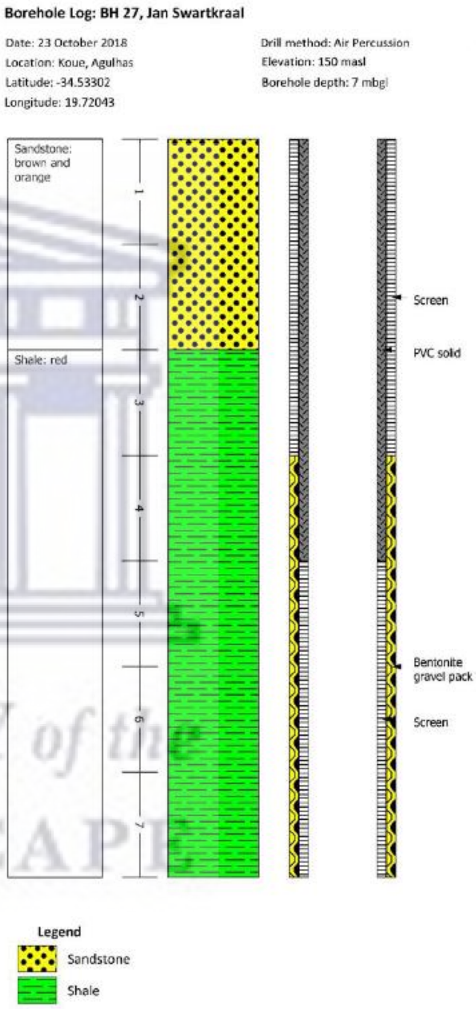


Figure 37: Drilling log of the 7 m borehole at Jan Swartkraal.

c. Hydraulic test (Pump test and Slug test)

The Jan Swartskraal site consists of two boreholes of different depths to measure groundwater-surface water interactions in relation to a tree evaporation site also installed here. At this site the interest was to determine main water sources feeding alien vegetation by looking at its interaction between the Jan Swartskraal River and the different groundwater zones. BH 26 (50

m) and BH 27 (7 m) intersect different weathering profiles with depth, consisting of sandstone on the surface, overlying shale from a depth of 2m. Both sets of hydraulic properties will therefore represent shale properties.

A constant discharge test was conducted on BH 26 during April –May 2019. The pump was lowered to a depth of 44 m, while the borehole depth was measured at 50 m.

The step drawdown test for BH 26 was conducted at respective rates of 0.25, and 0.6 litres per second (l/s). Each rate increased respectively after an hour interval.

Based on the results of the step drawdown test, the constant discharge test for BH 26 was conducted at a rate of 0.5 l/s. The static groundwater level was 6.75 mbgl before the test commenced, and the total drawdown after completion of the test was 14.8 m. At cessation of the constant discharge rate test, the water level showed very good recovery and returned to static conditions after 90 minutes of recovery.

The test results for BH 26 are illustrated in Figure 39 while Figure 38, Figure 40 and Figure 41 depict the results from the AqteSolve analysis.

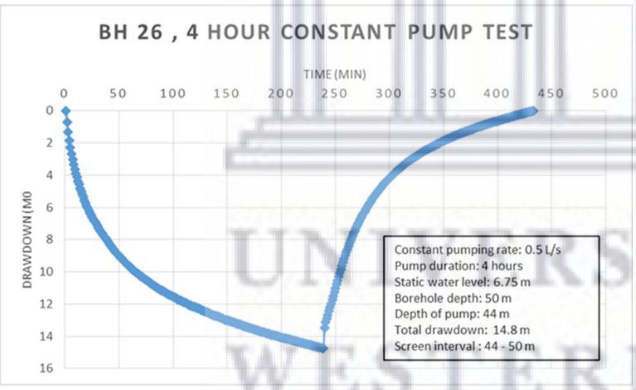


Figure 41: Drawdown and recovery from a 4-hour pumping test for BH26, Jan Swartskraal

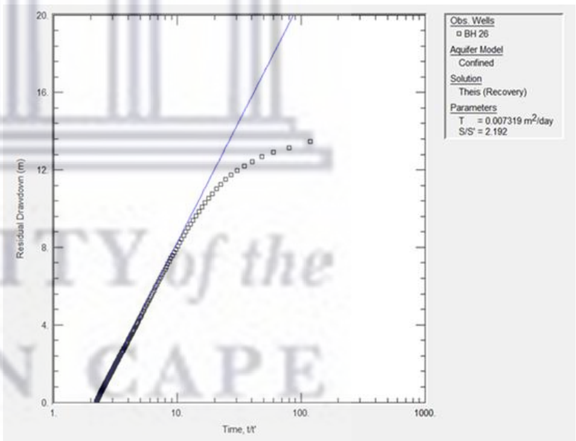


Figure 40: A 4-hour aquifer test at 0.5 l/s interpretation results using Theis Recovery r

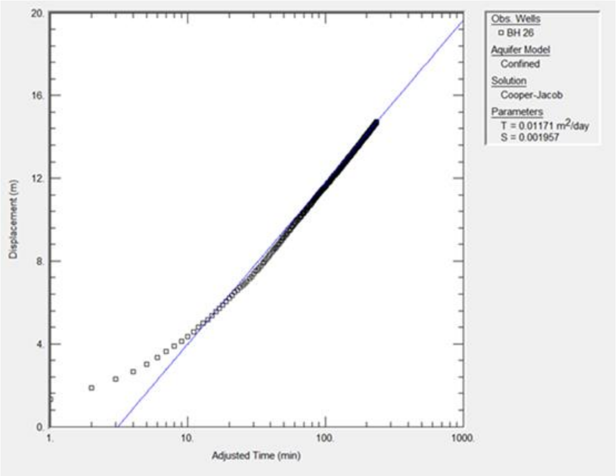


Figure 39: A 4-hour aquifer test at 0.5 l/s interpretation results using Cooper-Jacob method.

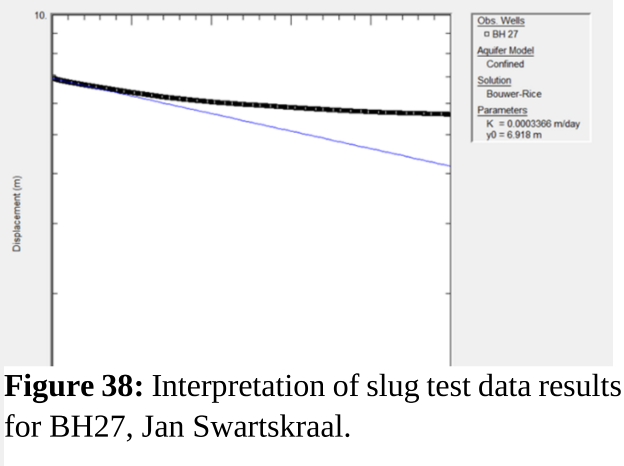


Figure 38: Interpretation of slug test data results for BH27, Jan Swartskraal.

d. Downhole EC and temperature logs

There is a notable increase in the EC in BH 26 at about 25m before and after pumping, which could indicate a presence of more saline groundwater at that depth. Before pumping, there was a large increase in EC with depth, whereas after pumping there was only a slight increase in EC with depth. Before pumping, groundwater could have been stagnant or flowing at a very slow rate and possibly still influenced by drilling processes. (Figure 43 and Figure 42).

The temperature profiles of BH 26 show groundwater flow changes due to pumping, with the warmer water from the screen section flowing up the casing after pumping.

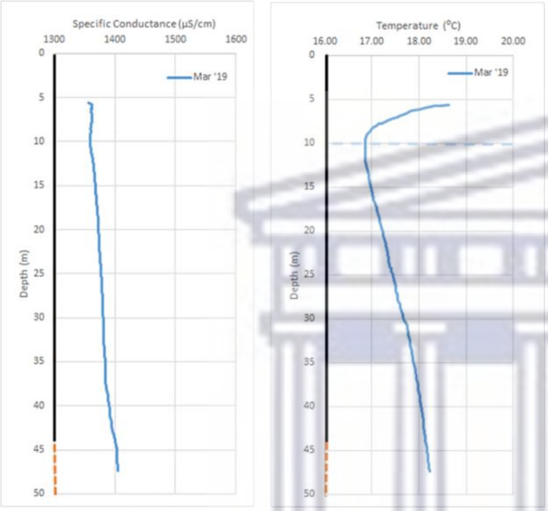


Figure 43: YSI down-the-hole logging results for BH 26, Jan Swartskraal 50 m. Initial log prior to pumping test, in March 2019.

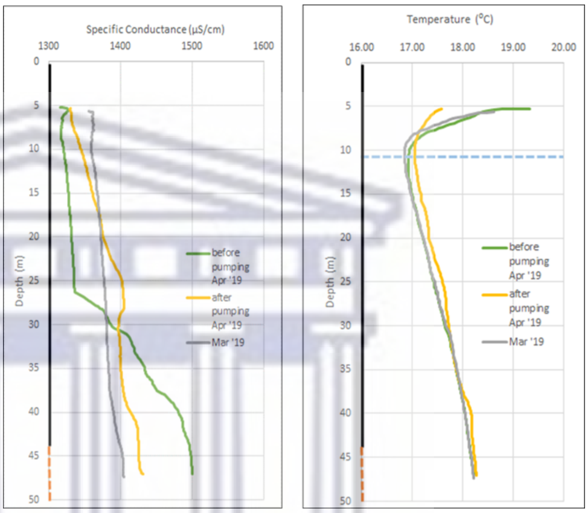


Figure 42: YSI down-the-hole logging results for BH 26, Jan Swartskraal 50 m. Initial log prior to pumping test, March 2019 and pre/post pump test, in April 2019.

e. Water level and temperature fluxes

The depth to water table in both the deep and shallow boreholes at Jan Swartskraal site show similar trends with response to rainfall events. The 7 m borehole dried during the May 2020 period the same period the pump test took place between April - May (Figure 44). In comparison to the pump test, it is evident that the borehole did not recover, however after receiving rainfall in June of above15 mm/day the water table rose in both the deep and the shallow borehole, with distinct increase in the shallow borehole. It is assumed that the recharge to the shallow aquifer is from rainfall.

The hydraulic head in the deeper borehole is higher than the shallow borehole, which indicates groundwater flow from the deep to shallow aquifer, possible connectivity. Deep groundwater is contributing to the shallow aquifer especially during the dry period up to June 2020. After the June – July 2020 wet period, the water tables are at the same level.

Groundwater intercepted by the 50 m borehole (BH26) at Jan Swartskraal does not experience temperature changes which is similar to observations at Sandfontein and Tussenberg (Figure 44). The shallow borehole show inverse relationship between temperature and the water table. The dryer the borehole becomes the temperature increases.

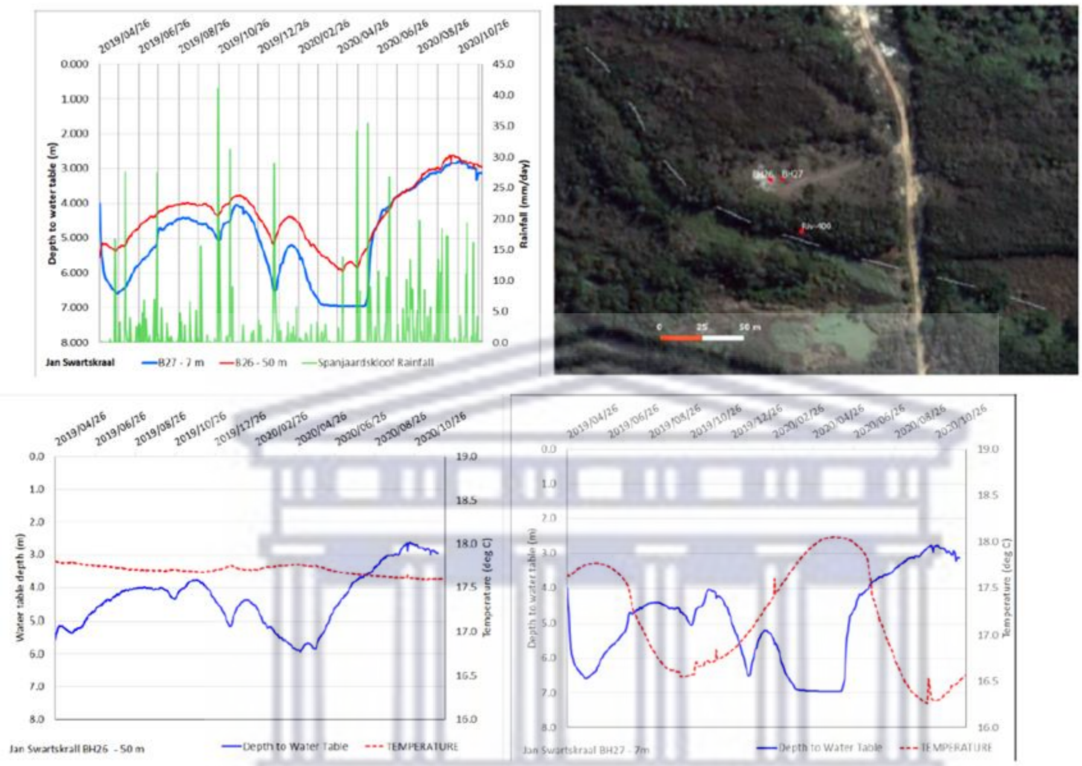


Figure 44: Variations of the water table and water temperature in boreholes at Jan Swartskraal, and the layout of boreholes. Riv-400 is the location of the river. (Source Layout: Google Earth Image

f. Environmental stable Isotopes

Isotope sampling at the Jan Swartskraal site commenced in July 2019. The Isotope signature of the river at this site, was not particularly more similar to BH27 (7m shallow borehole) or BH26 (50m deeper borehole), although a slightly smaller margin between compositions of the river and BH27 (7m) were observed. Isotope compositions of the river with BH 26 (50m) and BH 27 (7m) at this site differed by a margin ranging between approximately 6 -10 ‰ for δ2H and 1-2 ‰ for δ18O. The river was more similar to BH 27 (7m), although not by a large margin. The dual isotope plot also indicates that the river and groundwater samples plot in similar regions, however a close look shows no clear overlap between the river and groundwater samples at this specific site. Based on the isotope analysis conducted, interactions between the shallow and deep aquifer at this location require further investigation. A continuation of data collection and the use of radon as a tracer, going forward, could give more definitive findings, at such sites, where some level of uncertainty exists. The assessment the water table at this location, also indicates that the Jan Swartskraal river at this site is a losing stream, since the water table of BH 27 and BH 26 is always below the river bed. This results can be found in Appendix 2 _ Figure 59.

5.2.5 Boskloof

a. Geophysics results and interpretation

Resistivity was measured along a 400 m W-E transect on the western side of Boskloof River, and another 400 m W-E transect immediately to the east of this river (Figure 45). The western side of the river has land being prepared for flower production, while pastures and a eucalyptus plantation are on the eastern side.

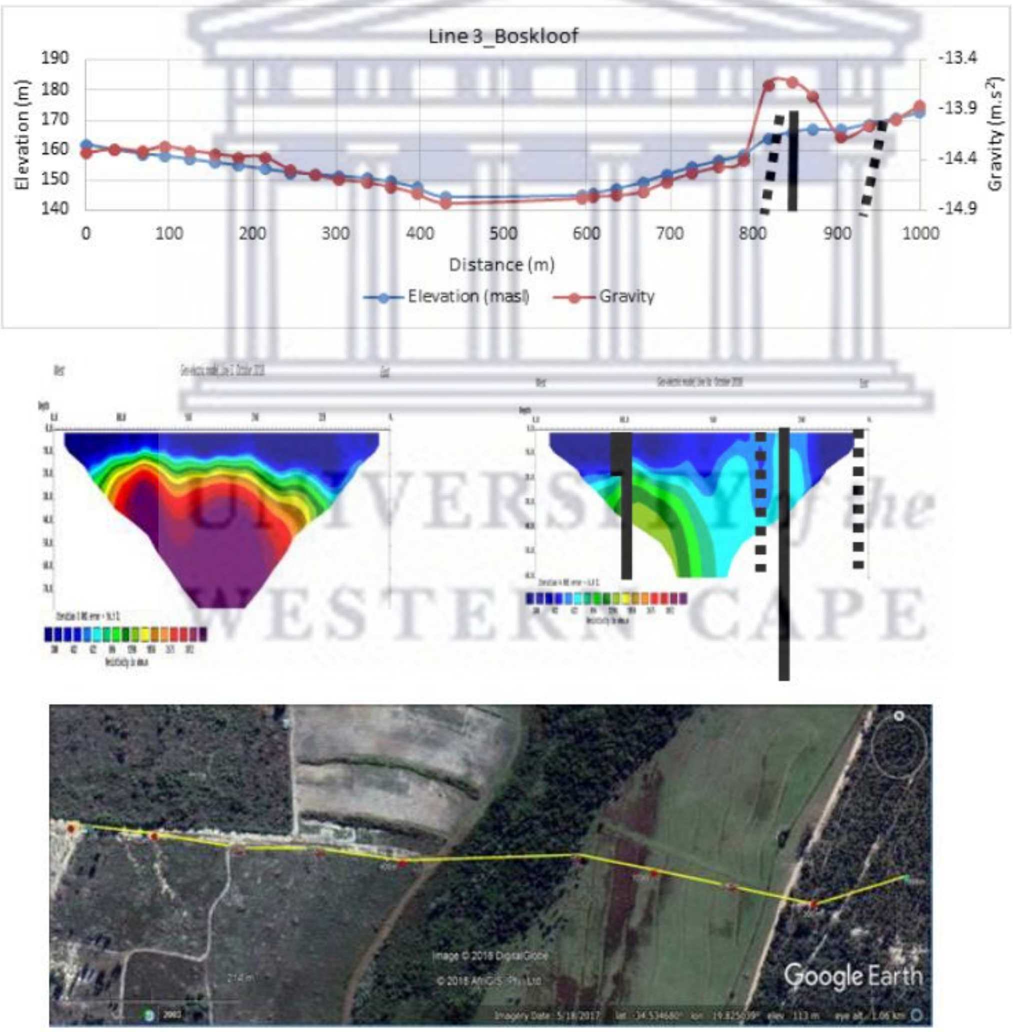


Figure 45: Gravity and electrical resistivity survey at the Bosklook site. Resistivity surveys were undertaken on both sides of the river.

Gravity anomalies one the eastern side (Figure 45) suggests the existence of a fracture on the upper part of the transect. No significant differences in gravity anomalies were detected on the western side. Resistivity values are less than 300 Ω m up to a depth of 20 m along the whole transect. This suggests the occurrence of sandstone which contains water. High resistivity values, > 2000 Ω m, were inferred at depths greater than 20 m along the transect on the western side of Boskloof River. The eastern side had in contrast resistivity values of 700 – 1000 Ω m at depths greater than 20 m. A zone of low resistivity values was observed at the location where gravity anomalies suggested the existence of a fracture. These relatively low resistivity values are due to weathering along the fracture zone that increase permeability and the occurrence of water.

b. Borehole lithology logs

Groundwater monitoring was undertaken at this site to establish whether there is an connectivity between groundwater at varying depths with the Boskloof River. The transect has a 5% gradient and covers pastures. BH 21 (60 m) was completed on 13 October 2018, BH 22 (20 m) on 14 October 2018, and on 17 October 2018 BH 23 (6 m).

BH 20 This borehole was drilled to a total depth of 100 m. The top 3 m had brown sandstone followed by 10 m of fine orange sandstone. Thereafter, fine grained sandstone occurred from 4 to 37 m, and was ultra-fine from10 to 17 m. The sandstone was orange from 4 to 13 m, and then white until 17 m. At 18 m, rock pieces were observed. From 38 to 100 m there was alternating medium grained sandstone followed by coarse grained sandstone. Quartz was observed from 50 to 61 m. Weathering of sandstone was evident from the surface up to 37 m.

BH21 This borehole was drilled to a total depth of 60 m below ground level. The top 25 m had weathered sandstone. The top 2 m had a brown colour followed by 2 m of clay that was orange in colour. Very coarse grained sediment with 5cm stones occurred from 7 to 12 m. Medium grained sandstone occurred from 13 to 26 m, 27 to 60 m there was an alternation of coarse and medium grained sandstone that was cream or orange in colour. Clay was noted at 33 - 35, 49 and 56 m.

BH 22 This borehole was drilled to a depth of 20 m. The very top layer had a brown muddy soil followed by 3 m of clay. An orange, medium grained moist sandstone was noted for 2 m followed by 7 m of very coarse sandstone with approximately 5 cm stones. The remanding 7 m was medium grained alternating orange and cream sandstone.

BH 23 This borehole was drilled to a total depth of 6 m which was were weathered. The first meter had muddy soil with stones followed by a meter of orange soil and then 2 m of cream clay and sandstone. The final 2 m were orange medium grained moist sandstone.

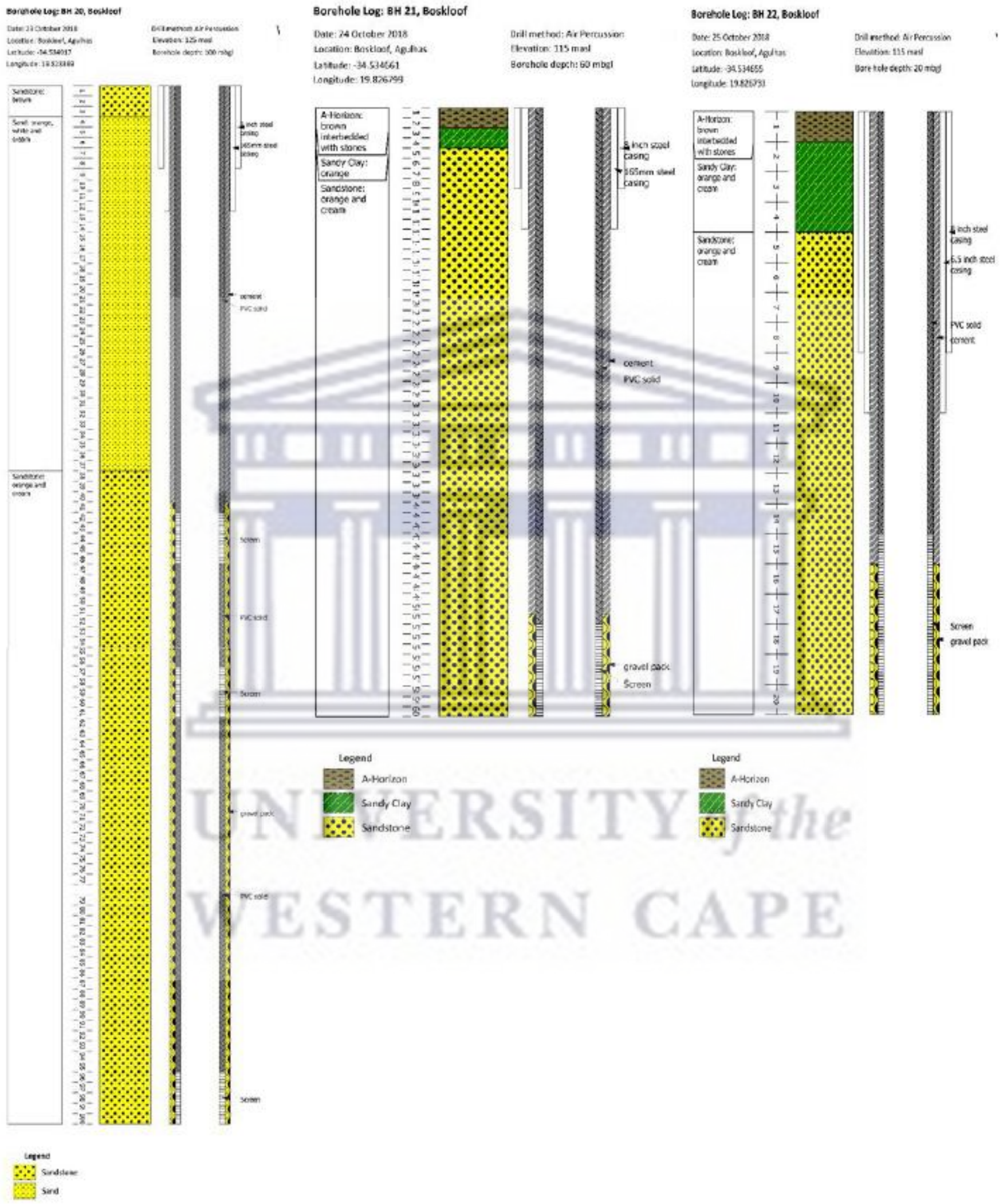


Figure 46: Drilling log for the boreholes at Boskloof

c. Downhole EC and Temperature logs

Referring to BH 20, there are groundwater inflows at about 42m and about 85m, depicted by a sharp increase in EC that is steady at those depths. Temperature increases with depth, with changes in the temperature gradient, confirming the groundwater inflow (Figure 48). The EC increases slightly with depth.

The temperature log of BH 22 shows groundwater flow through the aquifer above 15m, where temperature gradient is reversed. EC remains constant throughout the borehole (Figure 49) with a similar shallow aquifer value compared to BH21.

At BH 23 the EC and Temp seems to correspond to the middle section of the BH21 log, potentially corresponding to a discharge of the deeper water in this section of the aquifer (Figure 47). This need to be confirmed with the geochemical sampling whether these aquifer sections are linked.

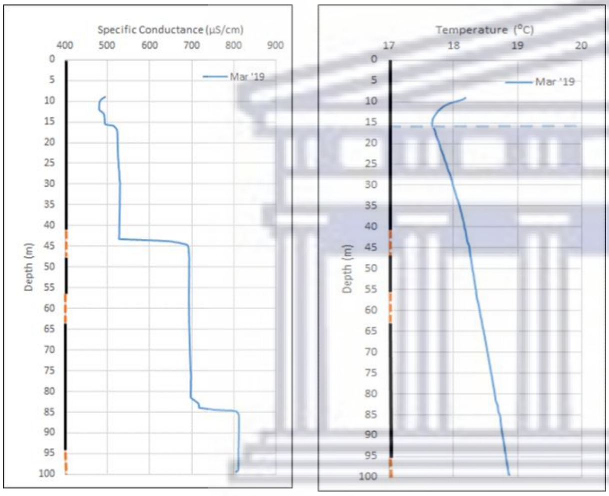


Figure 48: YSI down-the-hole logging results for BH 20, Boskloof 100 m.

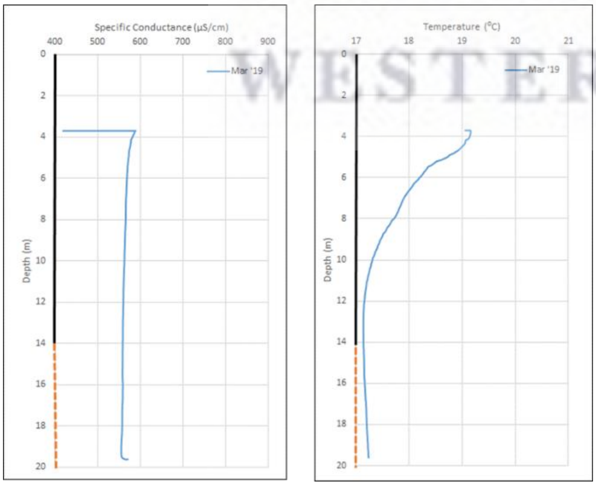


Figure 49: YSI down-the-hole logging results for BH 22, Boskloof 20 m.

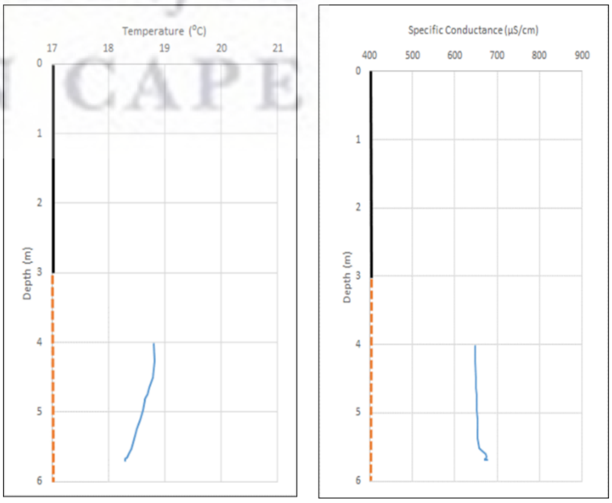


Figure 47: YSI down-the-hole logging results for BH 23, Boskloof 6 m. Initial log prior to pumping test, March 2019

d. Groundwater levels and temperature fluxes

This site is situated highland and presents the deepest groundwater levels comparted to other sites through the catchment, with an average of 10 m water level, however, this site doesn't display the highest elevation. The Boskloof site has 6 boreholes along an east-west 220 m transect descending towards the Boskloof Stream. Borehole depths range from 6 to 100 m. Sandstone occurs throughout with the exception of the 6 m borehole which has sandy clay, 3 – 4 m. Water level loggers occur in the 20 m and 60 m deep boreholes that are 5 m from each other. These boreholes are located at at the top of the valley slope. There is no difference in the depth to the water table in these two boreholes (Figure 50), which suggest that groundwater occurs in a single aquifer. Boskloof site initially show no significant changes during dry and wet periods for both shallow (BH11) and deep (BH12) boreholes up until March 2018, thereafter, there is a major shift in the groundwater levels due to pump test, it took a few months for boreholes to recover and stabilise. Boreholes at this site show gradual delayed response to rainfall. The water table declined to 12.6 m below ground level in June 2020, and by October 2020 had risen to 10 m.

Groundwater temperature in the deep aquifer, BH11 – 60 m at Boskloof did not change significantly during the monitoring period (Figure 51). Very little cooling occurred in the 20 m borehole (BH12) when the water table depth rose.

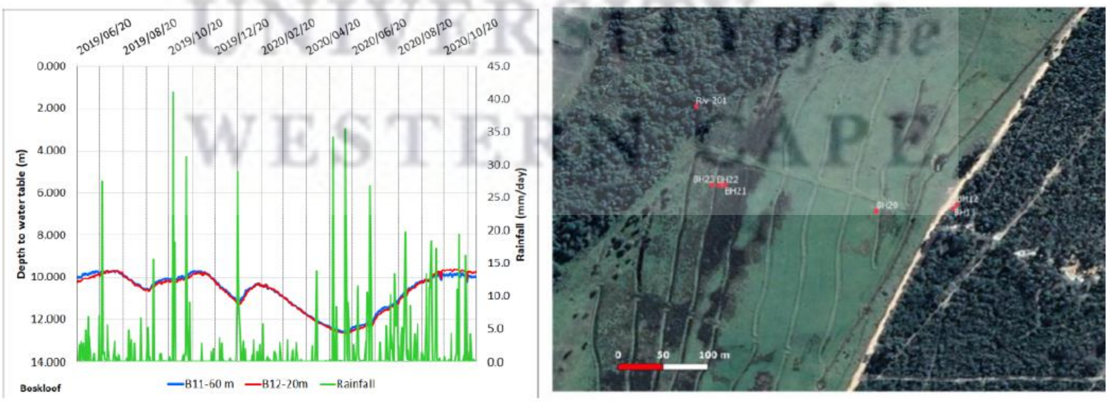


Figure 50: Water table fluctuations in the Boskloof boreholes, and the layout of boreholes along the valley slope with Boskloof River (Riv-201) on the western part. (Source Layout: Google Earth Image)

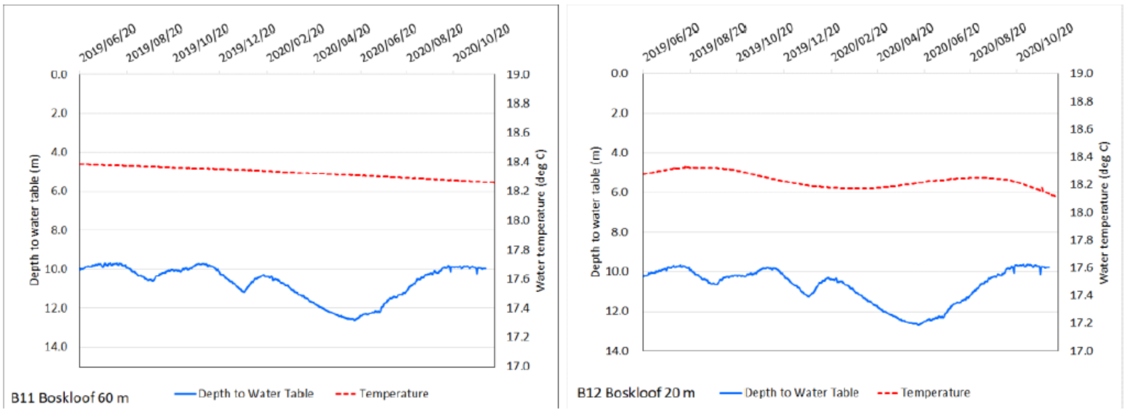


Figure 51: Water temperature changes for the Boskloof boreholes.

e. Environmental Stable Isotopes

Isotope data at this site is only available for October 2019, October 2020, November 2020 and December 2020. The Boskloof River in October 2019 had isotope values similar to those of both BH12 (20 m shallow borehole) and BH11 (60 m deeper borehole) with a marginal difference of approximately 2 ‰ for δ2H and less than 1‰ for δ18O. Meanwhile, the difference between river water and other boreholes at the site during this period (BH21- 60 m, BH22 - 20 m, BH23 – 6 m) was approximately 5 ‰ for δ2H and greater than 1‰ for δ18O. The similarities in isotopic compositions between the river and groundwater were not as pronounced, although still similar between the period of October 2020 to December 2020 between the river and BH11 (60m), BH12 (20m), BH21(60m), BH22(20m) (margin difference greater than 7 ‰ for δ2H and 1‰ for δ18O). Meanwhile, the river at this site and the shallow borehole BH23 (6 m shallow borehole) had very similar isotopic composition between the period of October 2020 – December 2020, with the difference usually being less than 3‰ for δ2H and 1‰ for δ18O. The results obtained in October 2019, give an indication of an interaction between the river and both the deep and shallow aquifer at this site. While, the results obtained between October 2020 and December 2020, mostly indicate the existence of a stronger interaction between the river and shallow aquifer, as compared to the deeper aquifer. Data at this site is limited, and only includes the period between October to December, which does not cover the bulk of the 2019 and 2020 year. A more extensive data set that includes data from earlier and later months of the year is required to make better conclusions.

5.2.6 Moddervlei

a. Geophysics results and interpretation

Gravity and electrical resistivity were measured along an 800 m long W-E transect running across the Nuwejaars River flood, also known as the Moddervlei (Figure 52). No major differences in gravity were measured on the western floodplain. The increase in gravity anomalies on the eastern floodplain could be indicative of sand/alluvial deposits within the flood plain. Very low resistivity values, < 10 Ω m, occurred along the western side up to a depth of 20 m (Figure 52). Such low resistivity values are likely due to sand material or weathered sandstone with saline water. On the eastern side, the zone with low resistivity values is inclined downwards. This could be due to an incline in the zone with saline water. Alternatively, salinity is reduced at shallow depths due to annual recharge of freshwater overflowing from the Pieterseiskloof River.

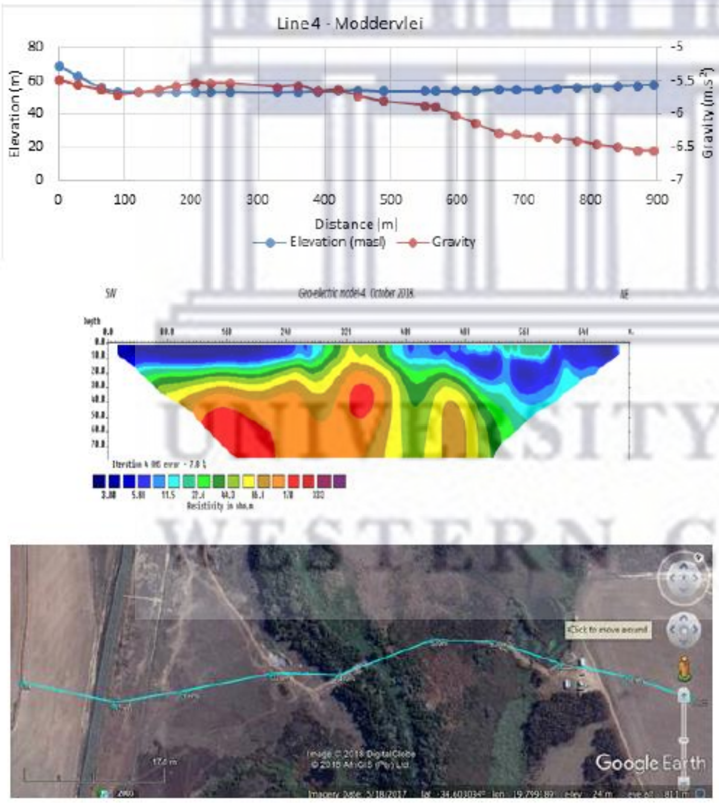


Figure 52: Gravity and electrical resistivity survey across the Nuwejaars River floodplain at Moddervlei

b. Borehole lithological logs

The lithology of this site Moddervlei falls part of the Bredasdorp and Bokkeveld geological group. These geological groups are made up of sandstone, minor siltstone, shale and undefined

Ceres subgroup under the Bredasdorp group. The first 1 m had road gravel which was expected as the borehole is about a 1 m away from a gravel road. This was followed by muddy and blackish soil (2 – 7 m). A thick layer of clay was present for 13 m below the blackish soil, and thereafter shale along the remaining 38 m. This shale layer was fine grained (22 -30 m), then medium grained (31 – 34 m), and finally coarse grained from 36 to 60 m in depth. BH 25 was drilled to a depth of 7 m and had subsurface material similar to BH 24 (Figure 53). This lithology properties yield low hydraulic conductivity, very low potential of groundwater – surface water interaction to take place.

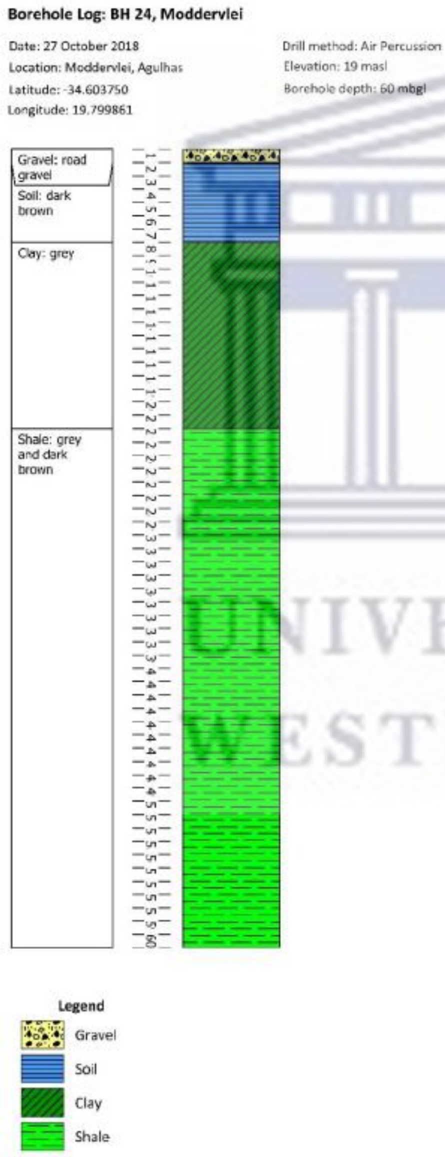


Figure 53: Drilling log for the 60 m borehole on the eastern floodplain on Nuwejaars River at Moddervlei

c. Hydraulic test (Slug test)

A slug test was conducted on BH 24 (Figure 55) in May 2019 to quantify the hydraulic conductivity. The slug test was repeated three (3) times to ensure saturation. The transducer that was installed in the borehole was set at a 20-second time interval, and it was left in the borehole to take readings until water level was representative of the SWL reading prior to the slug test. While doing the test this borehole showed quick response during the slug test. After the slug test, manual measurements were taken at a 1-minute interval in conjunction with the readings from the electrical contact water level meter. After 15 minutes there was a 100 % recovery of the water level.

Additionally, slug test conducted on BH 25 (Figure 54) in May 2019. The slug test was repeated three (3) times to ensure saturation. The transducer that was installed in the borehole was set to a 30 second time interval, and was left in the borehole to take readings until water level was representative of the SWL reading prior to the slug test. This borehole also showed quick response during the slug test (similar to BH 24) which is just situated 3 m apart. Every minute after the slug test manual measurements were also taken using an electrical contact water level meter. After 10 minutes there was a 100% recovery of the water level

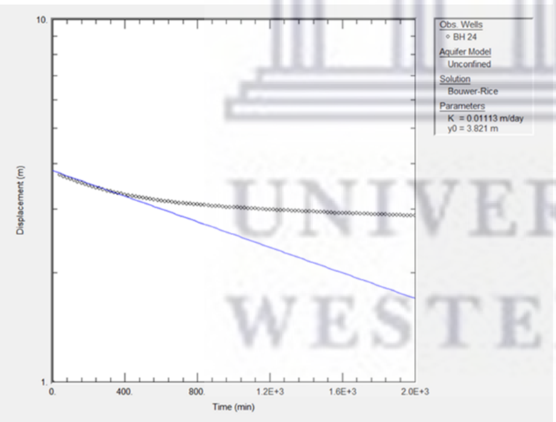


Figure 55: Interpretation of Slug test data results for BH24, Moddervlei

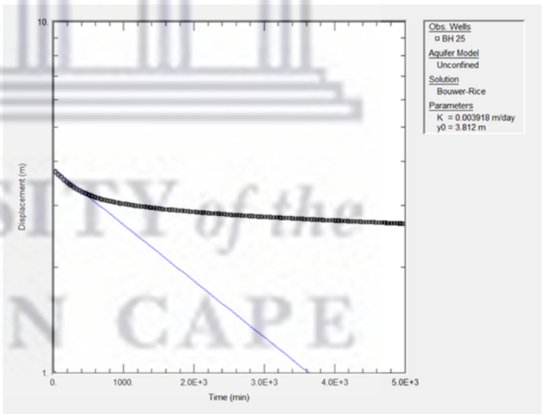


Figure 54: Interpretation of slug test data results for BH25, Moddervlei

d. Water level and temperature fluxes

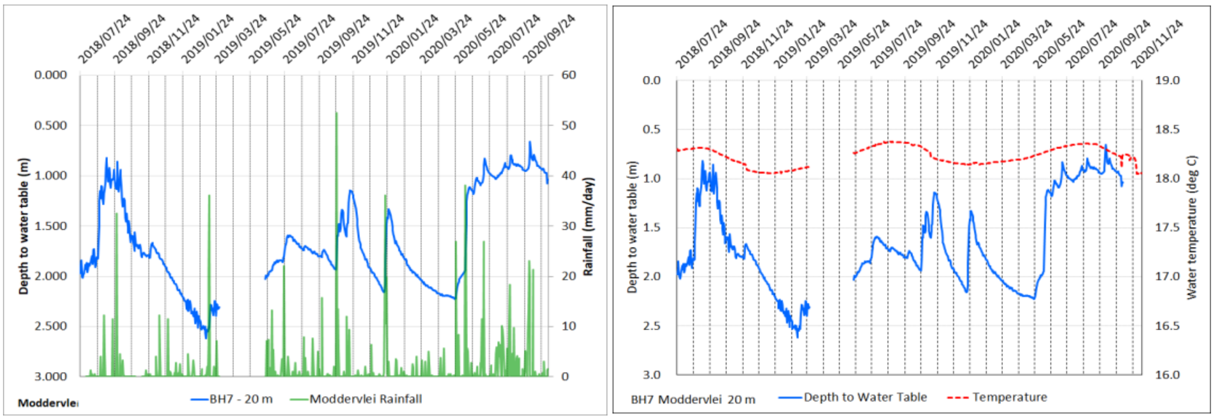


Figure 56: Water table and temperature fluctuations BH7 borehole at Moddervlei.

The Moddervlei site has 7 boreholes with depths ranging from 7 to 50 m. Silt occurs in the top 1 m, followed by 5 – 10 m clay, and then shale. Water level loggers occur in 2 boreholes. The 20 m borehole has reliable data (Figure 56). The water table responds quickly to rainfall over 20 mm/day. The 65 mm rainfall received over two days in early June 2020 caused the water table to rise from about 2.0 to 1.0 m. Flooding due to ponding of high rainfall events that occasionally occur enhances recharge at Moddervlei.

e. Environmental Stable Isotopes

Isotope data at this site is available from March 2018 to December 2020. Isotope compositions of the river at Moddervlei shows variations especially between the period of March 2018 and February 2019 (Appendix 2_ Figure 59). The river sample at this site was isotopically similar to groundwater from both the shallow and deep aquifer (BH4-50m, BH5- 20m, BH6- 50m, BH7-20m, BH8-8m), usually measuring a margin difference less than 5‰ for δ2H with the exception of the months of March 2018, July 2018 and February 2019. Clustering on the isotope plot between the river samples and groundwater can be observed on the isotope plots, whereby both the shallow and deep aquifer seem to feed the river during the majority of the study period.

5.3 Major ions

The major ions were generally present throughout the sampling campaign in all waters of the Nuwejaars Catchment and had the following order of abundance; chloride > sodium > magnesium > sulphate > calcium > bicarbonate > potassium over time for wet and dry season. Based on the proportions of cations and anions in groundwater and surface water, piper diagrams were generated (Figure 57). Groundwater and surface water in the study area belong to the sodium-chloride water type (Na-Cl water type), with exception to the outliers, which was possibly due to contamination during sampling or lab analysis phase. The similarities in water type between groundwater and river water indicate that these waters originate from a similar source. This suggests the occurrences of surface water – groundwater interactions within the study area is highly probable. Although piper diagrams give insight on the possibility of connectivity between the rivers and aquifers within the study area, these diagrams do not show differences in ionic concentrations between samples which would be necessary to establish the location of groundwater discharge zones. Concentrated and dilute samples may fall in the same position on the piper diagram despite the samples having vast differences in ionic compositions. This is a limitation of using piper diagrams to infer surface water – groundwater interactions.

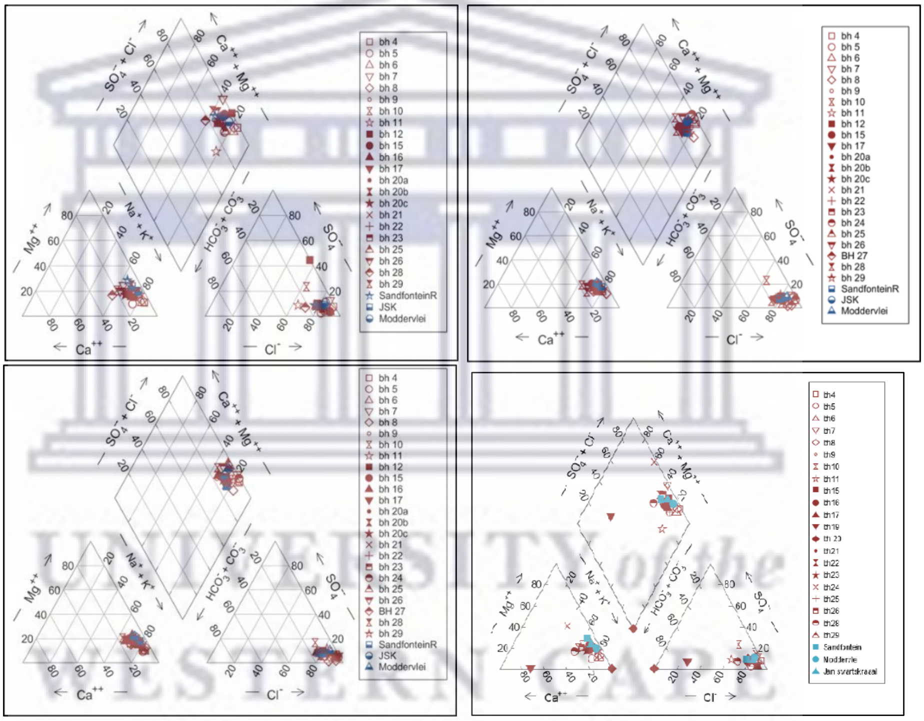


Figure 57: Piper diagram, showing similarities in ionic proportions of groundwater over time. A) June, B) July, C) August, D) November

5.4 Chapter Discussion

This section provides discussion of all the sites with regards to the results and findings obtained for objective one and objective two. Objective one is to characterise each study site from highland to lowland using multi-methodological approach using physical methods i.e geophysics, lithological logs of boreholes, down-hole logging, hydraulic tests, and using water level and temperature data from data loggers. Previous studies done by Kalbus et al., (2006) and Oxtobee and Novakowski (2002) proves that an integrated approach which encompasses the use of hydraulic test, lithology and geophysical logs proves to be useful for effective characterization of aquifer. It can also establish the potential nature of groundwater – surface water interaction based on the properties found, hence, this data was found to be useful for the present study.

Objective two focuses on determining the spatial – temporal variations of the water quality changes at the groundwater and/or surface water study sites. This objective will provide some insight on the gap found in previous studies done in the catchment, which found a need to improve an understanding of, and the capacity to predict spatial and temporal variations in GW-SW interactions, and their influence on available water resources (Parsons, 2004; Hughes, et. al., 2007; Tanner and Hughes, 2005). It is however, important to note that this system is complex and cannot be reviewed as having continually processes occurring from headwaters to lowlands. The properties are vastly different going downstream of the catchment at each study site, according to Banda (2019) and Manyama (2017) findings.

Based on the results, the majority of geophysical applications focused on characterising subsurface structure, revealing spatial variability in groundwater- surface water interaction and imaging hydrological processes (McLachlan et al., 2017). According to Freeze and Cherry (1979) surface geophysical methods cannot replace test drilling, but can give more in depth information about selection of the test-hole drilling which may lead to the lessening in the amount of drilling required. Thus, the data collected from the surveys being done was used in order to characterise the subsurface of the sites/ catchment as a whole and assisted with location for the boreholes to be drilled. The electrical resistivity profiles collected from highlands to lowlands show shallow weathering zones upland < 10 m deep while in the midslope show a deeper weathered zone with shallow water table (Low resistivity values). In the lowland area, Moddervlei the area was the only site that had no bedrock present, Very low resistivity values, < 10 Ω m, occurred along the western side up to a depth of 20 m. Such low resistivity values are likely due to sand material or weathered sandstone with saline water. The description of

Electrical resistivity values in accordance to material present in the subsurface was deduced by using a table created by Adeeko and Nordiana (2018) which aided the investigation of groundwater potential. The geophysical data according to Vouillamoz et al., (2012) and Manyama (2017) is not recommended to be used on its own but complemented with data sets (lithological logs and aquifer tests) to make sound conclusions based on the nature of groundwater – surface water interaction.

Aquifer test are widely used to attain aquifer hydraulic parameters, which influences groundwater movement and storage. The type of test done was a single-well test for all the sites. The reason behind the single-well test was based on the little to no response on the observation boreholes, which were observed. This could suggest that at those sites where aquifer tests were deployed can be classified as disconnected stream as explained by Winter et al., (1999). This type of river is seen in a study done by Lerner, (1996) where the author describes river as Remote stream. Similar condition was found by a study done by

The data obtained from the aquifer test was used to yield the transmissivity and hydraulic conductivity values presented in Table 8 and Table 9 found in Appendix 1. The results for transmissivity (T) show low values (see Appendix 1-Table 6). For the aquifer test done at Tussenberge, Jan Swartskraal and Sandfontein range between 0.0067 -0.011 m^2/day for transmissivity. The low transmissivity is associated with the weathered nature of the Table Mountain sandstone and the unfractured Bokkeveld shale formations, this was also discovered by Banda (2019). The sites show moderate drawdown suggest and low variation in in the saturated thickness during the test.

The electrical conductivity (EC) logging of natural water quality was conducted across all the boreholes in the study area to investigate fractures in the TMG boreholes and their effects on groundwater flow. According to the results obtained for Tussenberge, Spanjaardskloof, Jan Swartskraal and Sandfontein site indicate no major changes in the EC along the borehole depth, which indicates no major fractures present in the formation. Fractures are present in the multi screened deep (100 m) borehole located at the Boskloof site, according to the EC data, only slight changes in the temperatures are seen, whilst the other boreholes located at the site has no major changes in EC or temperature. Similarly at BH26, no changes in both temperature and EC is present indication no fractures.

The major ions data collected from both groundwater and surface water was used to create piper from wet season into the drier season (June, July, August, November) Using the piper diagram comparison was made based on the water type classified on the diagram. Overall both groundwater and surface water were classified as Na-Cl type water. The similarity in the major ion characteristics for both groundwater and surface water suggests the presence of connectivity between the two water sources as reported by Banda (2019) and Malijani (2020) whom both did major ion characterisation at different groundwater and surface water sites in the same catchment. However, further use of tracers would need to be used to assess or confirm this. Temporally, no distinct changes was observed based on piper diagram. Furthermore, this implies that all the water samples may originate from a similar geological environment based on the ionic ratios in the samples. This Na-Cl water type was similar to what was suggested by Madlala (2019) for the Berg River in Western Cape, South Africa, whom did a study based on spatial and temporal variations of surface water - groundwater interaction using multi-methodological approach.

A comparison of the isotopic signatures of surface water and groundwater can lead to the identification groundwater discharge zones within a catchment. Isotopes of the water molecule are particularly useful groundwater tracers because their composition is not usually altered by the medium through which water flows or by other elements of the water cycle. According to Levy and Xu (2012) isotopes of the water molecule δ2H and δ18O are also very useful tracers in the delineation of groundwater discharge zones and the quantification of groundwater discharge, because they can be applied in any kind of geological setting. Isotopic properties of water can therefore be used to assess interactions between groundwater and surface water. This technique was deployed in this study to assess nature of connectivity between groundwater and surface water. It was found that isotope compositions of surface water from the uplands had depleted δ2H and δ18O values, showing little to no evaporative signatures. According to Mencio et al. (2017), the lack of a distinct shift in isotope signatures of surface water from the meteoric line due to evaporation, especially during summer, suggests the influence of groundwater. The position of surface water samples from the uplands (Jan Swartskraal, Boskloof, Sandfontein, and Tussenberg) in relation to the LMWL remains constant and these samples also constantly plotted in the depleted quadrant of the dual isotope plot, near groundwater samples that suggests the input of groundwater in this region, based on the theory from Mencio et al (2017).

The differences in isotopic signatures between groundwater and surface water in the lowlands suggest little to no connection between the river and aquifer in the lowlands. Such differences can be observed between March 2018 to February 2019, during which isotope data for both the upper and lower regions of the catchment are available. The drilling report and geological observations, support findings that connectivity between the groundwater and surface water is limited in the lowlands show high variability. A study done by Ne´grel et al. (2003) similarily used stable isotopes (δ2H and δ18O) to characterise the spatial variations of isotopes inorder to understand the recharge zones. The study concluded that the stable isotopes of water (δ2H and δ18O) show that the alluvial (or riverbank) aquifer feeds the Loire River during the summer, but is not recharged by the river during flood periods in the winter. The alluvial groundwater thus has a purely local origin from precipitation. It is however important to note that the study done has a different climate. This temporal variation is seen in the lowland reaches of the catchment for current studies. The isotopic compositions of surface water and groundwater during the study period of Banda (2019) study period yielded same signatures as the present study.

The results proves the useful of using both physical and chemical method in assessing GW-SW interaction, identifying the type of connectivity at each site. Results and interpretations from each study site indicates how in the TMG group highland areas groundwater- surface water interactions takes place whilst in the lowlands in the more clay/shale areas of Moddervlei interaction between groundwater and surface water is variable depending on the season. In the mid-slope region of the catchment Jan Swartskraal show no signs of interactions, but with more extensive data better conclusions can be made.

Similarly to a study done by Banks et al., (2011) which focused on the spatial and temporal assessments done by using hydraulic, hydrochemical, and tracer-based techniques to determine the source and loss terms of the river and groundwater system and how their relative magnitude changes along the river from the catchment headwaters to low lands. This study was based in The Rocky River Catchment is located within Flinders Chase National Park on Kangaroo Island, South Australia. The current study followed similar approach. In addition, Banks et al., (2011) conclusion based on the nature of the connectivity (gaining or losing stream) was the common theme in all the results captured throughout the study period.

Chapter 6: The nature of groundwater – surface water interaction, conclusion and recommendations

6.1 Introduction

This study focuses on establishing the nature of groundwater - surface water interaction from mountain headwaters to coastal lowlands and to determine how these interactions influence the spatial-temporal variations of available water resources in terms quality at the catchment scale. Whilst objective one and two was covered in the previous chapter, this chapter will use the findings of the first two objectives to answer objective three and produce final conclusion and recommendations. The third objective uses data to characterise surface water and groundwater systems in terms of nature of connectivity within the catchment.

6.2 Nature of connectivity

In terms of the connectivity, this is argued using the literature provided by Winter et al., (1998) that states that interaction between groundwater and surface water can be classified as either gaining stream or losing stream. The interaction is regarded as gaining stream, when groundwater flows through the streambed into the stream whilst a losing stream is when water infiltrates through sediments to the groundwater. These statements are argued by Kalbus et al., 2006 with the addition that some streams or river reaches can be gaining at some reaches and losing in other reaches, similarly seen in this study, where there is an evident spatial variation along the Nuwejaars river from headwaters to lowlands.

This objective is based on the integration of several method combined in order to understand the nature of groundwater – surface water interaction with in the catchment. The different methods / techniques complimented each other and increased the integrity of developing sound conclusions at each site.

An assessment of the potential for streams losing or gaining water from groundwater was assessed by comparing the elevation of the water table with that of nearby river beds. Each of the research sites has boreholes drilled to different depths which allows an assessment of whether groundwater discharge occurs from either shallow and deep aquifers. The potential for a river to lose or gain water from groundwater can vary throughout the year depending on changes of water table elevation relative to the river bed level. The depth to the water table was compared with the altitude of the river bed to determine if there is a positive or negative hydraulic head between the two locations. A positive head indicates a potential for groundwater to discharge to the nearby river (gaining river), while a negative head means if a river has water, there is potential to recharge groundwater (losing river) Winter et al., (1998). This assumes that there is hydraulic connectivity. This comparison was done throughout the monitoring period (Figure 58). While a stream is located close to boreholes, groundwater in the immediate vicinity may not always flow to this stream, but to a lower point further distant from the boreholes.

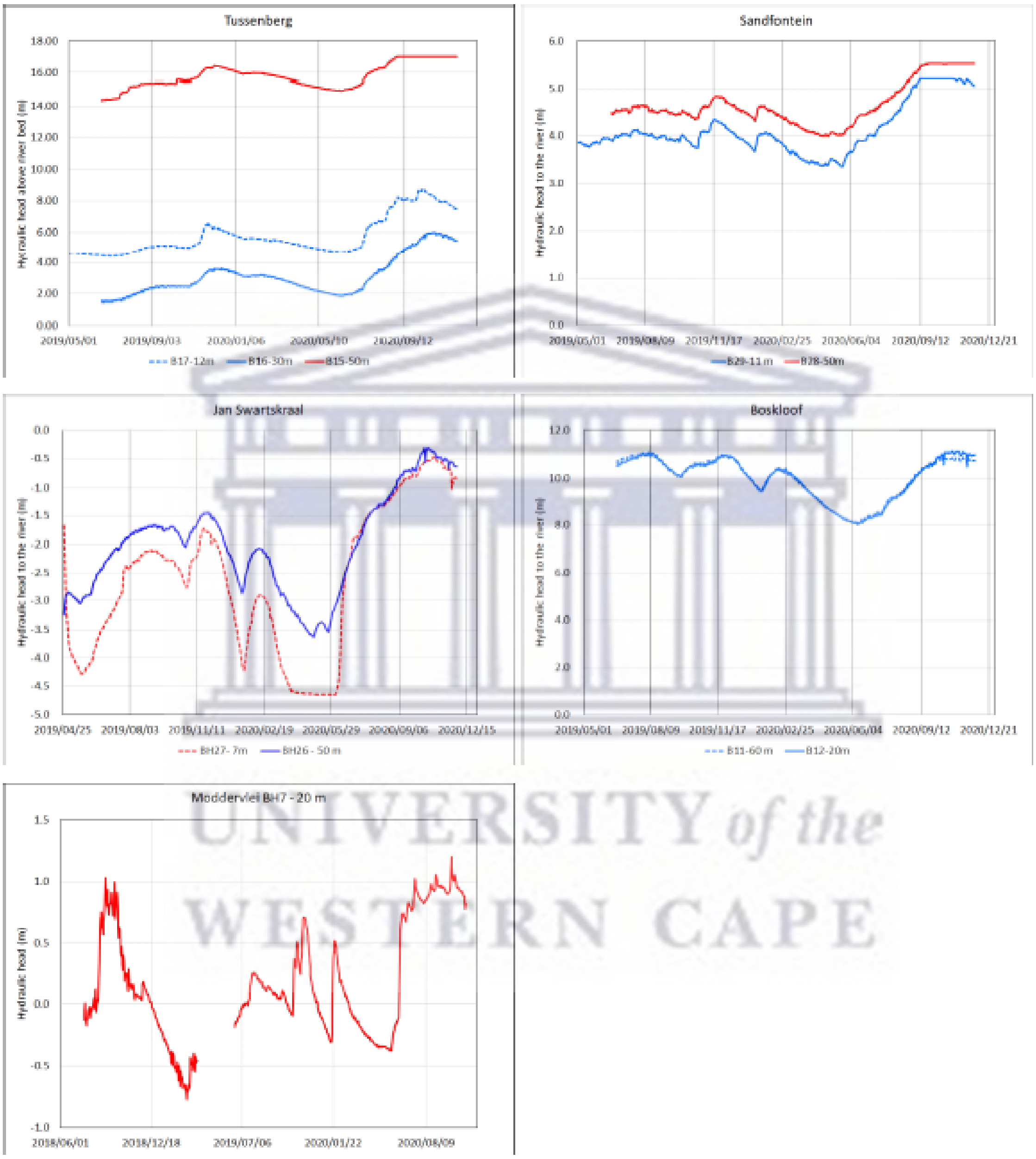


Figure 58: Elevation of the water table relative to the depth of the river bed of the nearby stream (+ve/-ve water table is above/below river bed). Tussenberg boreholes are 120 - 248 m from stream, Sandfontein, 58 – 60 m, Jan Swartskraal, 32 – 34 m, Boskloof 263 m, and Moddervlei 112 m.

There is a positive hydraulic head between groundwater and adjacent streams at Tussenberg, Sandfontein, and Boskloof. If there is hydraulic connectivity between these streams and the adjacent groundwater, the streams have the potential to gain water from groundwater. These streams have been observed to have flows throughout the year. The water table at Jan Swartskraal boreholes is always below the river bed (Figure 58). Therefore, Jan Swartskraal is considered a losing stream in the midslope region of the study area.

The midslope reach of catchment at Jan Swartskraal site does not receive groundwater recharge and is mostly dry during the year based on the water level data collected at the site for both surface water and groundwater. At this site there is dense woody invasive plants which could possibly be one of the reason for the water table mostly found to be below the river bed due to transpiration, however, this needs to be quantified.

The Boskloof site has in addition to the two boreholes with water level data loggers, 4 other monitoring boreholes without data loggers but with static water level measurements done monthly. A comparison of the elevation of the water tables measured manually and by data loggers at all the boreholes. This reveals that a positive hydraulic head with respect to the Boskloof River exists along the 262 m long transect. The topmost boreholes are at an altitude of 20 m above the Boskloof River bed. The electrical resistivity survey done before drilling revealed the occurrence of a low resistivity zone from top of the valley to the stream. Groundwater from the upper area flows towards the Boskloof stream. This is evident from frequent waterlogging towards the valley bottom, which suggests groundwater seepage.

The Moddervlei site is situated in the lowland regions of the catchment based on the results this site show high variability between the water table and the riverbed. It is found during the dry seasons there is no contribution from groundwater to the river flows. However, the isotopic signatures suggests that the groundwater is the primary influence to the river water quality. In contrary during the wet seasons groundwater does contribute to the river flows, this happens because of the thick clay / shale top layer of this area, causes slow infiltration rates that in turn causes flooding and formation of pond around the boreholes and surface water runoff into the river. Additionally, this site is over grown with alien invasive trees, which could possibly be causing the variability between the groundwater and surface water levels seen in the data collected and analysed.

To conclude this objective the analysis show evidence of streams in the upland region (Sandfontein, Tissenberge and Boskloof) gaining. The Jan Swartskraal in the midslope region of the catchment is characterised as a losing stream and the groundwater-surface water interaction at the lowlying area Moddervlei have a seasonal behaviour.

6.3 Conclusion

6.3.1 Characterisation of sites.

Objective 1 of the current study focused on characterising each study site, from headwaters to lowlands using multi methodological approach focusing on only the physical methods such as geophysics, borehole lithology logs, borehole EC and pH logs, aquifer tests and water level data. The aim was to discuss how aquifer permeability and groundwater levels determine how groundwater will flow into rivers, thus a thorough characterization of the aquifer. There are both primary and secondary aquifers in the study area. Considering that the formation surrounding the river channel has low hydraulic properties, groundwater movement is slow and the discharge to the river is slow as well. Based on the data it was found that the low-lying areas show poor hydraulic conductivity, this is due to the thick impermeable layer of clay/shale present at this site. The upland areas which is situated in sandstone have high hydraulic conductivity hence quicker responses to rainfall events. The geophysical cross- sections suggests that there are structural features present upstream of the catchment which yields pathways for water flow / interaction to occur through those faults. Downstream of the catchment shower higher electrical resistivity values that confirm that thick clay layer found at the Moddervlei site causing surface water runoff during the wet season and low water table during the dry season as well as no flow present in the River based on the conclusion that the main source of flow comes from rainfall events.

Based on the findings it is recommended:

1. The sites without automated water level loggers get loggers in order to make comprehensive conclusions of all the sites;

2. Hydraulic test need to be done at all the sites for longer period in order to understand the extent of connectivity and hydraulic properties of each site, and

3. Extensive studies on the effect of alien invasive plants on groundwater and surface water level need to be researched as this has not been quantified, whilst most of the catchment is overgrown with alien invasive vegetation.

6.3.2 Spatial temporal variation of water quality

Objective 2 of the current study focused on determining the spatial- temporal variation of water quality at each study site from headwaters and lowlands. This was aimed to highlight similar signatures of water quality at each site to confirm groundwater – surface water interaction. In order to do so the study used both major ions and isotope signatures to understand similarities at each site. Plotting the trilinear piper diagram of both groundwater and surface water over time for all the study sites within the catchment including rainfall, plotted within the Na-Cl quadrant of the piper diagram. This suggests that the water source for all the water samples collected originates from similar geological environment. This finding indicate that there is possible groundwater – surface water interaction within the catchment, as the ionic ratios are the same. The Na-Cl type water is generally characteristic of coastal aquifer, which is defined by saline deep ancient groundwater. This finding is comparable to a study done by Smart and Tradoux who showed that TaMG aquifes generally have Na-Cl dominated groundwater.

The stable isotope results show minimal temporal variations. The isotopic signature of groundwater and surface water are similar and clustered together. Which infers the same recharge source or interaction between groundwater and surface water. Most of the data points collected plotted below the meteoric water line, this suggests that before infiltration or recharge takes place evaporation processes occur. The deep groundwater, shallow groundwater and surface water points within the highland area of the catchment clustered together on the graph suggesting same water source and interaction between the sources. In the lowland area of the catchment, there is a significant difference in the evaporative processes which interferes with the signature of the surface water. There is an evaporative signature for the shallow groundwater the level of enrichment of the heavy isotope is not as large as the surface water.

More conclusive findings could have been made if there were site specific EC and pH data available. However, due to time constraints and limited equipment at hand the EC and pH data was not available and therefore recommended that monitoring of the current sites be continued with the full scope of water quality parameters in order to gain more conclusive evidence on the extent of the spatial – temporal variation of water quality within the study area.

6.3.3 Nature of interaction

Objective 3 of this study was to define the type of interaction taking place within the catchment by integrating the findings from both objective one and two with the addition of Elevation of boreholes compared to that of the nearest stream. The results clearly shows that there is a distinct difference in the processes occurring in the upland compared to lowlands. The sites situated upland of the catchment are gaining streams whilst the lowland areas i.e. Moddervlei show seasonal variation in the nature of interaction taking place. With the results found in objective one and two concluded that the nature of interaction in the highland area of the catchment at Tussenberge, Spanjaardskloof and Boskloof site are gaining streams. It was observed during the wet season when the water table rises saturating the surface, which forms runoff after more rainfall occurred. Thus, the shallow groundwater processes contribute to the river flows. This was seen mostly in the upland areas of the catchment. The interaction is confirmed by the isotope and the water type of both the groundwater and the surface water which show that the water source is similar/ the same.

Based on these findings study concludes that with ongoing investigations at sites and the addition of more sites the nature of groundwater – surface water interaction can be further investigated with a more quantitative approach as a recommendation. Radon data is also recommended to be added to the environmental isotopic analysis as it will be a valuable tracer to determine whether water with similar hydrochemistry and stable isotopes originates from a bedrock environment or from a surface water environment.

6.4 Recommendations

- The sites without automated water level loggers get loggers in order to make comprehensive conclusions of all the sites;
- Hydraulic test need to be done at all the sites for longer period in order to understand the extent of connectivity and hydraulic properties of each site, and
- Extensive studies on the effect of alien invasive plants on groundwater and surface water level need to be researched, as this has not been quantified, whilst most of the catchment is overgrown with alien invasive vegetation.
- Full scope of water quality parameters should be consistently monitored at sites in order to gain more conclusive evidence on the extent of the spatial – temporal variation of water quality within the study area.
- Radon data as an addition to the environmental isotopic analysis as it will be a valuable tracer to determine whether water with similar hydrochemistry and stable isotopes originates from a bedrock environment or from a surface water environment.

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Appendix 1: Details of the boreholes drilled including the drilling logs and geophysical profiles.

Table 6: Aquifer Borehole Testing Network Details for current study

BH ID	Description	Site Name	Latitude	Longitude	Elevation (m)	Depth (mbgl)	Water level	CD pumping test rate (l/s)
15	PB	Tussenberge	-34.477446	19.74491	205	50	3.5	0.1
16	OB		-34.477418	19.744954	212	12	7.5	
17	OB		-34.47683	19.74601	212	30	4.4	
9		Spanjaardskloof	-34.52958	19.75255		60		
10			-34.52961	19.75252		20		
18			-34.477418	19.744954	205	50	10.7	
19	Slugtest		-34.52628	19.75374	180	20	6.5	
20		Boskloof	-34.534917	19.828389	125	100	7.9	
21			-34.534661	19.826799	115	60	2.2	
22			-34.534655	19.826733	115	20	2.6	
23			-34.534670	19.720556	115	6	3.3	
4		Moddervlei	-34.60535	19.79761	21	50		
5			-34.60535	19.79758	21	20		
6			-34.60561	19.79758	21	50		
7			-34.60561	19.79753	21	20		
8			-34.60531	19.79741	21	8		
24	Slug test		-34.603750	19.799861	19	60	2.4	
25	Slug test		-34.603705	19.799722	21	7	2.3	
26	PB	JanSwartskraal	-34.533078	19.720556	150	50	5	0.5
27	Slug test		-34.53302	19.72043	150	7	5.6	
28	OB	Sandfontein	-34.488722	19.695000	231	50	1.1	
29	PB		-34.488722	19.694972	231	11	1.3	0.6

Notes:

CD - Constant Discharge

PB - Pumped Borehole

OB - Observation Borehole

m - Metre

mbgl - metres above ground level

l/s - Litres per second

Table 7: Represents information on the geophysical profiles that has been done at the sites from the current study, which includes data for Gravimetric and Electrical resistivity method.

BH Number	**Latitude**	**Longitude**	**Distance on line: ER (Wet) (m)**	**Distance on line: ER (Dry) (m)**	**Distance on line (m): Gravity**	**BH Depth (mbgl)**	**Screen Depth (m)**
15	-34.477446	19.74491	500	N/A	865	50	44-50
16	-34.477418	19.744954				12	6-12
17	-34.47683	19.74601				30	24-30
18	-34.477418	19.744954	400	N/A	N/A	50	41-50
19	-34.52628	19.75374				20	14-20
20	-34.534917	19.828389	400 + 300	400	1000	100	41-46 56-61 95-100
21	-34.534661	19.826799				60	51-60
22	-34.534655	19.826733				20	14-20
23	-34.534670	19.720556				6	3-6
24	-34.603750	19.799861	700	800	900	60	35-45
25	-34.603705	19.799722				7	4-7
26	-34.533078	19.720556	N/A	400	N/A	50	44-50
27	-34.53302	19.72043				7	4-7
28	-34.488722	19.695000	N/A	200	N/A	50	41-50
29	-34.488722	19.694972				11	5-11

Notes: *N/A indicate that no Geophysics was done*

ER – Electrical Resistivity

Table 8: Summary of aquifer test results.

BH ID	**Depth (m)**	**Description**	**Total Drawdown (m)**	**Transmissivity (m^2/day)** Cooper Jacob Method	**Transmissivity (m^2/day)** Theis Recovery Method	**Pumping test rate (ℓ/s)**	**Test duration (min)**	**Recovery %**
BH 15	50	Pump Test	13.5	0.006705	0.006705	0.11	240	100
BH 26	50	Pump Test	14.8	0.01171	0.007319	0.5	240	100
BH 29	11	Pump Test	5.5	0.03415	0.0153	0.6	240	75

Table 9: Summary of Slug Test results

BH ID	**Depth (m)**	**Description**	**Hydraulic conductivity (m/day)**	**Screen interval (m)**	**Method (Confined)**
BH 19	20	Slug Test	0.00205	14-20	Bouwer-Rice
BH 24	60	Slug Test	0.01113	35-45	Bouwer-Rice
BH 25	7	Slug Test	0.003918	4-7	Bouwer-Rice
BH 27	7	Slug Test	0.0003366	4-7	Bouwer-Rice

Appendix 2 Environmental stable Isotope results

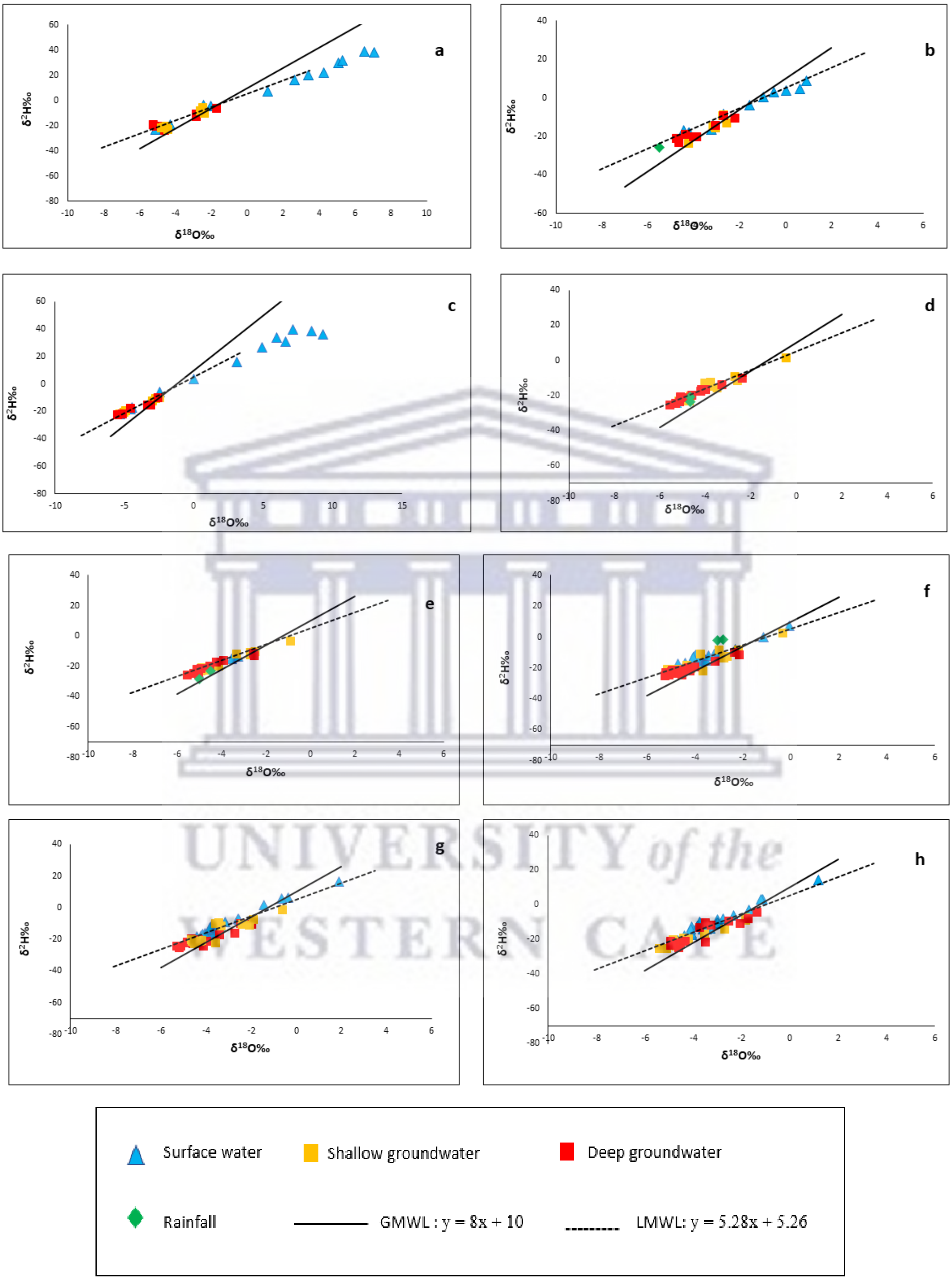

Figure 59: Stable isotope compositions of shallow groundwater (20m and below in depth), deep groundwater (above 20m in depth), surface water and rainfall in relation to the GMWL and LMWL, a) March 2018, b) July 2018, c) February 2019, d) July 2019, e) December 2019 (Mazvimavi et al., 2021)