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Assessing hydrogeological characteristics to establish influence of aquifer-river interaction in non-perennial river systems, Heuningnes catchment

By

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A thesis submitted in fulfilment of the requirements for the degree of

Master of Science (MSc)

in

Environmental and Water Science

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February 2019

Declaration

I, Vincent Santos Dzulani Banda, declare that project title *"Assessing hydrogeological characteristics to establish influence of aquifer-river interaction in non-perennial river systems, Heuningnes catchment"* 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 names: **Vincent Santos Dzulani Banda**

Signature:

Date: February 2019

Dedication

This work is dedicated to my beloved parents, brothers and cousins. Ada Moses Ganizo Banda (A Chilizwazwa) and Ama Jennifer Mhone (A Mayaka), you are my legends. I love you.

Acknowledgement

First and foremost, I express my gratitude to the Institute for Water Studies at the University of the Western Cape and the National Research Foundation (NRF) for funding this research.

I would like to thank my supervisors, Dr Haile Mengistu and Dr Thokozani Kanyerere for their tireless guidance and support throughout the research period. The consultations were so encouraging and kept me focused throughout the entire period of this research work. To Dr Jaco Nel, I thank you for the good guidance, suggestions and training you provided especially during field activities. You made my data collection a great success.

For the technical support, I thank Mr Shamiel Davids and Mr Evan Swartbooi for their assistance and services in the field and laboratory. I also offer my regards and blessings to my fellow Environmental and Water Science students who supported me in any aspect during the completion of this thesis. Nangamso Tuswa, Angelo Johnson and Phumlani Mqondeki, the real gurus, you were amazing.

To the farmers in the Cape Agulhas, I thank you for giving us permission to establish research sites in your property.

My heartfelt thanks go to my family for their support and understanding during my period of study all.

Above all, I thank Almighty God for His favour, protection and good health throughout this study.

Abstract

Assessing hydrogeological characteristics to establish influence of aquifer-river interaction in non-perennial river systems, Heuningnes catchment

Over half of total flows in the global river network are composed of non-perennial rivers. This indicates the importance of non-perennial river systems in supporting the biodiversity. It has been established that groundwater is one of the elements that control the flow regimes and classification (whether perennial or not) of a river system. However, the use of hydrogeological characteristics to establish the influence of groundwater on non-perennial river systems remain to be widely unpublished. This study, therefore, intends to conceptualize and explain the role of hydrogeological characteristics in non-perennial rivers, using the Heuningnes catchment in the Western Cape Province of South Africa as a case study. The study has argued that thorough characterization of aquifers is essential in order to adequately establish the extent of aquifer-river connectivity and how groundwater influences flows and chemical loading in non-perennial river systems. The study has three objectives namely: (i) to determine the aquifer characteristics (ii) to characterise the aquifer-river interaction and (iii) to conceptualize the groundwater flow system.

Records review, field, analytical and laboratory-based methods were used to collect and interpret geological, groundwater level, pumping test, hydro-chemical and environmental stable isotopic data in order to characterise groundwater occurrence, flow system and its interaction with the rivers of the study area. Water samples were taken from groundwater, surface water and rainfall during both dry and wet periods.

Results show that the study area has a topography-controlled water table with shallow depth to groundwater levels ranging on average from 3 - 10 m, which result into largely a local groundwater flow system. Transmissivity values determined from constant rate pumping test range between 0.17 and 1.74 m^2/day. Results exhibit that the low transmissivity values are associated with the weathered nature of the Table Mountain sandstone and the unfractured Bokkeveld shale formations.

Hydrochemical data results indicate that both groundwater and river samples in the upstream part of the study area are characterised as fresh water with TDS values of less than 1000 mg/l while the downstream part has saline waters with TDS ranging from 2000 – 35000 mg/l. Results also show that Na-Cl is the dominant water composition for both groundwater and river water. The order of major ion dominance is similar for the two water sources, with concentration ranges from high to low in the order of $Na^{+}>Mg^{2+}>Ca^{2+}>K^{+}$ and $Cl^{-}>SO_4^{2-}>HCO_3^{-}$ for cations and anions respectively. The similar patterns and trends in salinity and major ion data suggest the connectivity between the aquifer and the river. Environmental stable isotope data indicate river samples in upstream areas having depleted $\delta^{18}O$ (-4.3 to -5.12‰) and $\delta^{2}H$ (-22.9 to -19.3‰) signatures similar to groundwater indicating a stable and continuous groundwater contribution to the river flows. Meanwhile, high evaporative enrichment of $\delta^{18}O$ (1.13 to 7.08‰) and $\delta^{2}H$ (38.8 to 7.5‰) is conceived in river samples from downstream areas. Ionic ratios and isotope-salinity relationships suggest that groundwater chemistry is derived from sea sprays, evaporation and dissolution of Bokkeveld shale host rock.

Geological, hydrogeological, hydrochemical and environmental stable isotope data were used to develop a conceptual hydrogeological model which explains the role of groundwater in non-perennial river systems. Results indicate that the North East – South West fault on the north-eastern part of the study area seem to act as a conduit to groundwater flow thereby supplying water to the upstream rivers while the East -West fault in the northern part seem to act as a barrier to groundwater flow resulting into a hydraulic discontinuity between upstream and downstream areas. Meanwhile, the relatively low conductive formation in the downstream areas coupled with a relatively low hydraulic gradient (0.000843) suggests there is slow Darcian groundwater flows resulting in less flushing and high salinization of groundwater. Eventually, in the downstream part of the study area there is slow and minimal groundwater discharge to the rivers resulting into groundwater failing to maintain the river flows and pools. In general, rivers of the study area largely gain water from groundwater although the amount of groundwater discharge varies from one river segment to another in both upstream and downstream parts. The conceptual model has led to the development of a proposed optimum management of non-perennial rivers including the effects of groundwater abstraction on the river flows.

Key words: aquifer hydraulic tests, aquifer-river interaction, conceptual model, groundwater, hydro-chemistry

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Chapter 1: General introduction

1.1 Study overview

The overall target of this research is to assess and conceptualize the influences of groundwater on non-perennial river flows in semi-arid areas. The study uses the Heuningnes catchment as a case study to demonstrate how hydrogeological characteristics influence the interaction between aquifers and non-perennial rivers. It has been established by other researchers that aquifer-river interaction occurs when there is a hydraulic connection between the two systems (Fleckenstein et al., 2006; Woessner, 2000). This study argues that unless the hydrogeologic features of aquifers within non-perennial river systems are evaluated, the level of aquifer-river connectivity and how groundwater influences such systems may not be adequately established. The extent of such connectivity determines the rate of water and chemical movement between the aquifer and the river. This study provides information to the research question: “To what extent can hydrogeological characteristics be used to explain the availability and influence of groundwater on non-perennial river systems?” To enable decisions on how to properly manage and monitor groundwater resources in an ecologically sustainable manner and how groundwater influences flows in non-perennial rivers, it is important to evaluate such aquifer characteristics that control the exchanges of water between non-perennial rivers and the adjoining aquifer.

1.2 Background of the study

Over half of total flows in the global river network are composed of non-perennial rivers (Datry et al., 2014). This indicates the importance of non-perennial rivers in supporting the biodiversity. However, due to the effects of climate change and water resources development, the potential of perennial rivers transforming to non-perennial rivers is likely to intensify (Costigan et al., 2016). Therefore, to ensure proper management of non-perennial rivers, it is essential to comprehend the controls governing such rivers to flow and cease flowing periodically. It has been confirmed that groundwater is one of the elements that control the flow regimes and classification (whether perennial or non-perennial) of a river system (Robinson et al., 2015). During dry periods groundwater flowing into rivers is significant as it provides for river discharge forming permanent or intermittent river segments (Uys and O’Keffe, 1997). This occurs through exchanges of water between the aquifer and surface water through what is referred to as aquifer-river interaction.

In non-perennial rivers, the interaction between an aquifer and the river affects the occurrence of flows, existence of static pools and the amount of water stored beneath and adjacent to the river channel (Hughes, 2005). Identifying such areas within a river that interact with groundwater is fundamental to the protection and management of such systems. One of the approaches is to characterise the hydraulics of the surrounding aquifers, groundwater flow systems, topography as well as the local climate within the catchment. It is critically beneficial to classify the processes occurring between the river and the aquifer when conceptualizing the nature of interaction. For instance, Ivkovic (2009) categorises these processes according to the hydraulic connection, the dominant direction of flux between the two systems and also based on the potential impact of groundwater abstraction on a river system. As such, the components and processes of the aquifer that influences flows in non-perennial rivers needs to be properly evaluated.

The presence of pools and flowing water in non-perennial river systems is known to be linked to groundwater input most especially during dry or drought conditions (Rossouw et al., 2005). However, Bestland et al., (2017) suggest that such presumption may not always be true since some non-perennial rivers retain standing pools without having a direct connection with the underlying groundwater. It has been argued that pools are sometimes maintained by residual surface flows, irregular flow pulses and perched streambed (Bestland et al., 2017). Furthermore, Zimmer and McGlynn (2017) show that non-perennial rivers can act as focal areas for groundwater recharge and discharge especially on the headwater landscape. This indicates the importance of thoroughly understanding the hydrogeological characteristics in order to assess the interaction processes and evaluate the role of groundwater in non-perennial river systems.

There are two main factors that control whether a river system gains or loses water by interacting with the adjoining aquifer. The most important control of groundwater-river interaction is the existence of hydraulic gradient while the second control is the hydraulic conductivity of the channel perimeter (Chen, 2007). However, Younger (2007) argues that the head difference is not the single most important control to initiate the exchange of water and points out that the final deciding factor is the permeability of the channel perimeter. On the other hand, Bair and Lahm (2006) contend that the geologic factors influencing these exchanges are the permeability of the streambed material, transmissivity and coefficient of storage of the underlying aquifer. Furthermore, other researchers (Fleckenstein et al. 2006; Hatch, 2010; Weitz and Demlie, 2014; Hiscock and Bense, 2014; Tang et al., 2015) suggest that the magnitude of low river flows is mainly controlled by the hydraulic properties of both the aquifer and the material beneath the river. This entails the significance of evaluating such hydraulic properties as a way to understand the influence of aquifers on non-perennial river systems.

Most aquifer-river interactions studies (Chen and Shu, 2002; Ivkovic, 2009; Yang et al; 2012; Weitz and Demlie, 2014) tend to focus mainly on water management and conjunctive (optimal groundwater and surface water) use. Woessner (2000) argues that such approaches are sufficient in regional water management and may be inappropriate when investigating the ecological dynamics of aquifer-river systems. Therefore, it is important to adopt a focused assessment program on a local scale when addressing the spatial and temporal variations in aquifer-river exchanges. Fleckenstein et al. (2006) suggest that local connection between groundwater and the river may be as a result of the structure of the subsurface heterogeneity which may create losing or gaining conditions of the river. This means that areas of local connection could provide for low flows during dry periods, which requires knowledge of groundwater flow paths and the linkages between the two systems. As a result, there is need to investigate the occurrence of groundwater in such local areas in order to determine the controls of groundwater flows at a local catchment scale.

Exchange fluxes in aquifer-river interactions tend to vary spatially and temporally. This exchange of fluxes and its variation may have an influence on the total water balance for the two systems (Krause et al., 2007). Therefore, in order to understand the influence of groundwater on non-perennial rivers it is also important to assess the components of the groundwater balance for the catchment surrounding such river systems. Groundwater balance considers the different inflows and outflows to a groundwater system and its subsequent change in storage and it is critical in groundwater system characterization (Karamouz et al., 2011). As such, an understanding of the groundwater balance can be used to explain the changes in the flow regimes in a non-perennial river system as a result of the changes in some of the components of the system.

In South Africa, about two-thirds of the river networks are non-perennial (Rossouw et al., 2005) signifying the relevance of undertaking this study. There have been some studies and debates focusing on non-perennial rivers in the country, although the focus has been on determining environmental flow requirements for such rivers. Rossouw (2011) suggests that some non-perennial rivers may have flows and pools in certain parts of the river which are sustained by groundwater, subsurface water or channel surface flows when there are little evaporation losses. Furthermore, Avenant et al. (2014) indicate that the sustainability of such flows or pools may be dependent on the amount of groundwater flowing into such pools. Meanwhile, Seaman et al. (2010) argue that the influence of groundwater on non-perennial rivers becomes more important with an increase in dryness of a river flow. Therefore, the nature of non-perennial rivers is mostly influenced by the interactions between the aquifer and the river.

There have been different studies in South Africa focusing on assessing the hydrogeological characteristics. However, most of such studies have focused on aquifer characterization for the purpose of groundwater development. Furthermore, although some studies have assessed the interactions between aquifers and rivers (such as Saayman et al., 2004; Xu et al., 2002; Winde and van de Walt, 2004; Le Maitre and Colvin, 2008; Weitz and Demlie, 2014) most of such studies have focused on perennial rivers and other surface water bodies. This means that research on the influences of aquifers on non-perennial river systems continue to lag behind. This study, therefore, attempts to use the hydrogeological characteristics to understand the influence of groundwater on non-perennial rivers using the Heuningnes catchment in South Africa as a case study.

1.3 Research problem

The use of hydrogeological characteristics to establish the influence of aquifers in non-perennial river systems remain to be widely unpublished. This means that mechanisms controlling the permanence of flows in some segments of non-perennial rivers especially during the dry period remain to be poorly understood (Costigan et al., 2016). In non-perennial river systems, aquifer-river interaction must be thoroughly evaluated to comprehend the influence of groundwater on the occurrence of water pools and flows within the river bed. The background to the problem is that non-perennial rivers have been, historically, considered as systems of low ecological and economic value by scientists and policy makers (Skoulikidis et al., 2017). Most research work on aquifer-river interaction has focussed on perennial river systems in which the methods used to assess the interaction mostly rely on the presence of flowing water. In South Africa, as much as some studies focusing on non-perennial rivers have acknowledged the importance of aquifer-river interactions on such systems (Seaman et al., 2010; Rossouw, 2011; Seaman et al., 2013; Avenant et al., 2014), a detailed study on the relationship between aquifers and such river systems seems to be overlooked. This implies that knowledge on the influence of groundwater on non-perennial river systems remains unaccounted for and therefore may lead to poor management and continued degradation of water resources in such systems.

1.4 Research question and thesis statement

In order to have a more understanding of the influence of groundwater in non-perennial rivers, the current study puts forth the following research question: “To what extent can hydrogeological characterization be used to explain the availability and influence of groundwater on non-perennial river systems?”

The present study argues that thorough characterization of aquifers is essential in order to adequately establish the extent of aquifer-river connectivity and how groundwater influences flows and chemical loading in non-perennial river systems.

1.5 Research aim and objectives

The aim of this research is to develop a hydrogeological conceptual model that explains the influence of aquifers in non-perennial river systems, using Heuningnes catchment in Western Cape, South Africa, as a case study. A conceptual model, which would be developed at the end of the study would ultimately improve the understanding of the influence of groundwater on non-perennial river systems. The outcome of this study would form critical platform for designing implementation plans for using and managing water resources within non-perennial river systems. In order to achieve this aim, this study addresses the following objectives:

i. Determine the aquifer characteristics
ii. Characterise the spatial and temporal variation in aquifer-river interaction
iii. Conceptualize the groundwater flow system of the study area

1.6 Significance of the study

Non-perennial rivers are prevalent in areas of low annual rainfall with high temperatures as well as in steep, small elongated catchments (Snelder et al., 2013). However, these rivers are vulnerable because of lack of adequate protection and management and partly because previously non-perennial rivers have been perceived as systems of low ecological and economic value (Skoulikidis et al., 2017). The Heuningnes catchment, where this study has been carried out, is considered as one of the areas of high conservation importance for both terrestrial plants and wetland biota (Russel and Impson, 2006). Influence of groundwater in sustaining the ecological health of non-perennial rivers becomes critical with increasing dryness. A better understanding of the influence of aquifer characteristics on the non-perennial river ecosystems would help in the development of future flow restoration and management of such rivers. The ecological dynamics of interactions between aquifers and rivers needs to be assessed at a local scale similar to where the current study has been conducted.

A comprehensive characterization of aquifer hydraulics, which mainly governs the exchange flux between the aquifer and a river, is one of the outcomes of this study. Aquifer parameters such as hydraulic conductivity and storativity are critical in groundwater resource development as well as for the conceptualization of groundwater flow system. The hydrogeology and occurrence of groundwater in the study area is therefore investigated in order to understand the groundwater flow mechanisms. Temporal and spatial variations at which the aquifer within the study area interacts with the non-perennial rivers are also investigated. In view of the above, this study therefore aims to develop a hydrogeological conceptual model in order to understand the hydrogeological features and processes which influence the non-perennial rivers of the Heuningnes catchment. This would provide a basis for the management of such rivers in an ecologically sustainable manner.

1.7 Scope and nature of the study

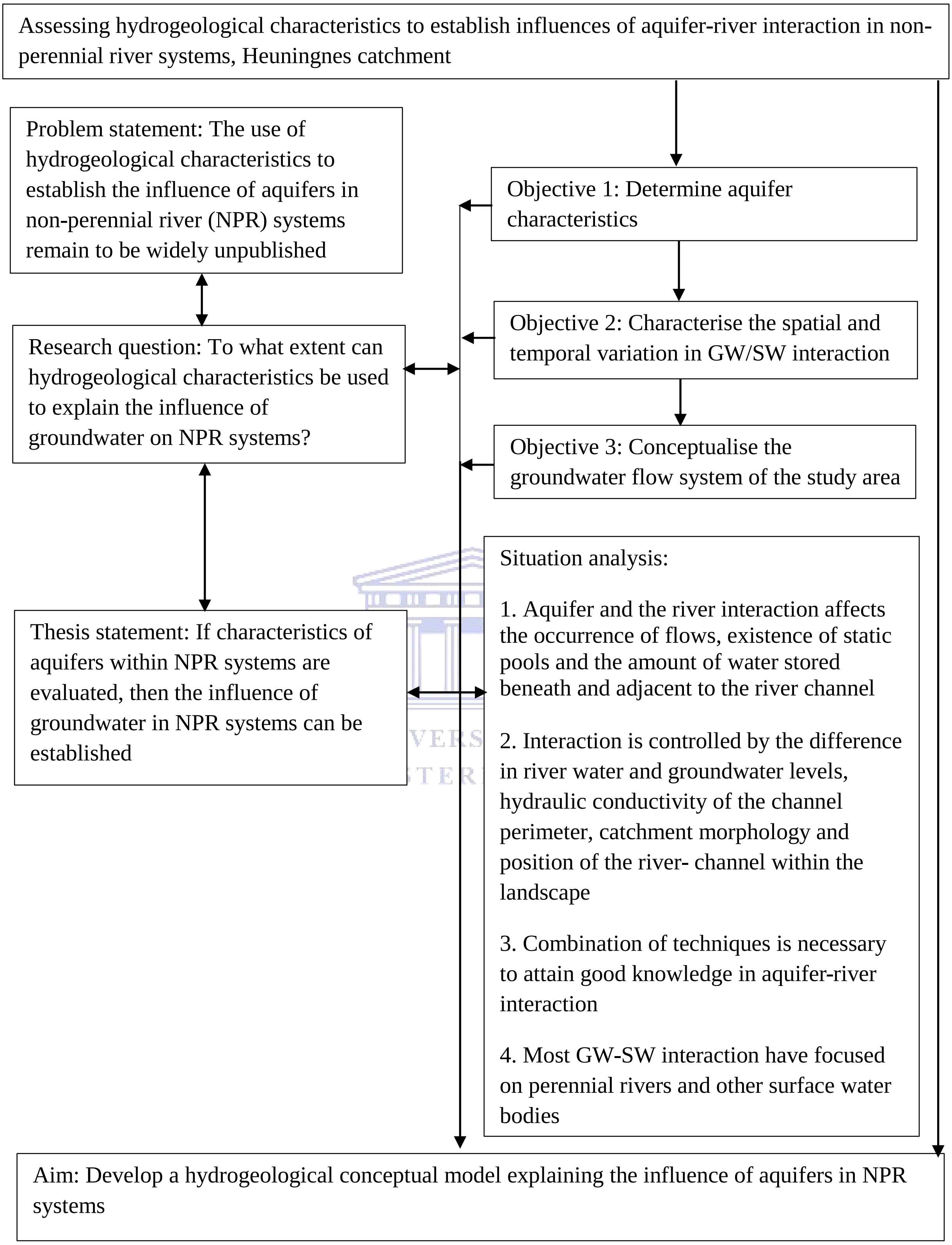
Hydrogeological characterisation involves comprehensive assessment of the aquifer using different forms of data including geology, hydraulic properties and the aspects of water chemistry. The geological structure is appraised to delineate groundwater units and establish the manner in which groundwater occurs in an area. The aquifer hydraulic parameters include the hydraulic conductivity, transmissivity, storativity, specific yield and porosity. These aquifer parameters determine the storage capacity and how much water can the aquifer release and they are therefore used to understand the groundwater flow dynamics. Analyses of water chemistry is conducted to aid decision relating to quality of water for various uses as well as understanding groundwater flow mechanisms.

The current study focuses on establishing the manner in which groundwater occurs in the study area, determining the aquifer hydraulic properties (transmissivity and storativity) and applying various hydro-chemical and environmental stable isotope analyses for assessing the groundwater flow mechanisms. Data on geological maps, groundwater levels, pumping tests, groundwater and surface water chemistry and some components of the groundwater budget in the study area are collected to develop a hydrogeological conceptual model which is used to explain the influence of groundwater on on-perennial rivers. Analytical, interpretative and graphical methods are used to display and analyse the collected data.

1.8 Conceptualization of the current research project

This research forms part of the University of the Western Cape's Institute for Water Studies project entitled "Ecologically sustainable management of non-perennial rivers". The overall aim of the project is to improve understanding of the relationships between river flow, ecosystem characteristics and services provided by non-perennial rivers as well as the prediction, decision-making and management related to the ecological and social consequences of flow modifications of non-perennial rivers. The factors that determine whether a river is perennial or not are climate, landscapes, land-forming processes at various scales and interactions between surface water and groundwater along these rivers. The ecosystems occurring on non-perennial rivers are made up of abiotic (non-living) and biotic (living) elements, as a result the physicochemical characteristics of water along the non-perennial rivers are also being assessed in this bigger project. Therefore, the main components of the bigger project are hydrology, hydrogeology (groundwater), geomorphology, water quality, aquatic fauna and riparian flora and vegetation. This bigger project has seven objectives in which the second objective is to establish how interactions between surface water and ground water affect the quantity and quality of non-perennial river flows in different physiographic settings. It is from this second objective where this current study is based on.

1.9 Research framework



Assessing hydrogeological characteristics to establish influences of aquifer-river interaction in non-perennial river systems, Heuningnes catchment

Problem statement: The use of hydrogeological characteristics to establish the influence of aquifers in non-perennial river (NPR) systems remain to be widely unpublished

Research question: To what extent can hydrogeological characteristics be used to explain the influence of groundwater on NPR systems?

Thesis statement: If characteristics of aquifers within NPR systems are evaluated, then the influence of groundwater in NPR systems can be established

Objective 1: Determine aquifer characteristics

Objective 2: Characterise the spatial and temporal variation in GW/SW interaction

Objective 3: Conceptualise the groundwater flow system of the study area

Situation analysis:

1. Aquifer and the river interaction affects the occurrence of flows, existence of static pools and the amount of water stored beneath and adjacent to the river channel

2. Interaction is controlled by the difference in river water and groundwater levels, hydraulic conductivity of the channel perimeter, catchment morphology and position of the river- channel within the landscape

3. Combination of techniques is necessary to attain good knowledge in aquifer-river interaction

4. Most GW-SW interaction have focused on perennial rivers and other surface water bodies

Aim: Develop a hydrogeological conceptual model explaining the influence of aquifers in NPR systems

Figure 1.1: Research framework indicating the key elements of the current study

1.10 Outline of the thesis

Chapter 1 provides an overview of the current research and outlines the research problem, research question, thesis statement, objectives, significance and scope and nature of the study. Chapter 2 presents a physiographic description of the regional setting of the study area and that of the study sites. Chapter 3 provides a review of various studies relating to hydrogeological characterisation and how they can be used to assess the role of groundwater in different environments including non-perennial rivers. The research design and data collection and analysis methods are presented in Chapter 4. Chapter 5 demonstrates the use of aquifer characteristics in understanding their role in aquifer-river interaction and how such aquifer characteristics influences river flows in non-perennial river systems. The use of hydrochemistry and environmental stable isotopes in assessing and characterising the interaction between aquifers and rivers is demonstrated in Chapter 6. Finally, Chapter 7 provides a summary of major findings and a conceptualization of the groundwater flow system which is used to explain the role of groundwater in non-perennial rivers.

Chapter 2: Description of the study area

2.1 Introduction

The present chapter provides a description of the study area where the study is conducted. The physiographic characteristics at regional and local scales are described in order to understand how they influence the interaction between aquifers and rivers of the study area. The chapter focuses on describing features such as geology, surface topography and climate which influence the interaction between groundwater and rivers but also determining the extent and nature of non-perennial rivers.

2.2 Regional setting description

2.2.1 Location of the study area

The Heuningnes catchment is located in the Western Cape Province of South Africa within the Cape Agulhas Municipality in the eastern Overberg district. It lies between 34^0 20’ and 34^0 50’ S latitude and 19^0 33’ and 20^0 17’ E longitude. The Heuningnes catchment lies in the tertiary catchment G50 within the larger Breede-Gouritz Water Management Area. The catchment has five quaternary catchments namely G50B, G50C, G50D, G50E and G50F (Figure 2.1). A quaternary catchment is a fourth order catchment in a hierarchal classification system in which a primary catchment is the major unit (DWA, 2017), which forms the basic hydrological unit for water resource management in South Africa. Different sources estimate the area of the Heuningnes catchment to be between 1400 and 1938 km^2. Bickerton (1984) indicates that the effective area for the catchment is 1185 km^2.

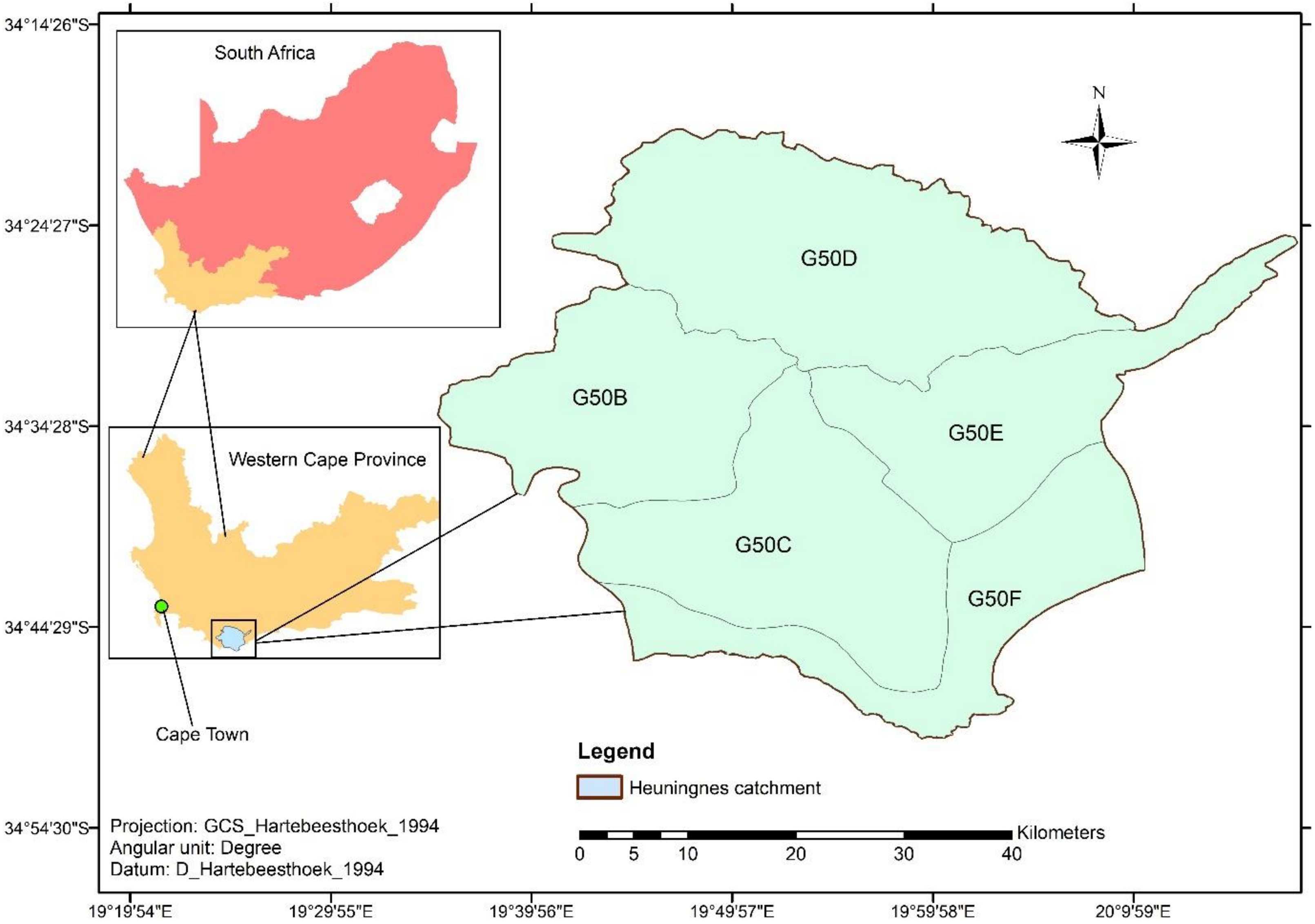


Figure 2.1: Location of the study area with respect to South Africa

2.2.2 Topography and landform

The topography of the study area varies considerably between the upper and lower parts. The landform is characterised by an undulating topography in the northern part while the southern and south-eastern part has a relatively flat area sloping gently towards the seashore (Figure 2.2). As such, surface water drainage is towards the coast in the south and the regional groundwater flow would be expected to be similarly towards the coast from the high elevation areas. The relatively flat topography area has less than 35 m elevation difference over a distance of approximately 30 km in the NW-NE strike (Figure 2.2).

Due to the greater resistance in weathering processes, the most noticeable feature in the landscape forming high ground and mountain ranges are the Table Mountain sandstone (Bickerton, 1984). Meanwhile, lower elevations form in less resistant shales characterized by rounded hilly nature of the Bokkeveld shales especially in the upper part of the Heuningnes catchment (Bickerton, 1984). Generally, the highest topographic elevation is in the northern and north-western part of the catchment reaching approximately 250 m above mean sea level (amsl) while the lowest elevation is located in the southern part reaching 0 m amsl along the coastal line (Figure 2.2).

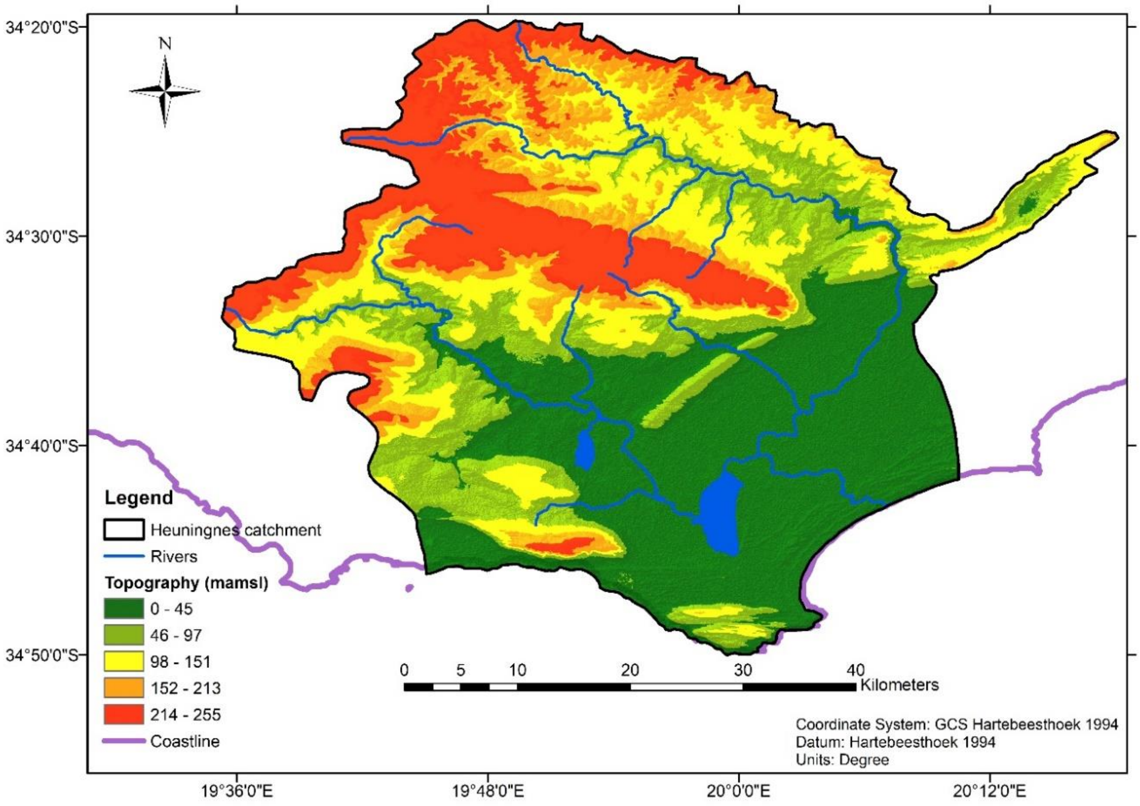


Figure 2.2: Topography of the Heuningnes catchment

2.2.3 Local climate

The Heuningnes catchment falls within the Mediterranean climate with cold rainy winters and hot dry summers. Rainfall is mainly cyclonic with some orographic rainfall occurring in the upper reaches of the catchment. It has been confirmed that rain bearing winds are mainly from the west or south west and rainfall is higher on the south faces of the mountain than on the north facing slopes (Bickerton, 1984). Mean annual rainfall along the coast ranges from 445 mm in the east to 540 mm in the west and rises to about 650 mm on the low hills that form the region's northern boundary, with 60 – 75 % of the precipitation falling in winter (May to October) (Kraaij, 2009). Therefore, it is expected that groundwater levels would rise during these months as a result of rainfall recharge and most rivers would be expected to be have high flows. These characteristics may have an influence on the interaction between the aquifer and the rivers.

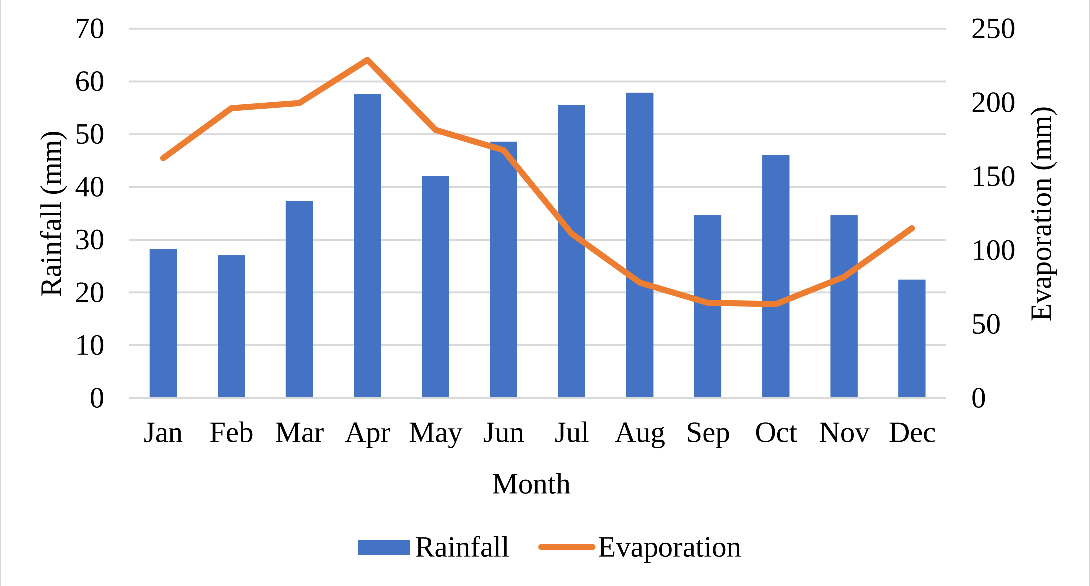


Figure 2.3: Average monthly rainfall and evaporation (from Class A pan) for Bredasdorp (G5E001) from 1980-2015 (Data source: DWS, 2017)

The catchment experience temperatures range from 20-30°C in summer to 12-18°C in winter (Herdien et al., 2005). Kraaij (2009) reported that the highest mean monthly temperature recorded is in January and the lowest record is in August. As such, evaporation and evapotranspiration may vary during these different months. This may have an implication on the catchment water balance including the groundwater balance which may influence stream generation from groundwater as well as aquifer-river interaction. However, it must be noted that drought conditions were experienced during the study period in the study and most parts of the Western Cape Province. As such, rainfall amounts were expected to be lower than the normal with high than average temperatures.

2.2.4 Rivers and drainage pattern

The Heuningnes catchment has the Heuningnes River as its major river which has two tributaries; the Kars River and the Nuwejaars River. The Kars River arises on the northern slopes of the Soetmuisberg and Bredasdorp mountains before flowing southwards and entering the Heuningnes River. The Kars River has six tributaries namely Twee, Leeu, Klein Sout, Klipdrif, Groot Sanddrif and the Grashoeks (Bickerton, 1984). The Nuwejaars River has the following tributaries: Koue, Wolwegatskloof, Jan Swartskraal, Boskloof and Uintjieskuil (Bickerton, 1984). The Nuwejaars River flows through the north-eastern reaches of the Agulhas national park into one of the South Africa's largest freshwater lake called Soetendalsvlei (Russell and Impson, 2006). The overflow of this lake confluences with Kars River downstream forming the Heuningnes River (Hoekstra and Waller, 2014).

The upper segments of the Nuwejaars and Kars Rivers have been identified as priority rivers for conservation initiatives due to their relatively unimpacted nature and high numbers of indigenous fish species (Herdien et al., 2005). Meanwhile, water quality is considered to be good in the headwaters of these waters and deteriorates as the rivers flows downstream (River Health Programme, 2011). Along the Nuwejaars River are a system of wetlands which are linked to the streams of the Nuwejaars River. The development of the wetland system is partly influence by the low gradient of the area. The wetland system drains most of the Southern Agulhas Plain forming several seasonal and permanent water bodies, notably the Soetendalsvlei and Voëlvlei (Figure 2.4) (River Health Programme, 2011). The lower part of the Nuwejaars River system also has a number of smaller pans which are not linked to any fluvial systems or are partly fed by small local channels (Russell and Impson, 2006). These pans are ephemeral whereby they flood during winter rainfall and dry up during the summer evaporation.

It is expected that these rivers may be subjected to naturally high flow variability due to the nature of Mediterranean climate experienced in the study area. Seasonal weather extremes in terms of floods and droughts are likely to occur in such environments. As such, during dry periods the river will have sections that have either permanent flows, isolated pools or sometimes completely dry as indicated in Figure 2.5.

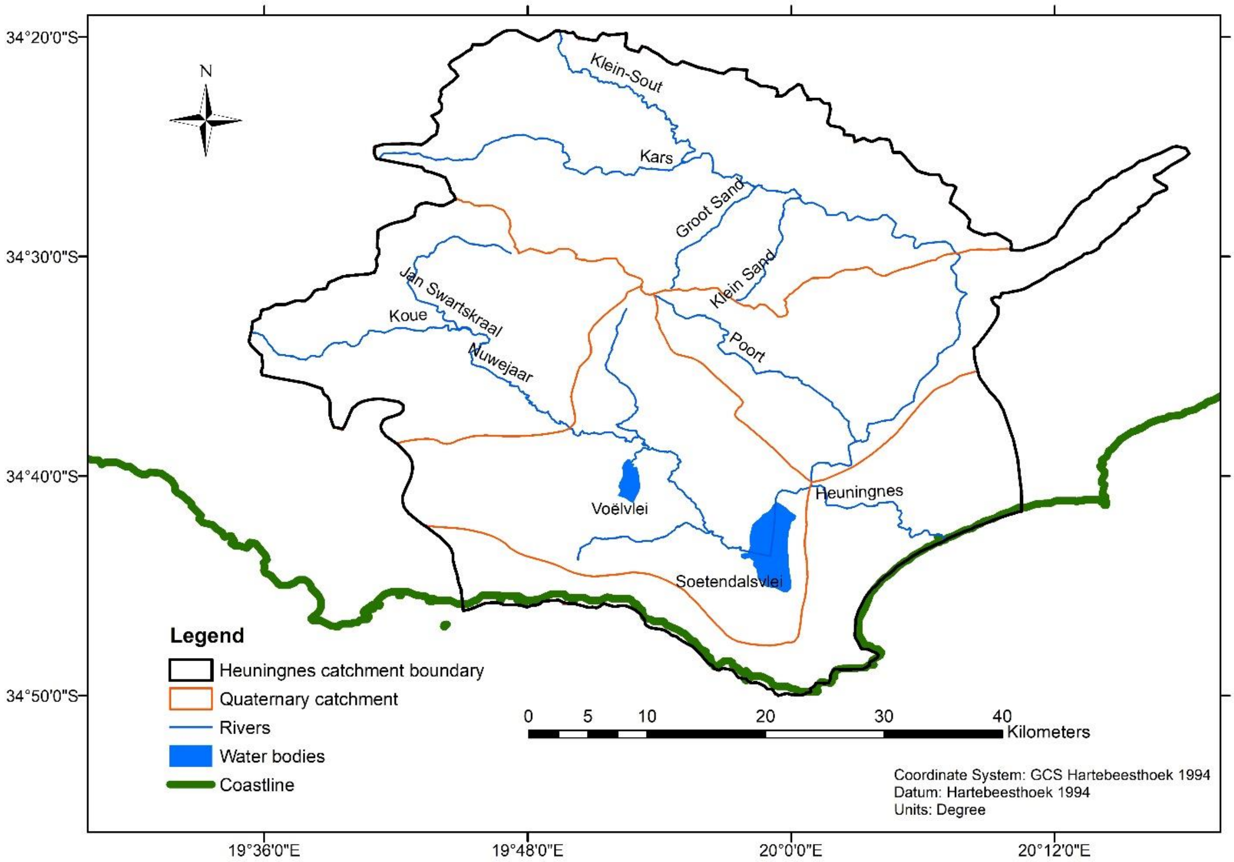


Figure 2.4: Rivers of the Heuningnes catchment

Figure 2.5: Nuwejaars River close to SANParks offices in the Agulhas Plain indicating its nature of non-perennial

2.2.5 Landcover and land-use

Land cover on the Agulhas Plain, in the east, is still largely natural and includes shrubland, grassland, bushland, wetlands, and waterbodies such as Soetendalsvlei as shown in Figure 2.6.

Wheat, barley and livestock farming are a significant industry for this area. In the cultivated areas, dryland agriculture is the most dominant type of farming (River Health Programme, 2011) which gives an indication that the area receives low or insufficient rainfall. Meanwhile, orchards and vineyards cover a small percentage of land resulting into small scale irrigation farming. This would mean that groundwater use for irrigation may not be prevalent in this catchment compared to other catchments within the Western Cape. Meanwhile, urban development comprises only a small percentage of the catchment and includes the towns of Bredasdorp, Elim, Napier, L'Agulhas and Struisbaai. Anthropogenic activities in these areas may also influence the quantity and quality of the different water sources, hence the need to assess such potential influence before making conclusive interpretations.

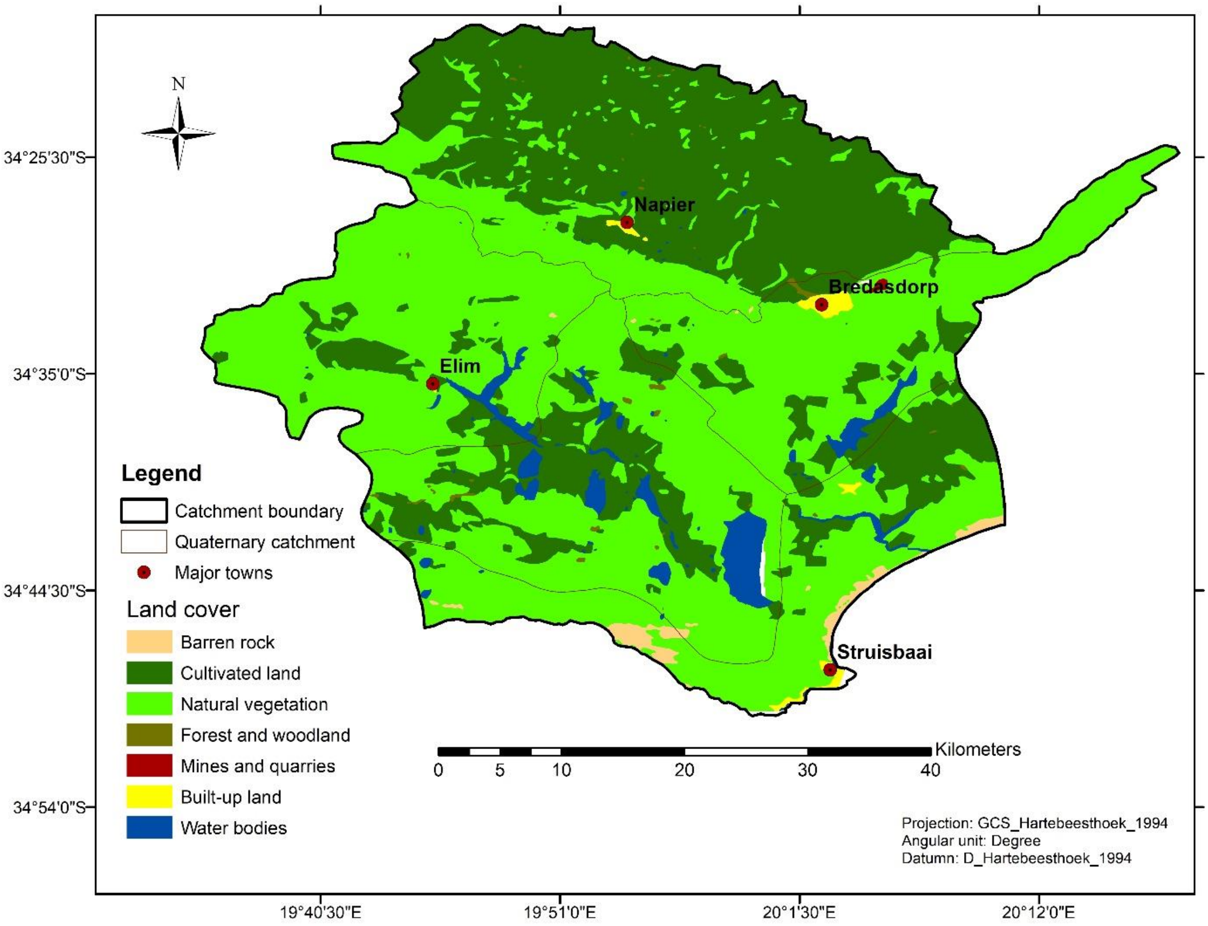


Figure 2.6: Landcover and land use for the Heuningnes catchment

2.2.6 Geology

The Heuningnes catchment is largely composed of the following main geological formations: The Table Mountain, Malmesbury, Bokkeveld, Cape Granite Suite and Bredasdorp Groups. Malmesbury and Cape Granite are basement rocks which are overlaid by the Table Mountain and Bokkeveld Groups.

The Table Mountain Group (TMG) comprises the first of three subdivisions of the Cape Supergroup. It consists of quartzitic sandstones derived from coarse sands deposited within the Agulhas Sea, and along its coastal plane. It was deposited during the Ordivician, Silurian and earliest Devonian Periods, approximately 500-400 million years ago. The Table Mountain Group overlies the basement formations of Malmesbury and Cape Granite Suite. Although the outcrop area is relatively small, these rocks underlie the whole of the coastal plane at varying depths of up to ~100 m (Chand Environmental Consultants, 2016). They outcrop again along the coast between Struisbaai and the western boundary of the catchment. Meanwhile, the Cape Granite Suite is late Precambrian to early Cambrian in age and have a composition ranging from low silica to high silica values. The Cape Granite Suite consists of coarse- grained granite underlying the TMG formation.

The Bokkeveld Group constitutes the middle subdivision of the Cape Supergroup comprising of a cyclic alternation of fine-grained sandstone and mudrock units that conformably overlie the Table Mountain Group in an off-lapping succession (Thamm and Johnson, 2006). Bokkeveld strata consist largely of shales and thin interbedded sandstones derived from marine continental slope muds of early to mid-Devonian (400 - 370 million years old) age. In the Heuningnes catchment, the Bokkeveld formation lies between the TMG and the Bredasdorp Group. The Bokkeveld Group rocks occupy the largest area comprising an alternating sequence of shales and sandstones.

The Bredasdorp Beds is characterized by tertiary to recent alluvium, calcified dune sand, calcrete, calcarenite and basal conglomerate. In the Heuningnes catchment, the formation occurs within the Soetendalsvlei towards the mouth of the Heuningnes River. It forms an important component of the southern part of the catchment.

An examination of the geological map (Figure 2.7) shows a number of fairly large faults cut the TMG of the Napier-Bredasdorp Mountains, trending northeast- southwest and east-west. Bickerton (1984) reported of two major fault lines are present in the catchment running almost east/west. One fault line lies just south of the Bredasdorpberge and the other lies just north of

Soetanysberg further south. It is expected that the faults would influence the groundwater flow system by either acting as a conduit or barrier to flow.

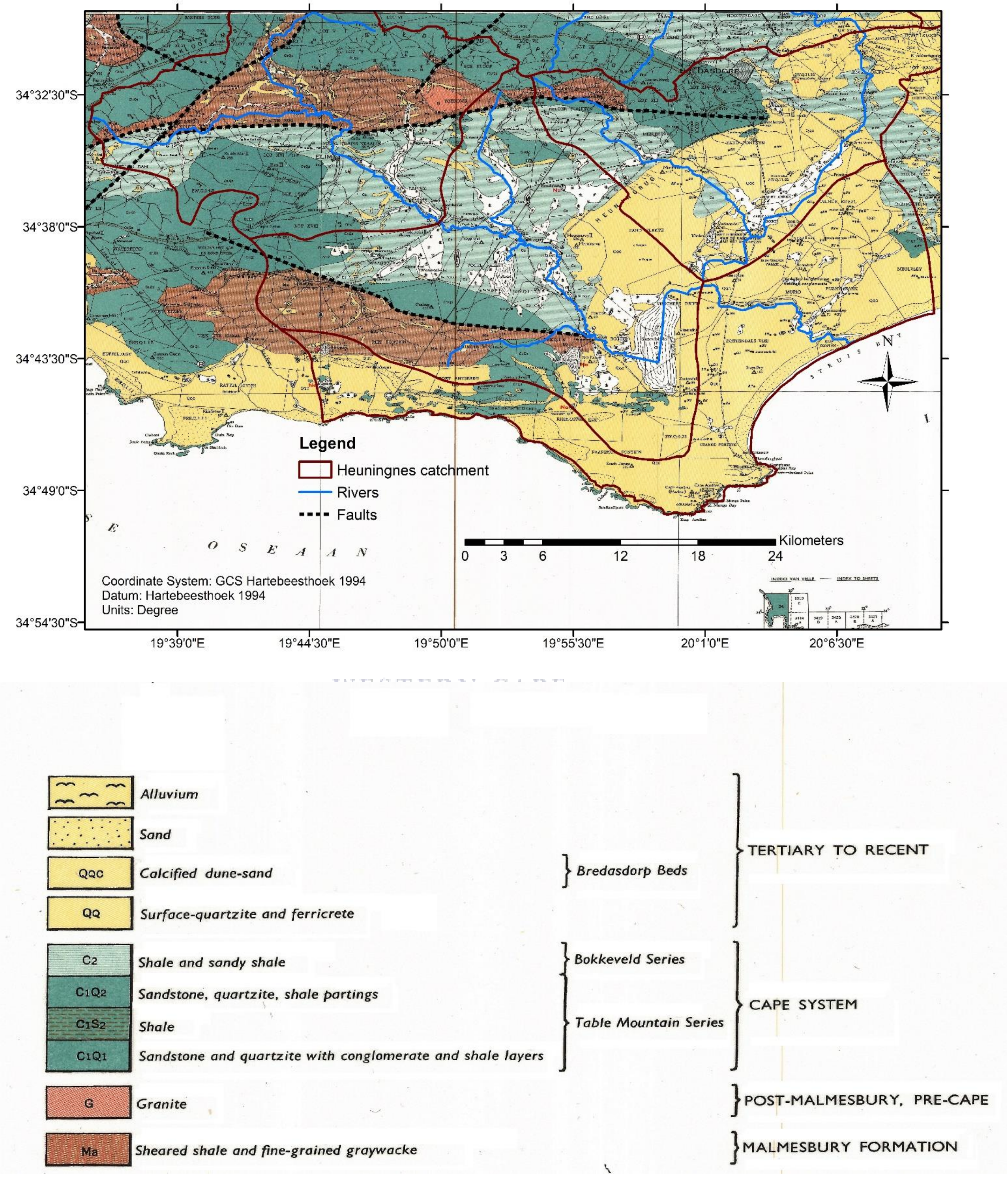


Figure 2.7: Lithological groups and geological formations of the Heuningnes catchment (Adapted from 1:125,000 geological map of Bredasdorp, Department of Mines, 1963)

As earlier mentioned, the Heuningnes River has two major tributaries: the Kars and Nuwejaars Rivers. According to Bickerton (1984), the upper catchment of the Kars River is dominated by Table Mountain Group sandstone, quartzite as well as shales of the Heuningberg Mountain. Further downstream, east of Bredasdorp, the river transverses calcified dune sand and coastal limestone of the Bredasdorp Beds. Meanwhile, the upper part catchment of the Nuwejaars River is dominated by the sandstone, quartzite and shales of the Table Mountain Group. Further downstream near Elim, the Nuwejaars River transverse shale and sandy shale of the Bokkeveld Group (Bickerton, 1984). These different geological formations would influence the different extent of aquifer-river connectivity affecting both quantity and quality of exchanged water.

2.2.7 Hydrogeology

Existing studies have shown that the local area in the study area are known to be water scarce (Golder Associates, 2010). The area is comprised of both primary (intergranular) and secondary aquifers. The intergranular aquifer exists along the rivers and in areas where there are the Bredasdorp Group rocks. The secondary aquifers are mostly associated with fracture sets in the hard-consolidated sediments of the Bokkeveld and the TMG. The TMG is a regional fractured sandstone rock aquifer whose groundwater flow is primarily controlled by fractures. Due to the faulting and fractures, the TMG has high yields in most areas and the fracturing is prevalent within the TMG as a result of its brittle and competent nature of the arenaceous deposits (Weaver et al., 1999). The quartzites of the TMG effectively contain no primary porosity as the quartz have been remobilized due to lithification which has filled the voids between the original sand grains (Weaver et al., 1999). Therefore, groundwater occurrence is through secondary porosity due to weathering and micro-fracturing. Due to its fractured nature, groundwater recharge rates are expected to be relatively higher in the TMG especially where it outcrops in the higher mountains. Meanwhile, the Cape Granite, which outcrops in fewer areas across the catchment has a low groundwater potential whose flow is through fractures and some weathered profiles.

The Bokkeveld Group is more argillaceous and therefore less susceptible to brittle deformation (DEAP, 2011). Meanwhile, important aquifer forms in the basal conglomerates and the calcarenites of the Bredasdorp Group. The basal conglomerates have developed in discrete drainage channels which were subsequently filled with coarse gravels prior to the deposition of the overlying sediments thereby forming high yielding aquifers (SRK Consulting, 2008). Table 2.1 indicates the stratigraphy and hydro-stratigraphy of the main geological groups present in the Heuningnes catchment.

Table 2.1: Stratigraphy and hydro-stratigraphy of the geology within the Heuningnes catchment (after Blake et al., 2010)

Stratigraphy		**Hydro-stratigraphic unit**
Group	**Description**	
Bredasdorp	Alluvium	Quaternary aquifer
Bokkeveld	Shales and minor sandstones	Aquitard
Table Mountain	Sandstone, quartzite, siltstone, minor shale	Aquifer, mini-aquitard, meso-aquitard
Cape Granite Suite	Granite	Basement aquiclude
Malmesbury	Metasediments	Basement aquiclude

The sediments of the Bokkeveld Group yield normally saline water and have low groundwater potential (SRK Consulting, 2010). This may be attributed to the shale rich structure of the host rock resulting into low recharge and poor water quality. The TMG is characterised by having groundwater of low total dissolved solids and good quality especially in the Heuningsberg. Around the coastal plain area south of Bredasdorp, the water quality in the Bredasdorp Group has also good quality. The groundwater generally has an electrical conductivity (EC) of less than 700 µS/cm. The Bredasdorp Aquifer is an important source of groundwater for the towns of Struisbaai, Agulhas and Suiderstrand (Chand Environmental Consultants, 2016). Likewise, the Cape Town Hydrogeological map indicates the availability of potentially high yielding aquifers in areas covering the Table Mountain Group and some portions of the Bokkeveld Group. Groundwater in these high yielding areas is good and EC rarely exceed 1000 µS/cm. The map shows that groundwater in the fractured aquifer tends to be of sodium-chloride nature. The map also indicates that EC in the Cape Granite Suite varies between 300 and 3500 µS/cm and the groundwater has a sodium-chloride-sulphate nature with low yield in such rocks. Meanwhile, the map shows groundwater in the Bredasdorp Group having EC between 700 and 1500 µS/cm and the groundwater tends to be of a sodium-chloride-calcium-alkaline nature.

2.3 Selection of study sites

The study sites for this research are along the Nuwejaars River catchment which falls in quaternary catchments G50B and G50C (refer to Figure 2.1) with a total area of 760 km^2. All the groundwater monitoring sites (boreholes and piezometers) are located within the G50B and G50C quaternary catchments. The Nuwejaars River and its tributaries, which covers whole of the two quaternary catchments is used in the current study. The study sites occur in a transitional area characterised by an undulating topography in the northern and north western part while the southern and south-eastern part has a relatively flat area sloping gently towards the seashore (Figure 2.8). The upstream part has elevation reaching about 250 m amsl while the downstream area has a topography of less than 35 m elevation difference over a distance of approximately 30 km in the NW-NE strike (Figure 2.8). The study sites are dominated by the sandstone and quartzite of the Table Mountain Group, shale and sandy shale of the Bokkeveld Group and the Bredasdorp's carbonates.

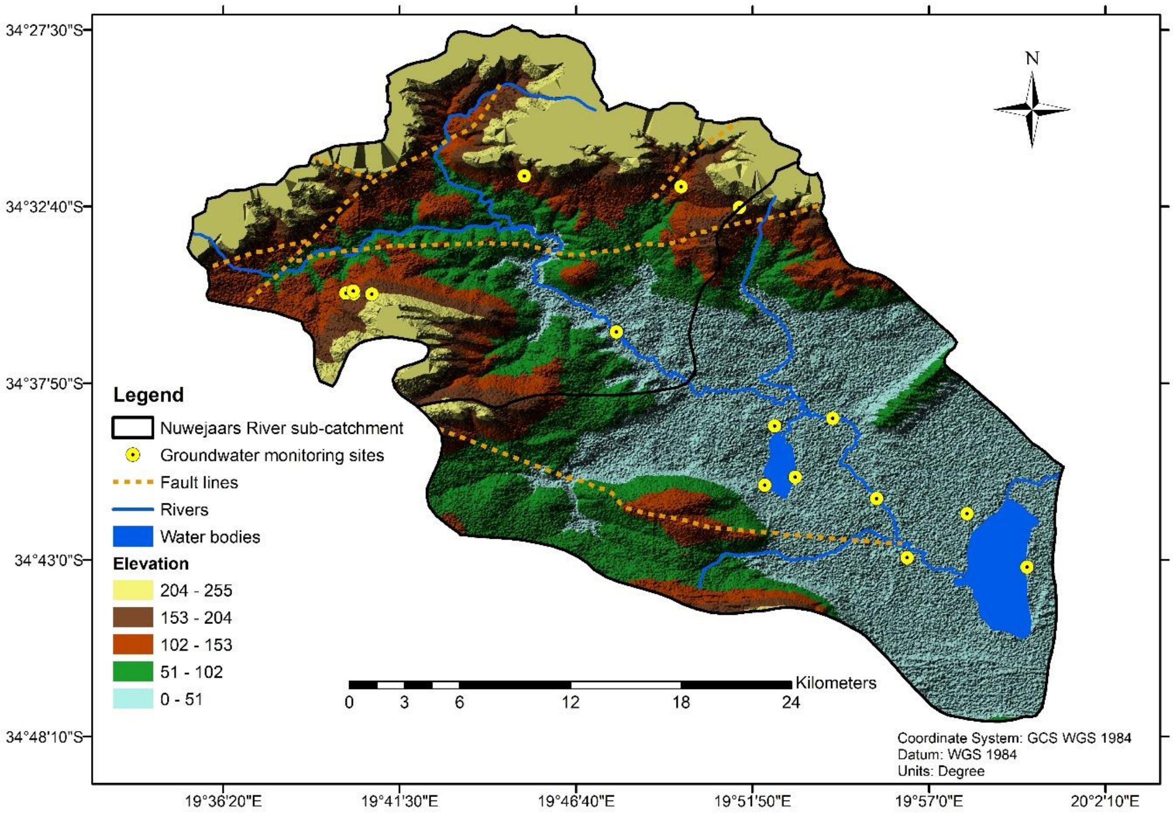


Figure 2.8: Spatial distribution of sampling sites with major rivers

Chapter 3: Literature review

3.1 Introduction

The previous chapters have provided the general introduction and description of the study area. This chapter starts with providing a brief review of previous studies done relating to the hydrogeological characteristics in different settings across the world and within the study area. The manner in which groundwater occurs in different geological environments is also evaluated. The chapter then reviews the different methods for aquifer characterization, the methods for characterizing aquifer-river interaction and finally the aspects to consider when developing a hydrogeological conceptual model. An understanding of these components is essential to comprehend how groundwater influences non-perennial river systems. A theoretical framework which guide this research work is discussed in this chapter. The chapter ends with the conceptual framework on hydrogeologic characteristics and how the framework can be used to explain the influence of aquifers on non-perennial rivers.

3.2 Synopsis of previous work

The focus of this section is to provide a scope of what encompasses hydrogeological characteristics based on studies from different researchers. The different motives for hydrogeological characterization are also provided in this section.

Hydrogeological studies involve among other things the establishment of key wells for water level measurements, exploratory drilling to establish aquifer geometry, estimating aquifer hydraulic parameters and water quality assessment (Madhnure et al., 2016). It has been established that any change in the dynamics of groundwater flow and storage influences the hydraulically connected surface water bodies. It is therefore essential to assess such hydrogeological characteristics when assessing the role of groundwater in non-perennial river systems. Simulation of groundwater flow systems requires the analysis of hydrogeologic characteristics of local aquifers (Pandey and Kazama, 2011). Furthermore, analysis of groundwater characteristics in comparison to that of surface water including non-perennial rivers helps to provide information on the potential of the interaction between the two water bodies. Different studies on hydrogeological characteristics have been carried out in different geological and climatic settings. Some of such studies have focused on understanding the groundwater flow system while some studies focus on providing information on the groundwater conditions of an area to ensure for a sustainable development of groundwater resources.

In assessing the hydrogeological characteristics, Demiroglu et al. (2011) analysed the hydrological, hydrochemical and isotopic properties of the waters in a semi-arid catchment in Turkey. It was revealed that the groundwater was meteoric in origin and that both deep and shallow circulating groundwater systems existed. Meanwhile, Konkul et al. (2014) evaluated the hydrogeologic characteristics of a coastal aquifer in Thailand to explain the hydrogeological conceptual model of the groundwater system. The study assessed the aquifer type, direction of groundwater flow, groundwater type, hydraulic parameters and groundwater potential.

Madhnure et al. (2016) did an integrated hydrogeological study to support sustainable development and management of groundwater resources in a semi-arid catchment in India. The study identified the aquifer systems available in the catchment, aquifer hydraulic parameters (transmissivity, specific yield and infiltration rates) as well as water quality characteristics.

In order to understand the hydrogeological behaviour of a semi-arid carbonate aquifer system in Spain, Sanz et al. (2009) designed a conceptual model of groundwater flow system using a multidisciplinary approach. The study used lithological, groundwater level, aquifer hydraulic, groundwater and chemistry data. The model looked at the negative effects of groundwater over-abstraction on the quantity and quality of available resources in the area, on the river-aquifer relationship but also on the associated ecosystems. Attandoh et al. (2013) conceptualized the hydrogeological system of some sedimentary aquifers in Northern Ghana using physico-chemical parameters and local topography to understand the expected groundwater flow pattern and determine local recharge and discharge areas.

Moghaddam and Najib (2006) evaluated the hydrogeologic characteristics of an alluvial aquifer in a semi-arid north-western Iran using groundwater level contours, aquifer hydraulic parameters and hydrochemistry. Holland (2011) used aquifer hydraulic parameters in combination with the investigation of recharge values together with the isotope and hydrochemical analysis to produce a conceptual hydrogeological model in the hydrogeological characterization of crystalline basement aquifers in South Africa.

Rodriguez-Rodriguez et al. (2007) evaluated the hydrogeological characteristics of an endorheic system within a river catchment. A water balance model, morphological and hydrogeochemical data were used in which the results showed that the ecosystems were groundwater dependent. Leketa (2011) determined the hydraulic parameters of near river aquifers of the Modder River system in South Africa. This was aimed at characterising the hydrogeology of the sites along the banks of the River for the purpose of water conservation and understanding groundwater surface water interaction.

From the synopsis of the previous studies summarized above, it is evident that information on hydrogeological characteristics is used in various applications including groundwater resource development and management, groundwater flow conceptualization and aquifer-river interaction. However, limited studies have focused on the hydrogeological characterization for aquifer-river interaction in non-perennial river systems.

Studies on the hydrogeological characteristics of the Heuningnes catchment are limited. In addition, there is lack of historical data as the catchment has no active (open) groundwater monitoring stations at present. Records from the South Africa's Department of Water and Sanitation (DWS) network inventory (DWS, 2015) indicate that groundwater monitoring in the catchment ceased in the 1990s and up to the year 2000. Most water studies in the catchment have focused on the Heuningnes estuaries and the wetland (aquatic) ecosystem. These include studies by Herdien et al. (2005), Russell and Impson (2006), Kraaij et al. (2008), Hoekstra and Waller (2014) and van der Ende (2015).

Regarding groundwater, among the few consultant reports is the one conducted by SRK Consulting (June 2010) where boreholes were drilled with aquifer tests conducted on five production boreholes near Struisbaai. All the five boreholes were drilled into the bedrock of fine-grained sandstones of the Table Mountain Group (TMG). Three of the five boreholes showed very low blow yields of less than 0.5 *l/s*. One borehole had a blow yield of 12 *l/s* while the other borehole was dry as hardly any water was blown from it. However, from the pumping test results it was revealed that the blow yields were not representative of the boreholes as the yields were much higher. The pre-pumping water level ranged from 10.7 to 27.4 metres below ground level (mbgl) and the optimum pumping rate ranged between 0.4 *l/s* and 8 *l/s*. Table 3.1 shows the results of the pumping test conducted for the five production boreholes.

Table 3.1: Aquifer parameter results from Struisbaai production boreholes

Site/Borehole name	**Transmissivity (m^2/d)**	**Storativity**	**Method**
SB12	25.6	1.29E-0.3	Cooper-Jacob
SB13	5.0	5.69E-03	Cooper-Jacob
SB14	2.0	1.01E-04	FC Non-linear
SB15	1.0	1.01E-04	FC Non-linear
SB16 (Calibration test)	161	4.11E-03	FC Non-linear

Data source: SRK Consulting (June, 2010)

In a separate but similar project, SRK Consulting (April 2010) also drilled production boreholes at Bredasdorp. All the four boreholes were drilled into the sandstones of the TMG formation. Three of the four boreholes were flowing artesian and the rate of flow ranged between 1.8 *l/s* to 5 *l/s*. The pre-pumping water levels were 0, 11.7, +7 and +1 mbgl.

Table 3.2: Aquifer parameter results from Bredasdorp production boreholes

Site/Borehole name	**Transmissivity (m^2/d)**	**Storativity**	**Method**
BD10	69.9	1.25E-0.4	Cooper-Jacob
BD11	25.1	4.51E-03	Cooper-Jacob
BD12	20	2.79E-03	Cooper-Jacob
BD13	39.2	2.57E-10	Cooper-Jacob

Data source: SRK Consulting (April, 2010)

Some regional studies on groundwater assessment in Heuningnes catchment have been done mainly through government projects. The aquifer classification map of South Africa (DWA, 2012) classified the area as having major and minor aquifer system. The major aquifer region represented the high yielding region of good water quality and the minor aquifer region indicated areas of moderately yielding aquifer system of variable water quality. DWAF (2004) indicated poor groundwater quality in the eastern Overberg (where the Heuningnes catchment lies) especially where Bokkeveld shales occur and showed that the groundwater is saline in some shallow aquifers. However, since most aquifers are heterogeneous, it is important to assess hydrogeological characteristics at a site-specific scale in order to make meaningful plans for the management of the resource and how it might influence the interaction with the surrounding rivers.

With regards to hydrochemistry studies, most of the studies in the Heuningnes catchment have been focusing on the water quality of surface water bodies. A study by Apedo (2015) found that Na-Cl and Na-Mg-Cl are the main water types in the Agulhas plain. The study suggested that the water hydrochemical groups are of saline origin presumably typical of marine and deep ancient groundwater. Gordon et al. (2011) assessed the water quality status of the three main wetlands in the Cape Agulhas plain (Soetendalvlei, Voëlvlei and Waskraalsvlei) and found that the highest conductivity was observed during late autumn/early winter ranging from 2750 to 4200 µS/cm.

3.3 Occurrence of groundwater

The occurrence of groundwater is by and large determined by the lithology of geological materials, regional geological structure, geomorphology of landforms and the availability of recharge sources (Hiscock, 2005). Knowledge on the distribution of various lithological units is needed to delineate potential water bearing formations. Therefore, it is important to understand how groundwater occurs in the area and the different characteristics of these features and as they have a definitive control over the movement and localization of groundwater. Since the occurrence of groundwater is determined by the character, distribution and structure of the rock, the water is held and released in the voids or interstices within the rock itself (Meinzer, 1959).

The two major physical properties of a rock that control the amount and movement of water are porosity and permeability. Porosity of a rock is the fraction of a given volume of material that is occupied by void spaces. Porosity can be categorized as primary porosity which is the inherent character of a rock matrix or secondary porosity which develops as a result of structurally controlled regional fracturing in hard rocks (Freeze and Cherry, 1979). Therefore, aquifers may be grouped depending on the water bearing properties of the rock formation as primary or secondary aquifers. The hydraulic permeability of a rock is the capacity of that rock to transmit water under pressure. It is measured by the rate at which it will transmit water through a given section under a given difference of pressure per unit of distance (Meinzer, 1959).

It is important to distinguish the total porosity from the effective porosity of a porous material (Domenico and Schwartz, 1998). Total porosity does not require connectivity of pore spaces whereas effective porosity looks at the percentage of interconnected pore spaces. As such, total porosity relates to storage capability of the material while effective porosity relates to the transmissive capability of the material. Permeability is directly related to porosity in that the degree of connectivity of the pores dictates the permeability of the rock.

Figure 3.1: Primary porosity (left) and secondary porosity (right) of a rock matrix (Source: https://dpipwe.tas.gov.au)

The water contained in the interconnected pore spaces of a rock matrix is capable of moving in different directions. The type of aquifer in which groundwater is located play a role in the mode of groundwater flow (Hiscock, 2005). Flow of groundwater in primary aquifers is by seepage or matrix flow between the grains that make up the rock mass. This flow is dictated by the size of the pore spaces which depends on the size of the grains. Meanwhile, in fractured rock aquifers water flows through fractures and usually the permeability tends to be high than in seepage flow. The ability of the rock to store and transmit water make up the hydraulic properties of that rock (Weight, 2008). As such, groundwater occurrence in rocks lacking primary porosity is limited to secondary porosity developed by weathering and fracturing. This indicates the importance of knowing the type of aquifer before characterization is done, for example, fractured rock aquifer which is dominated by secondary porosity.

3.4 Characterization of aquifers

Maliva (2016) broadly defined aquifer characterization as processes by which the three-dimensional structure, hydraulic and transport properties and chemistry of aquifers are evaluated. This is carried out to estimate the storage potential and aquifer productivity to help inform the sustainable use and management of groundwater as well as to describe groundwater flow and transport processes. Engdahl et al. (2010) defined aquifer characterization as a quantitative description of the subsurface in terms of hydraulically important parameters such as hydraulic conductivity, porosity and other applicable quantities. Therefore, improved aquifer characterization can allow for a better conceptual understanding of aquifer systems. In this study aquifer characterization is used to explain subsurface lithologic variations, the distribution of the aquifer geometry, hydraulic head and the aquifer hydraulic properties. This is because the storage and movement of groundwater and solutes is mainly controlled by such aquifer parameters.

Activities such as groundwater withdrawal may affect stream discharge and therefore understanding the hydraulic connectivity between the aquifer and streams is essential to preserve stream flows (Menció et al., 2014). This is because the availability of groundwater and the extent to which it will influence rivers depends on the hydrogeological setting characterized by hydraulic parameters. For instance, pumping groundwater from aquifers near streams may result in a hydraulic disconnection between the stream and the aquifer (Wang et al., 2016). Therefore, characterization of aquifers forms the starting point for decision making and management of groundwater resources and how it might influence surface water bodies.

Different methods including geological mapping, borehole drilling, aquifer hydraulic tests and geophysical studies have been employed to generate hydrogeological information. Maliva (2016) pointed out that the selection of the approach for characterizing aquifers is dependent on different factors including the specific data requirements for the project, the feasibility of the method at a site and the budgetary and scheduling constraints. Nevertheless, the main consideration for choosing the appropriate method should be on how the data is going to be used (Maliva, 2016).

3.4.1 Geological mapping

The nature and distribution of aquifers are controlled by the lithology, stratigraphy and structure of the geologic deposit and formations. Lithology describes the mineral composition, grain size and grain packing of the rocks while stratigraphy describes the geometrical and age relations between various formations (Freeze and Cherry, 1979). Structural features include cleavages, fractures, folds and faults. Hiscock and Bense (2014) suggested that in unconsolidated strata, the lithology and stratigraphy become the most important controls of groundwater flows. Therefore, a clear understanding of the geology of an area is essential when identifying aquifers and understanding the mechanisms of groundwater flow. In this case geological maps become an important tool to figure out the geologic and hydrogeologic framework.

3.4.2 Borehole drilling and lithologic logs

Various aquifer characterization techniques are dependent on the drilling and construction of boreholes. Boreholes are important in aquifer characterization as they are used for collecting data on aquifer hydraulic properties, water samples and most importantly on the aquifer lithology. Three main types of boreholes are used in aquifer characterization and these are exploratory, production and monitoring (Maliva, 2016). Exploratory are primarily used for collecting hydraulic and lithologic data and water samples. Production boreholes are constructed to evaluate well yield while monitoring boreholes are constructed for water level data and samples for water chemistry analysis. Lithological logs are used to delineate the subsurface layer and for identifying aquifers. This can help to determine the depth and thickness of aquifer unit in the different geological units.

3.4.3 Aquifer hydraulic tests (Well hydraulics)

Aquifer hydraulic tests form part of aquifer characterisation by providing quantitative data on aquifer hydraulic parameters, which are transmissivity and storativity 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 (Hiscock, 2005).

Slug tests are done at a local scale to provide useful information of the site. However, slug tests do provide values of hydraulic conductivity representative of a small area around the vicinity of the piezometer. Aquifer tests are conducted at a larger scale and therefore can provide measurements of aquifer hydraulic parameters that are representative of the large volume of aquifer. The most common types of aquifer tests are step down and constant discharge tests. Step down tests involves pumping the well in a step wise increasing of the pumping rate. During each step, the pumping rate is held constant while the drawdown is monitored until it stabilizes. Analysis of discharge rate and drawdown data from step down tests provides a specific capacity of the well, as such, step down tests measure the well efficiency and well performance (Younger, 2007). Meanwhile, constant discharge rate involves pumping water at a constant rate throughout change in the potentiometric surface. Constant discharge tests provide information on well performance, aquifer characteristics as well as identifying the nature of the aquifer and its boundaries (Hiscock, 2005).

Different analytical methods have been developed to analyse and interpret pumping tests data (Kruseman and de Ridder, 2000). The applicability of each method is based on a set of assumptions but also depends on the aquifer type and conditions. These include Theis (confined), Cooper-Jacob time drawdown (confined), Cooper-Jacob distance drawdown (confined), Hantush and Jacob (leaky-confined), Nueman (unconfined), Moench (unconfined) and Moench (fracture flow). Likewise, slug tests have its set of methods such as Hvorslev (1951), Bouwer and Rice (1976) and Bouwer (1989). These methods are also used depending on the type of aquifer. For example, the Hvorslev method is principally used for confined aquifers with piezometers and auger boreholes that partially penetrate shallow sand or clay formations (Cheong et al., 2008).

In cases where there are little resources with no extensive determination of hydraulic parameters, indirect methods are used to estimate the hydraulic conductivity (K) from grain size distribution data. Researchers have presented different empirical methods including Hazen 1911, Kozeny 1927, Kozeny-Carman, Slichter, Puckett et al. 1985, Terzaghi and Breyer (Alexander et al., 2011; Lu et al., 2012). The methods involve conducting a grain size distribution by sieving and determining the percentages of formations passing and being retained (Lu et al., 2012). This is based on the fact that the flow of water in a formation occurs in interconnected void spaces and as indicated by Freeze and Cherry (1979) the hydraulic conductivity is related to the grain size distribution of the granular porous media.

Cheong et al. (2008) showed that Kozeny's equation is adequate for determining K of coarse sand, while Hazen's equation is adequate for determining K of fine to very coarse sand size, 0.1–3.0 mm, with a uniformity coefficient (Cu) less than 5. However, Alexander et al. (2011) pointed out that applying the methods in a heterogenous aquifer may not yield accurate results since most of the methods were derived based on the samples with a grain size of coarse silt or larger. Therefore, Alexander et al. (2011) combined the Hazen 1911 model for coarse grained material and the Puckett et al. 1985 model which was developed for finer grained samples. It is therefore important to do several grain size analyses over a large area and have an average so that the results are interpreted on a larger context. Since the determination of the grain size distribution destroys the sediment structure, the hydraulic conductivity is not representative of the true hydraulic properties of the subsurface. Nevertheless, the method provides information about the subsurface material and the hydraulic conductivity values can be as a first estimation for the design of further application (Kalbus et al., 2006).

The use of these indirect methods for estimating hydraulic conductivity would be applicable when trying to understand the hydraulic conductivity of river beds and the possibility of interaction with the underlying aquifer. Cheong et al (2008) used the grain size analysis, pumping tests, slug tests and numerical modelling to estimate hydraulic conductivity in a river side alluvial system in which they found that the estimates from the grain size analysis, pumping tests and those from the model had similar behaviour. Cheng and Chen (2007) applied several empirical methods (Hazen, Breyer, USBR, Slichter and Terzaghi) to estimate the hydraulic conductivity of an aquifer-aquitard system hydrologically connected to a river. It was noted that the hydraulic conductivity using Slichter and USBR methods were lower than the other three methods which yielded little differences. Each method has its own domain of applicability, for example Terzaghi is only applicable to sandy formations, hence suggesting the differences.

The hydraulic conductivity of a formation can also be evaluated in the laboratory through constant head or falling head permeameter tests. The constant head method involves passing water through the formation under a constant head and the volume of water passing through the formation is measured. Falling head tests involves saturating the formation to a certain head and water flows through the sample without maintaining a constant head (Domenico and Schwartz, 1998). Therefore, permeameter tests involve the use of Darcy's Law to estimate the vertical hydraulic conductivity and the approach has been used to calculate hydraulic conductivity values of stream bed sediments in river beds (Chen, 2004). Lu et al. (2012) performed permeameter tests to estimate the hydraulic conductivity of the river bed channel since it has significant impact on controlling the fluxes between groundwater and surface water in a river channel while Alexander et al. (2011) used this approach to delineate distribution of hydraulic properties in a highly heterogeneous glaciofluvial deposit.

Double ring infiltrometers have also been used to determine the hydraulic conductivity of soils or formations in the field. This involves driving two open ended metal rings into the soil (one ring of smaller diameter put inside the bigger ring) and water is poured into both rings maintaining the same level. The depth of water infiltrated in the inner ring is measured at period intervals and the experiment is continued until constant rate of infiltration is reached (Madhnure et al., 2016). As such, this approach may be suitable for use when determining the hydraulic conductivity of a dry river bed material which is applicable in non-perennial rivers. This may help in explaining the recharge and discharge processes occurring in a river.

In some circumstances, a combination of techniques has been applied to determine the aquifer properties. Walker et al. (2018) used pumping tests, falling head permeameter tests, grain size analysis and salt dilution tests to estimate the hydraulic conductivity and assess groundwater flow velocities around a non-perennial sand river in South Africa.

3.3.4 Geophysical studies

Geophysical methods (surface and subsurface borehole techniques) are used in aquifer characterization to provide information on the thickness of unconsolidated materials, depth of basement rocks, depth of the saturated zone as well as location of subsurface faults (Fetter, 2000). Surface geophysics is mostly employed during the early stages of hydrogeological investigations while subsurface techniques are done after boreholes are drilled to obtained detailed information on the aquifer. Although in groundwater studies geophysics studies are mostly qualitatively interpreted (Maliva, 2016), the technique can also provide quantitative data given quality assurance and control on data collection, calibration and processing. Vereecken et al. (2005) indicated that with the improved understanding on soil or rock electrical signatures, electrical structural models are available that have the potential for an improved quantitative aquifer characterization. For example, Soupios et al. (2007) correlated geophysics and pumping tests data to evaluate the aquifer parameters to other sites where no pumping test was carried out, thereby characterising an aquifer system over a large area.

Numerous studies have stated the potential benefits of using geophysics studies to characterise aquifers. Yadav and Abolfazli (1998) pointed out that the approach may be used in areas of low aquifer permeability such that using pumping tests may be difficult to obtain a better understanding of the hydraulic characteristics. The approach may also be preferred when there is not enough pumping test data thereby providing a better spatial distribution of aquifer hydraulic properties of an area (Ugada et al., 2014; Soupios et al., 2007). Furthermore, this approach can be used to map variations in the layered formations and structures such as fractures within rocks. Vouillamoz et al. (2008) suggested that the use of non-invasive geophysics methods such as magnetic resonance is helpful in remote semi-arid areas where there are only pumping boreholes with no observation boreholes. Chen et al. (2001) argued that the traditional way of characterising aquifers such as flow meter and slug tests are costly, time consuming and invasive therefore geophysics methods may be appropriate. This is sustained by Wempe (2000) who argued that using geophysical data to understand the structure of rocks is advantageous because it is less expensive and data is more spatially abundant than lab or field measured data. As such, the method is capable of providing rapid, dense and low-cost coverage hydrogeological data.

In general, geophysics methods provide spatially distributed physical properties in areas that are difficult to sample using other methods. However, Paillet and Reese (2000) argued that the principle limitation in using geophysics to characterise aquifers is that it does not give direct estimates of hydraulic properties of aquifer materials. The parameters are estimated on the basis of various formation models which require independent estimates of various constants. As a result, reliable values for these constants may not be available for a given study or sometimes the estimates are only approximate (Paillet and Reese, 2000).

There are many geophysical techniques which have been developed to characterise aquifers including seismic, electrical and electromagnetic techniques. It is recommended that at least two of the geophysical exploration techniques be used in aquifer characterization (Vereecken et al., 2005). For groundwater studies near the surface (depths of less than 250 m) electrical and electromagnetic methods are commonly used (K'Orowe et al., 2011). Soupios et al. (2007) used surficial geophysical methods to estimate aquifer hydraulic parameter in a semi-arid shallow sedimentary aquifer whereas Chandra et al (2008) estimated the hydraulic conductivity and transmissivity of hard rock granite aquifer from geoelectrical measurements.

Fluid geophysical borehole logging techniques have also been used in identifying the geological layering of a site, aquifer properties as well as vertical distribution of permeability. It is evidenced that fluid electrical conductivity (EC) logging can be used to characterize the vertical and lateral variations in salinity of the groundwater bodies, identify groundwater flows in the boreholes and provide information on the past groundwater circulation (Buckely et al., 2001). The technique involves determining how the EC varies with borehole depth either in natural or stressed conditions whereby zones of fluid flow are identified by the anomalies in the EC profiles (Doughty and Tsang, 2005). Therefore, the fluid logging technique is suitable in fractured rock aquifers where the fractured zones become the major pathway for groundwater flow.

Different studies have used a series of methods to obtain information on hydrogeological characteristics. Such integrated approaches are useful for proper characterization of aquifers since each method has some limitations. For instance, Paillet and Reese (2000) combined lithologic logs, geophysical logs and hydraulic tests to characterise a heterogeneous aquifer. Meanwhile, Al Badi (2013) integrated geological, hydrologic, aquifer hydraulic parameters to characterise a shallow quaternary alluvium aquifer with special attention to distribution of hydraulic conductivity, specific yield and aquifer geometry.

3.4 Characterising the spatial and temporal variation in aquifer-river interaction

Understanding the spatial and temporal variations in aquifer-river interaction is critical in the scientific management of water resources and aquatic ecosystems (Fleckenstein et al., 2010). Aquifer-river interaction is mainly characterised as connected or disconnected systems. Connected systems means that a river is gaining water from or losing water to a local groundwater system while disconnected systems are defined by an unsaturated zone which prevents active interaction beneath the surface water system and the aquifer (Banks et al., 2011). Therefore, in order for aquifers to have an influence on rivers there should be such a connection between the two water bodies. The interaction can be investigated at a local scale within river reaches or at an entire regional river system comprising multiple river reaches. The water exchange fluxes have an implication on both quantity and quality of either resource, water resource allocation and on groundwater dependent ecosystems (Sophocleous, 2002; Woessner, 2000).

Different methods have been used to assess the interaction between aquifers and rivers. Brodie et al. (2007) documented a wide range of methods including seepage measurements, field observations, ecological indicators, hydrogeological mapping, geophysics and remote sensing, hydrographic analysis, hydrometric analysis, hydrochemistry and environmental tracers, artificial tracers, temperature studies, water budgets and the use of modelling. They argued that some methods such as field observations or chemistry are also used to provide important information on catchment scale connectivity as well as on targeted areas for detailed investigation. Meanwhile, a detailed understanding and quantification of key process may involve the use of simple tools such as seepage meters or mini-piezometers. Brodie et al. (2007) pointed out that it is essential to use a combination of different methods in order to confirm the interpretation as well as to extrapolate findings in space and time. This study focuses on a review of the methods which provide qualitative understanding of the interaction processes at a local catchment scale.

One of the various methods to assess aquifer-river interaction is hydrometric analysis, which involves determining the hydraulic gradient between groundwater and surface water levels and the hydraulic gradient of the intervening aquifer and bed material (Brodie et al., 2007). Hydrometric analysis is based on Darcy’s law and is most commonly used to study groundwater movement in terrestrial aquifers (Menció et al., 2014). Therefore, water table and potentiometric surface maps can be used to provide information on distribution of hydraulic head throughout the aquifer system and eventually used to characterize the interaction between the two water bodies. Lines drawn joining points of equal hydraulic head (or groundwater potential) are referred to as equipotential lines and the construction of equipotential contours results in potentiometric surface map (Hiscock, 2005). This means that areas of high hydraulic head may be interpreted as active recharge zones while areas of low hydraulic head are typically groundwater discharge zones. Parsons et al. (2008) and Mencio et al. (2017) used a water table elevation map to determine the direction of the groundwater flux and its relationship with the river. Based on the shape of the aquifer potentiometric map, it was shown that contours pointing down the river indicate that the river is losing to the aquifer and contours pointing up the river indicate river gaining conditions. Meanwhile, hydraulically neutral conditions (no flow-relationship) showed contours approximately perpendicular to the river.

Interactions between aquifers and rivers can also be assessed through the use of mass balance methods. These methods are valid based on the assumption that losses or gains in surface water or changes in the properties of the surface water is related to a specific water source including groundwater (Kalbus et al., 2006). Water and chemical mass balance methods include the use of incremental streamflow methodology, stream hydrograph separation and hydrochemical and environmental and solute tracers (Kalbus et al., 2006).

The chemical composition of groundwater is mainly influenced by its origin, the rock type hosting the water as well as hydrogeological characteristics of the area under study (Appelo and Postma, 2005). Usually, it is expected that groundwater would have higher concentrations of dissolved constituents than surface water since groundwater is more exposed to soluble materials in the different geological formations (Todd and Mays, 2004). However, this would be mostly applicable when the surface water body is not contaminated, for example, from anthropogenic activities. 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).

Analysis and interpretation of environmental tracers has been widely used to determine sources of water and dissolved chemicals within a catchment and thereby characterize aquifer-river interaction process (Winter et al., 1998; Menció et al., 2014). The relationship between dominant composition (water type) between any two water bodies usually indicate trends along the flow path or mixing between such water bodies. The use of chemical mass balance is widely applied since the method also determines the spatial and temporal dynamics of chemical loading to a river or an aquifer (Keery et al., 2007). In most cases, groundwater chemistry is different from the chemistry of the connected river (Weight, 2008). Again, natural tracers are used on the basis that the mixing of end members has a distinctive physico-chemical, chemical or isotopic composition. Therefore, the degree to which groundwater chemistry deviates to the chemistry of the river can be used as an indicator of mixing among the various water sources.

The chemical mass balance method would be preferred in non-perennial rivers as it would allow sampling, measurements and determinations from such segments within a river which are not flowing, for example in pools, thereby allowing better spatial distribution. This is contrary to other methods such as hydrograph separation which require measurements from flowing water. Brindha et al. (2014) analysed for major ions in groundwater and surface water to assess the interaction and it was found that the pattern of ion dominance and the dominant water types were the same for both groundwater and surface water. This indicated that groundwater and surface water were of the same type chemical composition and hence there was interaction between the two systems.

Field physico-chemical parameters (such as electrical conductivity, temperature and pH), major ions and stable isotopes are commonly used to argue possible mixing and qualitatively evaluate fluxes. The use of electrical conductivity (EC) mapping can show to differentiate between groundwater and surface water ionic strengths (Harvey et al., 1997). If a given section of a river is recharged from discharge of groundwater, change in the EC would occur whereas a river reach which is not connected to groundwater is not expected to have major modification of the EC (Weight, 2008). Typically, groundwater has higher total dissolved solids than surface water and therefore have greater ionic strengths and greater electrical conductivities (Harvey et al., 1997). As such, groundwater discharge zones may be identified by their elevated EC relative to that of surface water. Using the EC and water type characteristics, Moseki (2013) confirmed of the interaction between groundwater, river and the surrounding pools. The EC from the pools, river water and groundwater were of the same order. Furthermore, the pool water and groundwater plotted on the same area of the piper diagram and they both had the same water type suggesting that there is mixing between the water bodies.

Groundwater temperatures are relatively stable over a year whereas river water temperatures tend to vary on daily and seasonal basis due to air temperature, rainfall, stream inflows and solar radiation (Kalbus et al., 2006; Oxtobee and Novakowski, 2002). Time series temperature data helps identify gaining river reaches when relatively constant temperature is evident and losing or disconnected reaches are identified by rapid diurnal temperature changes. Brodie et al., (2007) suggested that it is necessary to install temperature equipment below the streambed to detect significant temperature variations. Continuous time series temperature data needs to be recorded in both surface and groundwater if the method is used to achieve the desired information. Long term temporal temperature data ensures proper characterization of river segments as being gaining or losing streams. In many cases, distributed temperature sensing technology provides improved spatial and temporal resolution (Westhoff et al., 2010). Temperature based methods are quick and easy to perform and therefore become attractive to use for detailed delineations of discharge and recharge zones with high resolutions (Kalbus et al., 2006). Yao et al. (2015) used high resolution temperature measurement data to characterise groundwater and hyporheic inflow zones in an arid region from where it was noticed that river sections with groundwater input had a larger decrease in water temperatures. Use of temperature, therefore, offers an opportunity for better understanding of the spatial and temporal dynamics in aquifer-river interactions in arid and semi-arid environments.

Environmental stable isotopes are widely applicable to characterize the possibility of interaction between the water bodies (Brodie et al., 2007). Environmental isotopes have the advantage over artificial tracers because they facilitate the study of various hydrogeological processes on a much larger temporal and spatial scale through their natural distribution in a hydrological system (Kovalevsky et al., 2004). Isotopic data has also been widely used to understand movement and occurrence of groundwater and identify groundwater recharge and discharge conditions. Aggarwal et al. (2005) argued that under arid and semi-arid conditions, isotope techniques constitute virtually the only approach for identification and quantification of groundwater recharge.

In water studies, the most commonly used stable isotopes are those of oxygen ($\delta^{18}O$) and hydrogen and ($\delta^{2}H$). In groundwater studies, applications of stable isotopes use the variations in isotopic ratios in atmospheric precipitation due to the fact that precipitation is the input to the hydrogeological system (Kovalevsky et al., 2004). Stable environmental isotopes are measured as the ratio of the two most abundant isotopes of a given element (Clark and Fritz, 1997). The ratios are expressed in delta (δ) units as per mil (‰) deviations relative to the known standard:

δ (‰) = $[(R - R_{standard}) / R_{standard}] \times 1000$

where R and $R_{standard}$ are the isotope ratios, $^{2}H/^{1}H$ or $^{18}O/^{16}O$, of the sample and the standard, respectively (Freeze and Cheery, 1979).

The main significant causes of the shift in relative ratio of the isotopes of oxygen and hydrogen are evaporation and condensation processes. The different forms of water have different vapour pressure and freezing points due to their different masses. This means that during evaporation of water and rainout from the atmosphere there are differences in ^{18}O and ^{2}H concentrations in water (Appelo and Postma, 2005). This results in meteoric waters being depleted in the heavy isotopes of oxygen and hydrogen relative to the ocean water while evaporative systems such as rivers and lakes become relatively enriched (Gat 1996). Therefore, correlating the oxygen and hydrogen isotopic values can help in establishing the origin of groundwater and the temperature during infiltration (Varsányi et al., 2015). This is because isotopically light molecules evaporate preferentially than the heavy ones making residual water enriched in heavy isotopes (Mazor, 2004).

The origin of the water is determined from location of isotope values in the $\delta^{18}O$ against $\delta^{2}H$ diagram such that samples plotting on the local meteoric water line (LMWL) are considered to be of meteoric origin whereas samples deviating from the LMWL could originate from other sources (Varsányi et al., 2015). Therefore, a difference in the isotopic composition of groundwater and river water would be expected. Meanwhile, isotopically depleted waters are associated with cold regions while enriched waters are found in warm regions (Clark and Fritz, 1997). This may relate that depleted waters (more negative isotope value) infiltrated in the colder period while enriched waters may have infiltrated in warmer period. These characteristics can be used to explain the recharge-discharge processes, origin of water and the possibility of the two water bodies interacting. In addition, isotope data can be used to complement the information obtained from geochemistry and physical hydrogeology (Clark and Fritz, 1997).

Moseki (2013) used environmental stable isotope data to assess interaction between a shallow groundwater system and a non-perennial river in the Eastern Cape Province of South Africa where it was found that the water samples from the boreholes and the river had similar isotopic signatures signifying possible mixing. All isotope data samples plotted nearer the evaporation line and both samples were relatively enriched with deuterium indicating a possible interaction between groundwater and the river water. Demlie and Titus (2015) used environmental stable isotope of hydrogen and oxygen as well as tritium radiogenic isotope and chemistry data to characterize a fractured rock aquifer from which they identified that recharge was from modern precipitation. Demlie et al. (2008) also used a combination of hydro-chemical and isotope data to assess groundwater occurrence and dynamics in a fractured volcanic aquifer system. They conceptualized the groundwater flow system into shallow fast circulating freshwater, mixed and moderately mineralized groundwater and deep, old mineralized thermal waters. Dindane et al. (2003) characterized a heterogeneous shallow aquifer using hydro-chemical and isotopic data where it was found that groundwater recharge followed a long flow path and there was mixing between old and modern water. Bouchaou et al. (2008) applied multiple isotopes and geochemical tracers to investigate sources of recharge, salinization and residence time in a shallow alluvial aquifer. They found that the major sources of recharge were the high mountains, old water was being used and that agricultural return flow and seawater intrusion were some of the sources affecting groundwater quality.

As recommended, researchers have used combination of the methods to characterize the groundwater surface water interaction. Yang et al. (2012) characterized interactions between groundwater near the river and surface water based on comparison of surface water with groundwater levels, stable isotopes and major ion signatures. Andersen and Acworth (2009) investigated the interaction between an aquifer and a stream using temperature and electrical conductivity and head gradient between the stream and adjacent boreholes. Oxtobee and Novakowski (2002) air photo interpretation, electrical conductivity and temperature surveys, hydraulic head measurements and isotopic analysis to understand exchange processes between a fractured rock aquifer and a bedrock stream.

3.5 Hydrogeological conceptual modelling

A hydrogeological conceptual model is a qualitative and pictorial description of the groundwater flow system in the form of block diagram or a cross section (Anderson and Woessner, 1992). Due to the complicated nature of groundwater problems, it is usually difficult to thoroughly understand complex hydrogeological systems. Therefore, a conceptual model serves to simplify the field conditions and organize the various flow processes so that the hydrologic system can be analysed with ease. This involves making assumptions that summarize the understanding of how water enters, flows and leaves the aquifer system which provides a conceptual model as a theoretical form of water mass balance calculation. As such, conceptual groundwater models are used to improve knowledge of groundwater flow processes in order to test existing hypotheses of how specific systems behave and predicting response to various environmental stresses (Turner et al., 2015). Therefore, development of a conceptual understanding is an iterative process such that it should be updated as more data become available and as the understanding is improved. Conceptualization of groundwater flow system is necessary for future numerical modelling which can be used by decision makers to manage water resources.

Constructing groundwater conceptual models involve initially defining the geological framework (cross section) and delineating the lithology, aquifer thickness and confining units (Rushton, 2003). Information to produce the geological framework may be obtained from the geological maps, borehole logs, geophysics and field mapping. The geological framework is followed by the development of the hydrologic framework which involves identifying the boundaries of the hydrologic system, defining hydro-stratigraphic unit, preparing a water budget and defining the flow system (Betancur et al., 2012).

Younger (2007) provided the two types of boundaries in hydrogeological studies: physical boundaries which are associated with real geological or landscape features and conceptual boundaries which are defined in terms of the hydraulic characteristics. Physical aquifer boundaries include outcrop area of the aquifer strata, a fault, a river cutting into an aquifer and the coastline along which an aquifer meets the ocean. A groundwater divide and a flow line are some examples of conceptual boundaries.

A hydro-stratigraphic unit is defined in order to determine number of layers controlling groundwater flow in a system (Wilson, 2005). This means that estimates of the aquifer hydraulic properties and hydrochemistry parameters are used to distinguish different hydro-stratigraphic units. The hydro-stratigraphic units are either categorised as aquifers, aquitards or aquicludes depending on their capabilities of transmitting water.

Development of the groundwater mass balance involves the identification and quantification of various inflow and outflow components of a groundwater system. The input to a groundwater system is referred to as recharge which may be as a result of precipitation or surface water infiltration. Outflows are in the form of abstraction, baseflow and evapotranspiration. It is at this stage of developing a conceptual model where flows between the aquifer and its surroundings is determined and the interaction between groundwater and surface water is evaluated (Izady et al., 2014). Once the groundwater budget is developed, the dominant direction of groundwater flow may be evaluated where recharge and discharge areas are identified and indicated.

The final stage in the development of the model involves integrating all the forms of geological and hydrologic data in the study area, since the groundwater flow model is a form of mass balance (Izady et al., 2014). Geological frameworks are constructed using data from borehole logs, geophysics and geological maps whereas the hydrologic framework is produced from such data as groundwater levels, aquifer hydraulic properties and hydrochemistry and isotopes.

Weitz and Demlie (2014) integrated and interpreted geological, hydrological, groundwater level, hydrochemical and environmental isotope data to conceptualize the hydrogeology and understand the groundwater-surface water interactions of a Lake catchment lying within a coastal plain. The developed conceptual model indicated that groundwater and surface water in the area were highly connected where in some sections the aquifer fed the surface water body and the opposite was observed in other sections of the catchment. While assessing the origin of groundwater in an aquifer under semi-arid climate, Dindane et al. (2003) used isotopic and hydrochemical composition in combination with the geological and hydrogeological data. Olayinka et al. (1999) used a combination of geological, geoelectrical, static water level, and hydro-chemical investigations to identify the nature of groundwater occurrence and flow pattern. These studies indicate the need for a comprehensive understanding of the hydrogeological characteristics for evaluating and conceptualizing the groundwater flow system and how groundwater interacts with surface water bodies.

3.6 Theoretical and conceptual frameworks

Darcy Law, an empirical law, which explains the flow of fluid through a porous media is employed as the theoretical framework for this study. Darcy Law is valid for slow laminar flow and it works on the fact that the amount of fluid flow between two points is directly related to the difference in hydraulic head between the two points, the distance between the points, and the interconnectivity of flow pathways in the rock between the points (Younger, 2007). The area of highest hydraulic head often coincides with where aquifer sediments outcrop and allow high groundwater recharge (Reid et al., 2009). Meanwhile, the lowest hydraulic head coincides with discharge areas and surface water features such as wetlands, streams or lakes. The ability of the medium through which the fluid is flowing (interconnectivity) determines the hydraulic conductivity whereas the difference between the points creates the hydraulic gradient. Hydraulic conductivity describes how easily groundwater flows through a particular type of rock or soil. This depends on the porosity and permeability of the aquifer. Meanwhile, hydraulic gradient indicates the slope of the groundwater level from which groundwater flow direction can be determined.

In general, Darcy's Law provides a basis for description of groundwater flow in all hydrogeological environments. These are homogeneous and heterogeneous systems, isotropic and anisotropic media flows, fractured rock or granular media, steady state and transient flows, flow in aquifers and aquitards as well as for saturated and unsaturated flows (Freeze and Cherry, 1979). Groundwater flow is mainly influenced and controlled by the aquifer geometry and geology. The flow of groundwater can be considered at micro level through to large regional flows whereby geology and topography determines these flow scales.

Darcy's Law has several principles: (i) flow will not occur if there is no pressure gradient over a distance (ii) if there is a pressure gradient flow will occur from high pressure towards low pressure (iii) the greater the pressure gradient through the same material, the greater the discharge rate (iv) the discharge rate will be different through different formations even if the pressure gradient is the same in such differing formations (Freeze and Cherry, 1979). In fractured rock aquifers, Freeze and Cherry (1979) argued that Darcy Law is valid if an assumption is made that the fracture spacing is sufficiently dense that the fractured media hydraulically acts in the same way as granular porous media.

For groundwater to have an influence on other water bodies including non-perennial rivers, there must be some form of flux between the two water bodies. The magnitude of flux depends on the connectivity between the aquifer and the river and the extent to which the channel of the river intersects the saturated part of the aquifer (Hiscock and Bense, 2014). Therefore, the theory of Darcy Law has been used in this study to interpret data, understand groundwater flow system in the study area but also used as a guide to answer the research question posed in this study.

Hydrogeological characterisation is employed as a conceptual framework for the current study. Hydrogeological characterisation involves evaluating various characteristics of the aquifer using different forms of data. This include evaluating the structure (geology), hydraulic properties and the chemistry of aquifers. The aquifer structure is evaluated to delineate groundwater units and establish the manner in which groundwater occurs in an area. The aquifer hydraulic parameters include the hydraulic conductivity, transmissivity, storativity, specific yield and porosity. These physical properties determine the storage capacity and how much the aquifer can release water. Analyses of water chemistry is conducted to aid decision relating to quality of water for various uses as well as understanding of groundwater flow mechanisms. In general, hydrogeological characterization may be carried out to help inform the sustainable use and management of aquifers and their interaction with other water bodies. This study used the concept of hydrogeological characterization to answer the research question "To what extent can hydrogeological characterization be used to explain the availability and influence of groundwater on non-perennial river systems".

Chapter 4: Research design and methodology

4.1 Introduction

The current chapter aims at describing and explaining the research design and methodology that were followed to collect and analyse the necessary data for the research project in order to answer the research question and objectives set in the first chapter. The chapter therefore covers the following aspects: the research design approach, data collection and analysis methods, quality assurance and quality control and research integrity.

4.2 Research design

4.2.1 Research design approach

The study was designed to follow an integrated approach by assessing different characteristics influencing groundwater flows, hydrochemistry and the interaction between aquifer and rivers in general. An experimental study type was followed through the use of a field trial where measurements were conducted at different sites within the study area. This approach was used as it allows the assessments (quantitative and qualitative) to be done during both dry and wet periods in order to incorporate possible seasonal variations in the measured data.

4.2.2 Sampling design

The current study used a purposive sampling design, which is the type of non-probability sampling in which the units to be observed are selected on the basis of researcher's judgement (Mouton, 2001). The technique is selected based on the characteristics of a sampling population and the study objectives to explain and characterise the possibility of interaction between the aquifer and non-perennial rivers. Therefore, samples from the rivers were collected at points which are close to the boreholes and piezometers.

4.3 Research methodology

This research study employed a quantitative research methodology. Quantitative research methodology is an approach for testing objective theories by quantifying variables and examining the relationships between variables. Quantitative research involves generating numerical data which can be transformed into useable statistics as well as being used to uncover patterns in the research. In this study, numerical data were collected and analysed on groundwater levels, aquifer hydraulic parameters, hydrochemical and isotopic composition as well as other components of the groundwater balance were made.

4.4 Data collection and analysis methods

4.4.1 Aquifer characterization

The first objective of this study is to characterize the aquifer systems by analysing the groundwater levels, determining aquifer hydraulic parameters through the use of aquifer tests as well analysing the structural characteristics of the rocks from electrical conductivity logging and geological maps. The hydraulic parameter of interest in this study is transmissivity to help explain groundwater flow.

Regarding the aquifer hydraulic parameters, aquifer tests were conducted in 3 boreholes that were drilled prior to this study. Pumping was conducted using a 0.37 kW (0.5HP) submersible pump and a 6.5 kW generator. Appropriate discharge rates were achieved by observing the time it took for the discharging water to fill up a 25 *l* bucket. A plastic ball valve placed at the bottom of the bucket was used to control and attain the required the discharge rate. The pumped water was discharged at a distance of greater than 80 m from the pumping hole, thereby preventing the water from recharging the aquifer which would affect the test results.

A constant rate test was conducted at each tested site since the aim was to estimate the hydraulic parameters. A preliminary (trial) aquifer test was conducted to determine the suitable pumping rate for the tests. A low pumping rate of 0.5 *l/s* was decided for the trial tests since most of the boreholes were dry during drilling, from where a high drawdown of 17 m in 30 minutes was observed. This further gave an idea that the sites are of low yielding. For this reason, it was decided that the main pumping test should be conducted at a lower rate than 0.5 *l*/s.

In general, the selected pumping rate should be large enough to ensure that drawdown can be measured accurately in the pumping well but should not result in excessive drawdown. A pumping rate of 0.35 *l/s* was chosen for Spanjaardskloof site, 0.29 *l/s* for Uitsig site whereas the borehole at Moddervlei site was pumped at a rate of 0.24 *l/s*. The boreholes were pumped for an average time of 1 hour with the recovery period ranging between 2 – 3 hours. Step-drawdown tests were not conducted because the purpose in this study was to determine the storage and hydraulic aquifer parameters which are mainly governed by the aquifer physical properties and not by the abstraction rate. Storativity and hydraulic conductivity are inherent aquifer properties which in an average homogeneous aquifer should remain constant irrespective of the abstraction rate (Gomo, 2011). Meanwhile, step-drawdown tests are conducted to check performance efficiency of pumping boreholes which is useful when deciding on the maximum yield which an individual borehole can sustain.

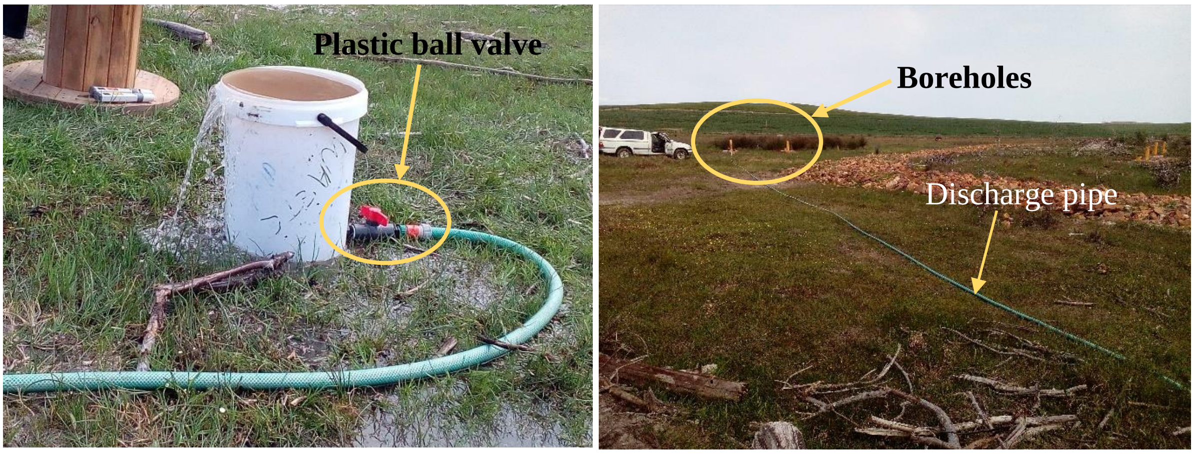


Figure 4.1: The plastic ball valve for discharge control (left) and the discharge pipe (right)

Solinst automatic groundwater level loggers (Model 3001) with a 0.05% full scale accuracy were used to monitor depth to groundwater levels during both the pumping and recovery period. The loggers were set to take measurements at 2 minutes interval for the entire test. The level logger measures absolute (total) pressure, therefore, the actual water pressure was calculated by subtracting barometric pressure from the absolute pressure. A barologger was placed in one of the boreholes above the water level to measure the barometric pressure. In addition, depth to groundwater levels were taken manually using an OTT KL 010 water level meter during the tests at different time intervals as check measurements. Drawdown was measured by subtracting all subsequent depth to groundwater levels from the initial static water level.

Analysis of aquifer tests data is done according to characteristics of the borehole, aquifer system and test configurations (Kruseman and de Ridder, 1994). These include Theis (confined), Cooper-Jacob time drawdown (confined), Cooper-Jacob distance drawdown (confined), Hantush and Jacob (leaky-confined), Nueman (unconfined), Moench (unconfined) and Moench (fracture flow) (Kruseman and de Ridder, 1994).

Constant rate pumping tests are most often interpreted using the Theis (1935) or the Cooper-Jacob’s (1946) semi-logarithmic approximation (Meier et al., 1998). Different researchers have analysed drawdowns in confined and unconfined aquifers using the Cooper-Jacob regardless of differences between field conditions and theory. However, if the method is to be used in unconfined aquifers there is need to ensure proper interpretation of late-time data when well bore storage effects have dissipated (Halford et al., 2006).

Based on the drilling logs, the aquifer was considered to be unconfined. The Cooper-Jacob method, which is an adaptation of the Theis method, was used to analyse the pumping test data. This is because the method is not only relatively simple to use but also with the plots of time drawdown it can provide visual evidence for the presence of aquifer boundaries. For example, a barrier boundary causes drawdown to steepen beyond what would be expected while a recharge boundary (such as inflow from a river) leads to a lessening of the drawdown (Younger, 2007). The Cooper-Jacob method is also preferred as it removes the influence of well skins and partial penetrations which would otherwise interfere with the ideal conditions (Butler, 1990). Using the time drawdown method, the following relations was used to calculate transmissivity:

$$T = \frac{2.3Q}{4\,\pi\,\Delta s} \qquad (4.1)$$

where T is the transmissivity in (L^2/T); Q is the average discharge (flow rate) in (L^3/T) and Δs is the hydraulic gradient (change in drawdown) between two points over one log cycle (L) of time.

The applications of these method can be done manually using logarithmic plots, however, several software (computer programs) have been developed to determine the various aquifer hydraulic parameters. AQTESOLV Pro^{TM} version 4.5 software was chosen for the analysis of these aquifer test data since it allows for the analysis of both pumping and slug test data as well as single well and multi-well test data. The software also allows for a visual and automatic curve matching to solution type curves. Furthermore, the software provides solutions for various pumping test scenarios including constant rate, step drawdown and recovery rate. Depending on the aquifer type for the boreholes in the study area, an unconfined analytical solution was used to estimate the aquifer parameters.

In order to provide a further insight on the subsurface lithology of the sites under study, electrical conductivity (EC) logging was conducted in all the boreholes. A YSI 600 V2 Optical

Monitoring System probe which measures EC, pH, temperature and the pressure of the water column was used for logging the borehole. Firstly, the probe was tied to a rope and then dropped into the borehole for 3 – 5 minutes in order to acclimatize to the borehole conditions before it was taken out (to the atmosphere conditions) for approximately 3 minutes. The probe was then lowered into the borehole again at 30 cm interval with an average time of 20 seconds at each depth until the probe reached the bottom of the borehole. The collected data was downloaded and processed using an EcoWatch Lite software.

Groundwater levels were continuously obtained by the data Solinst automatic groundwater level loggers described above. The loggers which were installed in four sites across the catchment were programmed to collect water level data on an hourly basis. The same analysis as described above was applied from which finally the hourly water levels were converted to average daily measurements. Meanwhile, groundwater levels for other boreholes and piezometers which had no data loggers were monitored using a manual water level meter approximately every two months. The groundwater level data was monitored for a period of 13 months from June 2017 to July 2018.

4.4.2 Characterizing temporal and spatial variation in aquifer-river interaction

There are a wide range of methods for assessing the interaction between aquifers and rivers namely 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. This study used the hydrochemistry and environmental tracer methods since they can provide information on connectivity at a catchment scale as well providing spatial and temporal dynamics of chemical loading to a river or an aquifer (Brodie et al., 2007).

Water samples were collected along the rivers as well as from the boreholes and piezometers available in the catchment during both wet (rainy) and dry periods. Sampling period in October 2017 is representative of the wet period which is characterised by more rainfall, high river flows, and low evapotranspiration while the March 2018 data is representative of the dry period with high evapotranspiration and low flows. Water samples were collected in polyethylene water bottles of 200 ml capacity. The bottles were manually filled beneath the surface of the water (grab sampling) at the middle depth of the river/pool in order to get a representative water sample. For deeper water in a river, a well rinsed bucket was used to collect the water from the river from which it was transferred to the sample bottle. Groundwater samples were collected after purging at least three volumes of a bailer depending on the borehole depth. The samples were only collected after the pH, temperature and electrical conductivity had stabilized. The groundwater samples were collected using a point source bailer connected to a marked cable tagline thereby allowing it to sample at a specific depth. This means that water was sampled around the borehole screen area in order to collect a representative sample of the aquifer chemistry. Two of the groundwater samples were collected directly from free flowing artesian boreholes. Meanwhile, water samples from piezometers were collected using a disposable bailer. Groundwater samples collected from wells close to the rivers were assumed to be representative of the groundwater around the rivers.

Figure 4.2: A stainless-steel point source bailer with a tagline for collecting groundwater samples

New sampling bottles including the cap were rinsed with sample water for three times before collecting the final samples. When re-using the bottles for sampling, the bottles were rinsed with dilute hydrochloric acid solution and were soaked in deionised water a few days before the sampling. The bottles were then rinsed with the sample water before collecting the sample. Water samples for isotope analyses were collected in double capped 50 ml polyethylene bottles to prevent isotopic fractionation due to evaporation. In cases where samples contain suspended sediments or particles, a 0.45 µm membrane filter was used to remove such particles as suggested by Hiscock (2005). A Garmin eTrex 30x Global Positioning System (GPS) was used to locate the sampling points and where necessary permanent marks were placed on such points to ensure that same points are sampled throughout the study. Temperature, pH value, dissolved oxygen and electrical conductivity were measured *in-situ* using a Hach^{TM} HQ40D portable multi-parameter probes since these parameters do change once the water samples are exposed to ambient conditions and during storage and laboratory analysis (Hiscock, 2005). The parameters were only recorded when the meter had stabilized. The probes were calibrated before each field trip using standardized solutions within the EC and pH ranges in the study area. Samples were properly labelled, transferred and stored in a cool box at 4°C until analysis was carried out to prevent any potential evaporation which could have changed the chemical composition of water.

All water samples were analysed for major ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO^{3-}), sulfate ($SO_4{}^{2-}$) and chloride (Cl^{-}) since these ions comprise over 90% of all dissolved solids in groundwater regardless of whether the water is fresh or saline (Freeze and Cherry, 1979). These parameters were analysed at the Western Cape’s Department of Agriculture (Elsenburg) Production Technology Laboratory using Radial ICP Spectrometer - Thermo Scientific Model number ICAP 7600. Alkalinity as bicarbonate was determined within 6 hours after collection using HACH burette titration method. Phenolphthalein indicator powder pillow, Bromcresol green-methyl red indicator powder pillow and Sulfuric acid standard solution (0.020 N) were used as the reagents for the titration process. The total alkalinity was equal to the bicarbonate alkalinity for all samples.

Measurements for stable environmental isotopes of oxygen and hydrogen were done at the Earth Sciences Department of the University of the Western Cape’s using an LGR DLT-100 Liquid Water Isotope Analyzer (Model 908-0008-2010), manufactured by Los Gatos Research Inc. (Mountain View, California, USA). The results were represented as deviation from Vienna Standard Mean Ocean Water (VSMOW) in per mil (‰) difference using delta (δ) notation from the equation:

$$\delta^{18}O\ (\delta^{2}H) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \text{ x } 1000 \qquad (4.2)$$

where R is the isotope ratio of the heavy to the light isotope ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) in both the sample and the standard. The sample ratios were standardized using a range of standards (high and low) calibrated against VSMOW2 and SLAP2 standard reference materials. The measurement accuracy was below 0.6‰ and 0.2‰ for $\delta^{2}H$ and $\delta^{18}O$, respectively. For referencing purposes, the resulting stable isotope data were plotted along with the local meteoric water line and global meteoric water line (GMWL). The Cape Town meteoric water line was used from data collected for a period between 1995 and 2008 while the GMWL was derived from the Craig (1961) equation: $\delta D = \delta^{18}O + 10$.

The major ions are represented either numerically or graphically using a contour map. However, this is disadvantageous since it is difficult to represent more than two or three substances on each map without the view being cluttered. This study, therefore, presented the major ion results in a Piper diagram. Piper diagrams consists of two trilinear diagrams (plots with three axes) and one diamond shaped mixed field. The trilinear diagram on the left-hand side represents the cation concentration while anion concentrations is represented on the right-hand side. Piper diagrams can plot numerous water analyses onto a single diagram and classify waters according to their chemical characteristics. The diamond shaped mixing field between the two trilinear diagrams allows the graphical interpretation of the mixing of two or more end member waters (Bair and Lahm, 2006). In this way similarities and differences between separate water analyses can be spotted, therefore, it is suitable for analysing spatial and temporal variations in interactions. The Geochemist's Workbench version 12.0 software was used to produce the diagrams. All field and laboratory measured data were captured in Microsoft Excel 2016 spreadsheet for ease of calculation and graph plotting. All spatial data analysis were done using ArcMap 10.3 for accurate plotting of various georeferenced maps including EC distribution.

4.4.3 Developing the hydrogeological conceptual model

Data integration of the geologic, hydrologic as well as recharge and discharge of the study area is used to develop the hydrogeological conceptual model. Information from the borehole logs and geological maps are compiled to construct the geological framework while the hydrological framework is developed from the aquifer hydraulic parameters, groundwater level data. This means that components of the study (findings from objective one and two) were used for the model development. Having collected all the necessary data, hydrogeological conceptual models that explain the role of groundwater on the river systems of the study area were sketched using Surfer 11 software. Information from environmental stable isotope and hydrochemical data is incorporated into the conceptual model.

The potential groundwater flow direction was determined by creating a groundwater level contour map. The depth to groundwater levels were measured using a water level dip meter while the elevation was determined using the GPS receiver. Therefore, the elevation of the groundwater level (hydraulic head) was calculating by subtracting the depth to water level from the surface elevation. Given this kind of data of more than three points, the groundwater contour map can be produced to deduce the direction of groundwater flow direction. The contours can be drawn manually by connecting points of equal heads (equipotential lines) from a minimum of three wells in a triangular configuration. However, a hand drawn procedure is labour intensive and time consuming, therefore, this study used the Vector Tool in Surfer (version 11) software since the software provides a quick and automated way of analysis and representation.

4.5 Quality assurance and quality control

All water samples were analysed in an accredited laboratory which is in accordance with the international standards. The field water quality parameters which changes during transportation and storage, were measured on site immediately during the sampling. During the measurement of water quality field parameters, the multi-parameter probe was calibrated on each field day. In addition, sample bottles were pre-rinsed for at least three times before collecting the sample for analysis. To ensure that same sites are monitored, a GPS was used locate the site and a permanent mark was placed in sites for easy identification. The reliability of the water quality results was checked by testing the error margin of major ion analysis. Since the major ions represent most of the dissolved ions, there is almost equal equivalent amounts of major cations and major anions in water in what is known as the principle of electroneutrality (Younger, 2007). This was done by conducting a Charge Balance Error (CBE) using the formula:

$$\text{CBE (\%)} = \frac{(\sum \text{meq cations} - \sum \text{meq anions})}{(\sum \text{meq cations} + \sum \text{meq anions})} \text{ x } 100 \tag{4.3}$$

It has been argued by some authors (Weight, 2004; Younger, 2007; Hiscock and Bense, 2014) that an ionic balance error of less than 5% is acceptable to be used for scientific investigations whereas errors from 5 – 10 % should be used with caution.

4.6 Research integrity

All field trips requiring more personnel involved students and technical staff from the University of the Western Cape to help with the work voluntarily. Legal considerations were adhered in this research by ensuring that permission was granted in all the sites before starting the experiment. These included all the sites where new groundwater monitoring were developed as well private boreholes.

This research applied several principles of ethical consideration. Most of the research sites, especially the boreholes, are located in private property. In order to access the sites, a request for permission was made to the farmers and South African National Parks who happen to be the rightful owners of the visited sites. The request was both in written and verbal form. This was done to achieve the principle of autonomous. The principle of justice was adhered to in this research by explaining to all the parties involved about the use of the data to be collected and the objectives of the research so that they are well informed. In addition, all the data requiring confidentiality were kept under such way such that they were not shared among other third parties neither used for other purposes apart from this research. The principle of beneficence was applied by ensuring that all the involved parties benefit from this research. Interested parties, for example the farmers, were provided with the research information and data upon request. Finally, the principle of non-maleficence was achieved by ensuring that no harm was done to the environment or property in whatsoever way in all the research sites.

Chapter 5: Aquifer characterization

5.1 Introduction

This chapter presents and discusses results on aquifer characterization of the study area, which forms the first objective of the current study. Firstly, interpretation on the geological characteristics and the hydraulic tests on selected study sites is provided. This aims to provide more understanding on the groundwater flow properties as influenced by the subsurface heterogeneities with the sites located in both upstream and lower elevation areas. The pattern and trends of groundwater levels is also determined in this chapter. The pattern of groundwater flow is controlled by the aquifer hydraulic properties as well as the configuration of the water table. This chapter, therefore, argues that in order to determine the aquifer influences in non-perennial rivers it is necessary to understand the hydrogeological controls to groundwater flows such that under natural conditions the exchange fluxes between the aquifer and the river would largely depend on the groundwater level hydraulic gradient and the aquifer hydraulic properties. Thus, in this study aquifer characterization is used to refer to the subsurface lithologic variations, the distribution of the aquifer geometry, hydraulic head and the aquifer hydraulic properties.

5.2 Borehole drilling and geological characterisation

Due to the poor distribution of groundwater monitoring points, new boreholes were drilled at four different sites within the study area. Three of the four sites (Spanjaardskloof, Boskloof and Uitsig) are located in upstream part of the study area and the other site (Moddervlei) is located on floodplain of Nuwejaars River. A total of 11 new boreholes, six shallow (8 – 20 m) and five deep boreholes (50 – 60 m), were drilled between May and June 2017. The boreholes were drilled to characterise the aquifer in order to determine the role of groundwater on the river systems of the study area. Boreholes in upstream areas are relatively far from the river compared to the boreholes in downstream areas. Understanding groundwater flow dynamics in uplands is important since groundwater discharge to rivers in such upstream areas support surface ecosystems both in the catchment headwaters as well as in the lower reaches of the river provided there is flow continuity.

Air rotary percussion method, which uses compressed air and a rotating bit to cause vibration and break rocks was used to drill the boreholes. Boreholes at Moddervlei site which is in a downstream area and near the Nuwejaars River are drilled in silt, sand, unconsolidated clay and shale formations. Meanwhile, at Spanjaardskloof, Boskloof and Uitsig the major formations are quartzitic sandstone with very fine grained (weathered) and coarse-grained units. The borehole lithologs are provided in the Appendix.

In an attempt to measure borehole productivity soon after drilling, a blow yield test was conducted in BH4 (50 m borehole situated at Moddervlei) where a blow yield of 1.3 *l/s* was observed. Meanwhile, in rest of the sites barely no water was blown out in the deeper (50 – 60 m boreholes) whereas shallow (20 m boreholes) were completely dry. This could be either due to improper siting of the boreholes or low borehole yield. Blow yield tests are conducted on a drilled borehole to give a preliminary indication on the rate at which groundwater can be pumped or abstracted from a borehole.

The boreholes are named in such a way that there is continuity from the other existing three boreholes in the study area. Table 5.1 provides the information of the boreholes. Meanwhile, the depth to water levels were measured two weeks after the drilling.

Table 5.1: Borehole information from the study area

Borehole ID	**Depth (mbgl)**	**Screen length (m)**	**Depth to water level (mbcl)**	**Surface elevation (mamsl)**
BH4	50	11.2	2.9	21
BH5	20	11.2	5.16	21
BH6	50	8.4	2.45	21
BH7	20	11.2	2.42	21
BH8	8	5.6	2.61	21
BH9	60	11.2	5.53	149
BH10	20	11.2	6.38	149
BH11	60	14	10.64	135
BH12	20	11.2	10.49	134
BH13	55	16.8	3.16	152
BH14	20	11.2	3.14	152

mbgl = metres below groundwater level, mbcl = metres below borehole collar level, mamsl = metres above mean sea level

The depth to groundwater levels in the study area ranges between 2 and 10 m in both high elevation and low-lying areas. The boreholes having deepest groundwater levels (about 10 m) lie around Boskloof with BH11 and BH12, although the site does not have the highest elevation (Table 5.1). The possible reason for the relatively deeper groundwater levels around Boskloof is likely to be due to the area being situated close to faults as such big drops in hydraulic gradient indicate the fault as a barrier to groundwater flow (Bense et al., 2013). However, a network of closely spaced groundwater monitoring points would provide more information on the role of fault zones on the hydraulic gradient, as successfully shown by Rajabpour and Vaezihir (2017).

5.3 Nature and trends of groundwater levels

Surface topography is one of the factors controlling the movement of groundwater as well as the interaction of groundwater and surface water bodies. The nature of the water table is important in conceptualizing groundwater flow systems and assessing the relationships between aquifers, rivers and its associated ecosystems. Therefore, it is necessary to consider how the surface topography relates to the occurrence of the water table. When the groundwater level elevation from the monitored months is compared to the surface topography, it is found that there is a good relationship between the two parameters. For example, in the month of July 2017, a plot of water level versus surface elevation demonstrates that there is a strong correlation ($R^2 = 0.9991$) (Figure 5.1). This is an indication that the study area has shallow groundwater levels such that the groundwater levels increase with increases in surface topography. This shows that the water table in the study area mimics the topography.

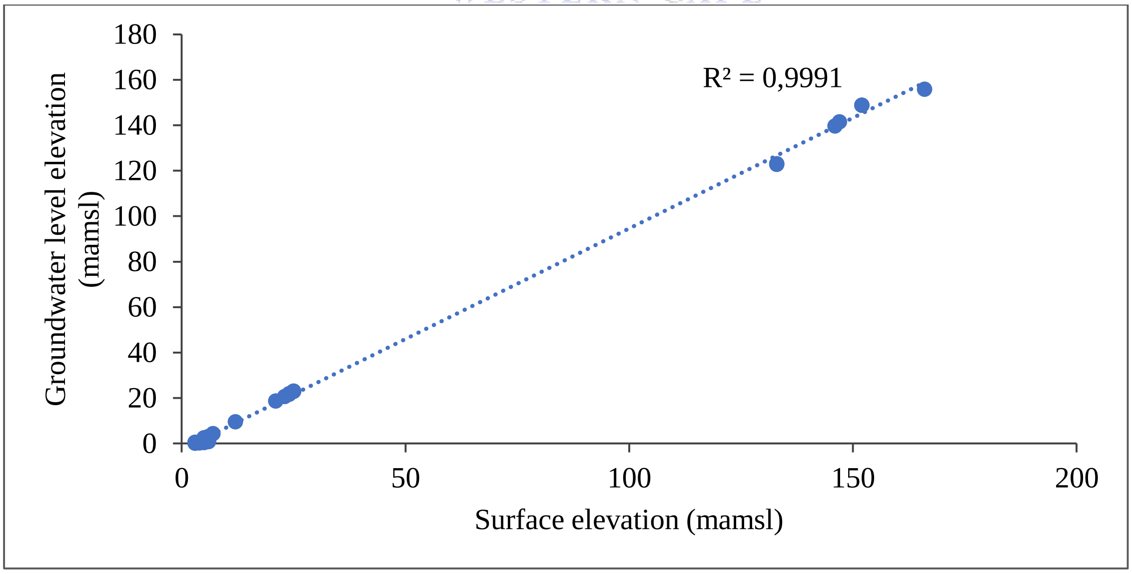


Figure 5.1: Scatter plots of depth to groundwater level against surface topography for July 2017

Under conditions where the water table mimics the topography, the average groundwater elevation is higher in highland than in lowland areas. Using the groundwater levels, two main groundwater flow regimes can be identified; the topography-controlled water table which closely follows the topography and the recharge-controlled water table which does not follow local topography but follows the regional topography (Hendriks, 2010). An illustration of the water table types is provided in Figure 5.2 (a) and (b). Based on such characterization, it can therefore be deduced that the study area has a topography-controlled water table such that groundwater will likely flow from high elevation to low elevation areas.

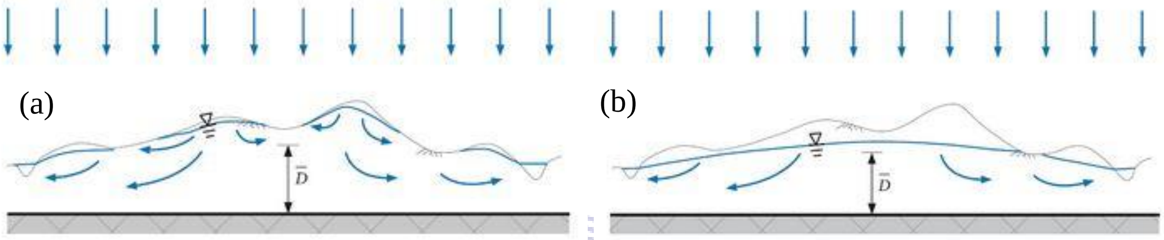


Figure 5.2: Groundwater flow regimes for a topographically controlled water table (a) and recharge-controlled water table (b). Illustration sourced from Hendriks (2010)

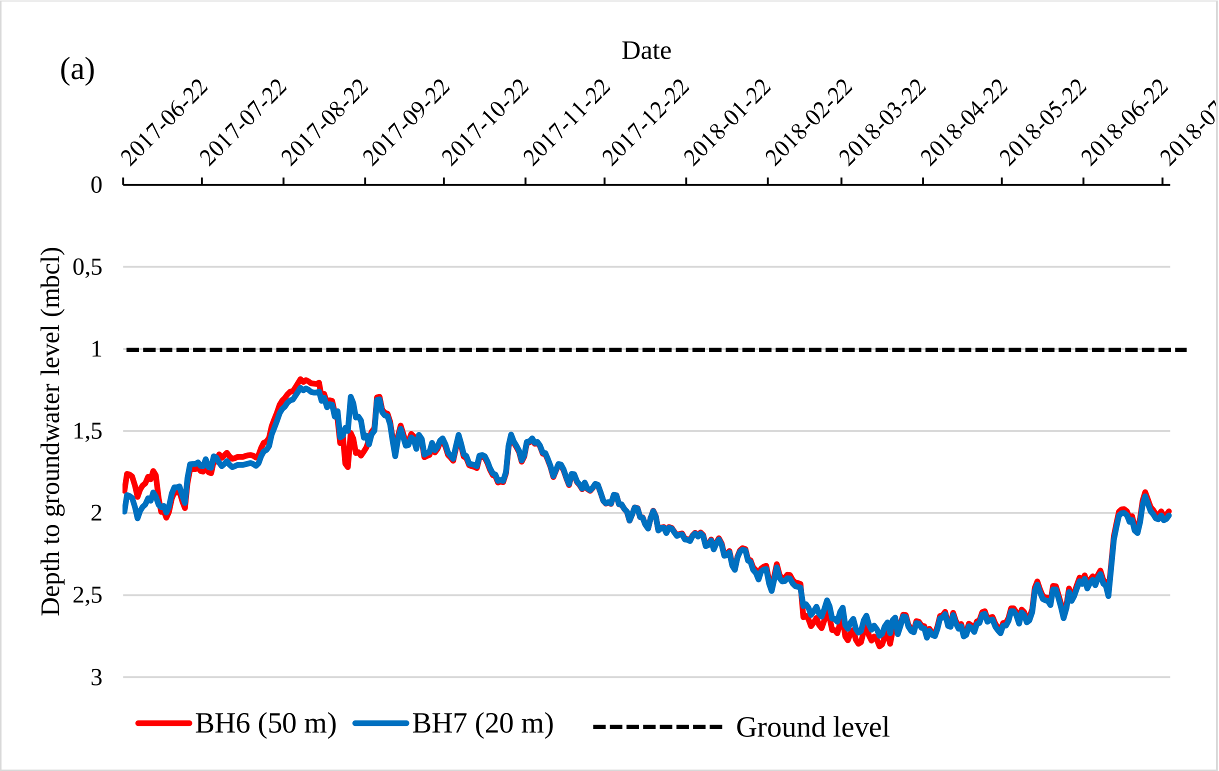
Groundwater levels are also compared in shallow and deep boreholes which have data loggers, from where continuous water levels were collected from June 2017 to July 2018 (Figures 5.3). Generally, results show that major head decline occurs in summer months from November to February due to low recharge, evapotranspiration and natural groundwater discharge. In this study groundwater head decline continues until April/May probably due to drought conditions prevalent during the study period. Decline in groundwater head results in the reduction in groundwater storage in an aquifer which would result reduced streamflow generation for a groundwater connected stream. Results of groundwater levels are presented in Figures 5.3 (a-d).

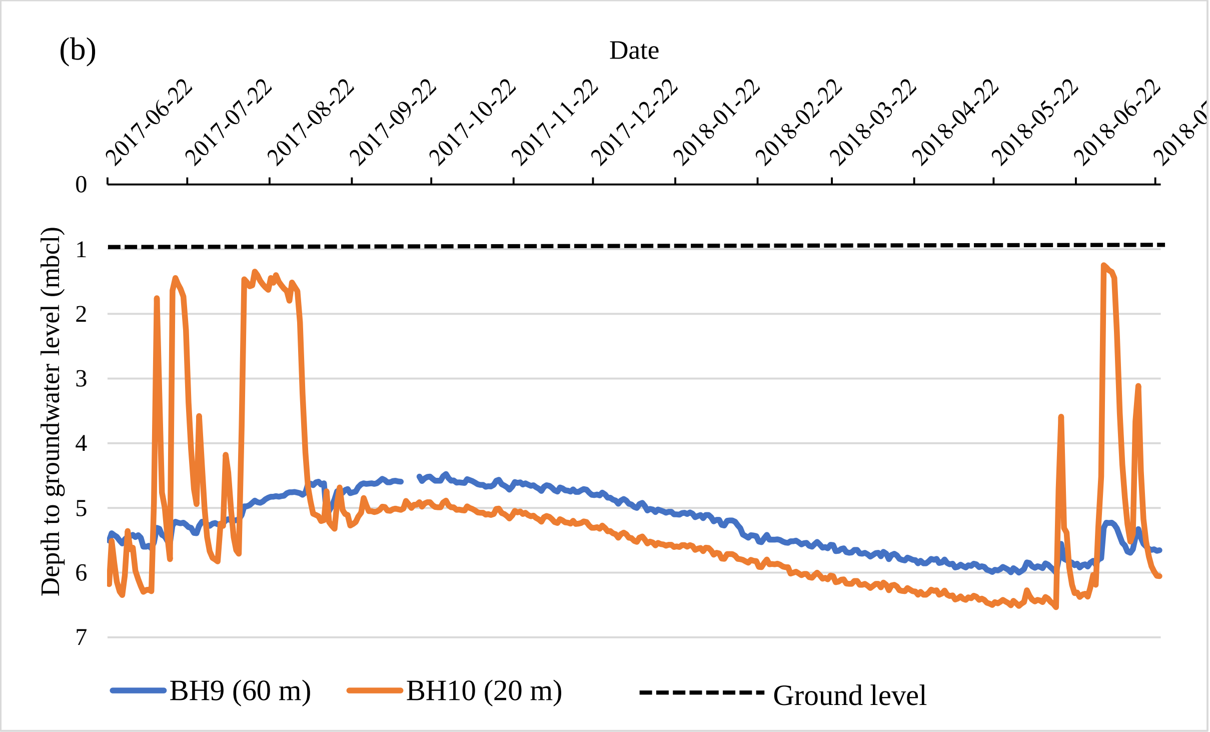
Groundwater level results from Moddervlei site show close groundwater levels and similar trend between the deep (BH6) and shallow (BH7) borehole over time (Figure 5.3a). This suggests there is connectivity between the shallow and deeper boreholes. During the wet period, boreholes show a good response to rainfall with the water table almost close to the surface.

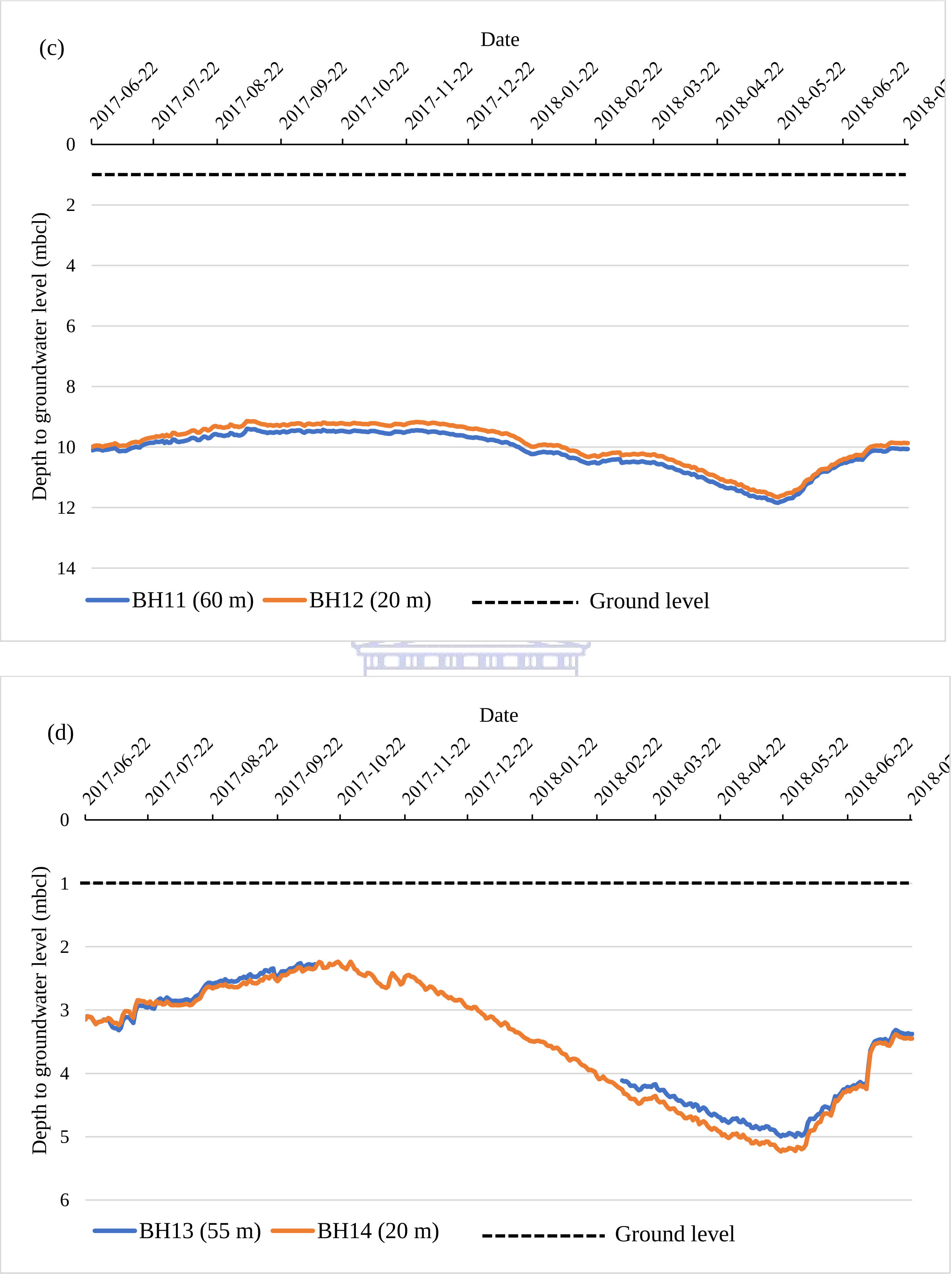
For Spanjaardskloof site, the deeper borehole (BH9) has a relatively shallow depth to groundwater level than the shallow borehole (BH10) (Figure 5.3b), suggesting upward vertical flows towards the upper Table Mountain sandstone units at the site. Meanwhile, groundwater levels from the shallow borehole show a direct and rapid response to rainfall events during the winter rainfall period, while there is gradual response to rainfall in the deep borehole. This indicates that the shallow borehole (BH10) experiences active and local recharge processes with short recharge paths. This water in the shallow aquifer drains away after a few days (Figure 5.3b) probably due to plant root uptake until the next rainfall event where the water level rises again rapidly.

Meanwhile, Boskloof site initially show no major variation during dry and wet periods for both shallow (BH11) and deep (BH12) boreholes up until March 2018, most likely due to the effects of drought conditions experienced during the study period. The site has relatively deeper depth to groundwater levels which results in a longer recharge path causing less variation in groundwater levels between the dry and wet periods.

Boreholes at Uitsig (BH13 and BH14) show a good response to rainfall whereby both shallow and deep boreholes have similar water levels during the wet season whereas during the dry season the deeper borehole has a slightly higher water level (Figure 5.3d). This site is close to springs, and the relatively shallow water levels from the deeper aquifer could be due to upward vertical and regional flows.


(a)
Date
2017-06-22
2017-07-22
2017-08-22
2017-09-22
2017-10-22
2017-11-22
2017-12-22
2018-01-22
2018-02-22
2018-03-22
2018-04-22
2018-05-22
2018-06-22
2018-07
Depth to groundwater level (mbcl)
0
0,5
1
1,5
2
2,5
3
BH6 (50 m)
BH7 (20 m)
Ground level


(b)
Date
2017-06-22
2017-07-22
2017-08-22
2017-09-22
2017-10-22
2017-11-22
2017-12-22
2018-01-22
2018-02-22
2018-03-22
2018-04-22
2018-05-22
2018-06-22
2018-07
Depth to groundwater level (mbcl)
0
1
2
3
4
5
6
7
BH9 (60 m)
BH10 (20 m)
Ground level



Figures 5.3 (a-d): Groundwater level trends during the study period, with each plot representing two boreholes located close to each other. The gaps in BH9 and BH13 are missing data due to faulty data logger

In general, there is a clear distinction in groundwater levels for the wet and dry periods. For the study period, groundwater levels during the wet and dry periods fluctuate approximately by 1.51 m at Moddervlei, 2.51 m at Boskloof and 2.85 m at Uitsig. Meanwhile, at Spanjaardskloof there is a fluctuation of about 1.13 m for the deep borehole and 4.98 m in the shallow borehole.

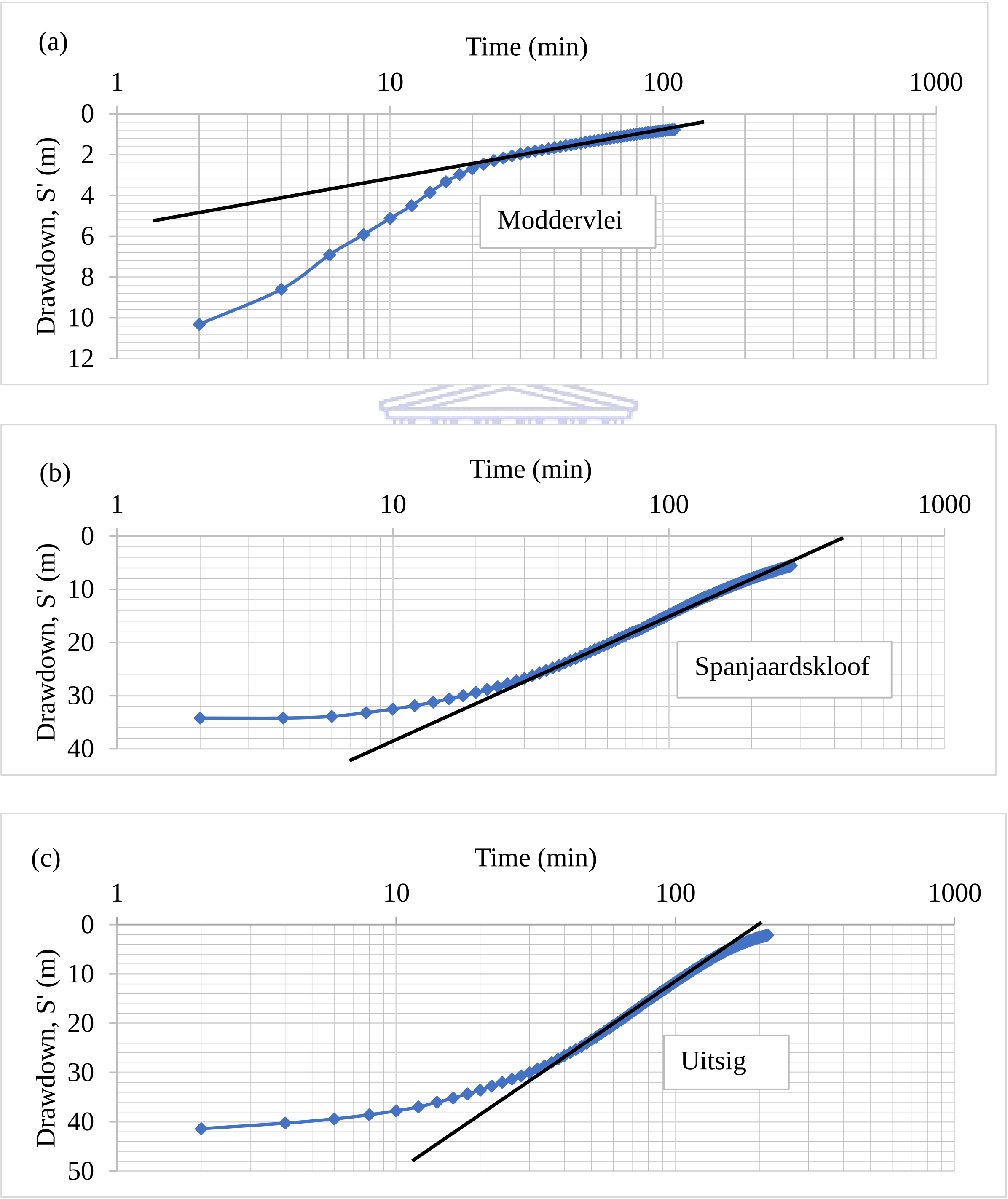
Fluctuations in groundwater levels at different sites within a catchment results in temporary changes in the groundwater flow systems due to temporal changes in hydraulic gradient. Although there are fluctuations in the water tables during the wet and dry periods, the water level configuration remains the same throughout the study (monitoring) period such that areas of high-water level remain high and areas of lowest water level elevations remain lowest. This suggests that the study area experiences steady state flow and that the flow system remains the same during both wet and dry periods. Theoretically, high groundwater levels than the river water level would mean that groundwater will be discharging into the river and its magnitude will depend on the aquifer permeability. These scenarios signify the importance of understanding groundwater head difference at different locations for the same aquifer system when identifying groundwater flow mechanisms.

5.4 Aquifer tests

Aquifer tests are used to obtain aquifer hydraulic parameters which govern groundwater movement and storage. In this study, constant rate pumping tests were done in 3 sites in the study area in order to determine the aquifer transmissivity and storativity. Pumping was done in the deeper boreholes and since there was little response in the shallow boreholes, the test was regarded as a single-well test with all the analysis done from the pumping borehole. Boreholes were pumped at a rate of 0.24, 0.29 and 0.35 *l/s* for one hour while recovery was from two to three hours. Recovery test is done mainly to measure the natural response of a stressed aquifer, but the test data is also critical in minimizing pumping test artefacts especially turbulent well losses during pumping. As such, time-recovery data is used for analysis to remove the effects of turbulent well losses during pumping. Aquifer test results showing transmissivity and storativity values are presented in Table 5.2 and the pumping test plots are presented in Figure 5.4 (a-c).

Table 5.2: Transmissivity and storativity values from the pumping tests

Borehole ID	Estimated T m^2/day	Estimated S
BH6	1.74	0.2559
BH9	0.24	0.1732
BH 13	0.17	0.158



Figures 5. 4 (a-c): Pumping tests plots from the recovery data

Results show that low transmissivity values of 0.17, 0.24 and 1.74 m^2/day were observed at Uitsig, Spanjaardskloof and Moddervlei sites respectively. High drawdown values were observed ranging from 11 m, 34 m, 43 m for BH6, BH9 and BH13 respectively as shown in Figures 5.5 (a-c). This suggests the huge variations in the saturated thickness during the tests. Meanwhile, storativity estimates range from 0.16 to 0.26. According to Todd and Mays (2004), for confined aquifer typical storativity values range between a minimum of 0.00005 and a maximum of 0.005 while Fetter (2000) indicates that for unconfined aquifers storativity values range between 0.02 and 0.30. Therefore, the storativity values obtained during this test confirm the characteristics of unconfined aquifers in the tested sites.

From the geological map, it was expected that the sites under BH9 (Spanjaardskloof) and BH13 (Uitsig) would have relatively high transmissivity values since the sites lie within a sandstone quartzite area belonging to the TMG as well as within fault zones. The high yielding TMG sandstone are mostly associated with the presence of joints and fractures. From the drilling formation it was revealed that these sites have several layers of fine-grained weathered sandstone rocks compared to fractured units resulting into poor fracture connectivity. It is therefore suggested that the estimated low T values are as a result of changes in the structural properties of the sandstone quartz rock in this part of the study area where there is fewer occurrence of rock fractures. This is supported by the findings by Xu et al. (2009) who from the analyses of fracture network and their network patterns concluded that the most important single factor controlling groundwater flows in the TMG aquifers is the connectivity of fractures.

The TMG is mostly dominated by fractured sandstones, therefore, it is necessary to understand the possible reasons for the fewer occurrence of fractures in the study area. It is hypothesized that the occurrence of fractures which would determine the occurrence of groundwater in the upper parts of the study area is largely influenced by the presence of geological faults, which are prevalent in the north and western sides of the catchment. Faults can either act as preferentially permeable pathways for groundwater flow in some geological settings while in certain circumstances fault planes might be impermeable as they become filled with material of low permeability.

Younger (2007) pointed out that during the development of some fault systems, fine grained materials known as “fault gouge” get dispersed throughout the fault plane. In addition, some large-scale faults have shattered masses of wall rocks known as “fault breccias” which may also have low to medium permeability than the formation on other side of the fault (Younger, 2007). Attandoh et al. (2013) also noted that weathering of the rocks modifies their hydrogeological conditions by reducing their primary permeabilities due to high compaction and low-grade metamorphism. The pore spaces in such formations may not be well connected, thereby limiting flows. Figure 5.5 shows the weathered granular rocks from the TMG formation which is suggested to limit groundwater flows.

Figure 5.5: Weathered brittle sandstone from BH13

It has been reported by Newton et al. (2006) that most fault zones developed in the TMG sandstones and siltstones get cemented such that they may act as aquicludes in some cases. Meanwhile, Xu et al. (2009) concurred that breccias available in fault core materials are common in the TMG formation such that they often serve as groundwater barriers.

It was noted during the drilling process that coarse grained sandstone had wet moist formation while the weathered brittle sandstones came out dry (Figure 5.6). This further confirm that the brittle fine grained TMG sandstone restricts the flow of water since it was the dominant formation, which explains the estimated low T values. In relation to Darcy’s Law, as much as the Law does not apply for flow under turbulent conditions, on the extreme ends the Law may not apply in very low permeability materials (Freeze and Cherry, 1979; Younger, 2007). This means that under low permeable formations, a minimum threshold hydraulic gradient is required for flow to take place. These findings show that making general assumptions on the aquifer hydraulic properties based on the generalized geological setting would provide little or misleading information since various geologic processes such as chemical weathering and cementation change the composition of the formation. As such, site specific investigations are necessary in order to obtain accurate information.

Figure 5.6: Brittle fine-grained sandstone and wet coarse-grained sandstone from BH9

To investigate the presence of fractures in the TMG boreholes and how they influence groundwater flow, electrical conductivity (EC) logging from the natural water quality was conducted in all the boreholes across the study area. Results from BH9 and BH13 show almost no major changes in the EC along the borehole depth (Figure 5.7), indicating that there are no major fractures in the formation. Apparently, it can be seen that a small fracture is present in BH9 between 50 m and 60 m as shown by an increase in conductivity suggesting groundwater inflow from a different layer. This is the depth where a saturated formation was encountered during the drilling thereby signifying the important role fractures play in the occurrence and flow of groundwater.

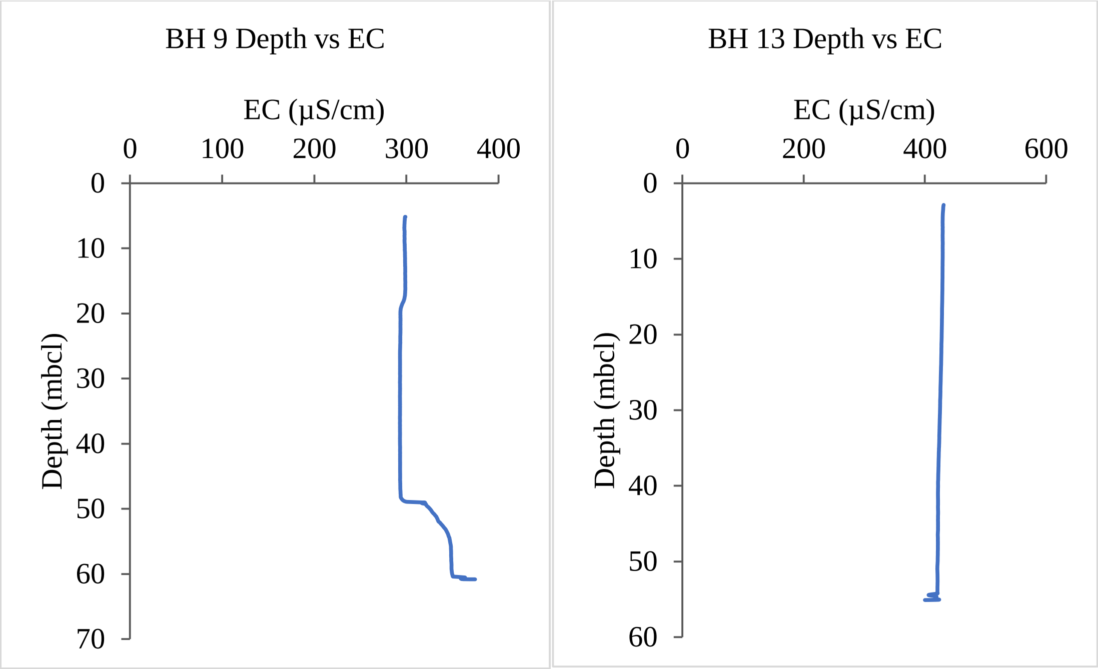


Figure 5.7: Electrical conductivity logging for BH9 and BH13

Pumping test in the lowlying areas was conducted at Moddervlei (BH6) which is characterised by the Bokkeveld shale formation overlain by sandy and unconsolidated clay layers. From the pumping test results it is evident that there is a boundary which is shown by the steepness of the plot (Figure 5.8). This shows the existence of a less permeable boundary as water flows from the unconsolidated top materials to the shale formation. The effect of boundary condition is realized after 70 minutes of pumping resulting in an increased drawdown as the rate of withdrawal from the pumping well approximates the withdrawal from the aquifer with an accelerated drawdown. This could be due to changes in the lateral variation during pumping as the radius of influence of expands until it encounters a low hydraulic conductivity formation, which is the of Bokkeveld shale.

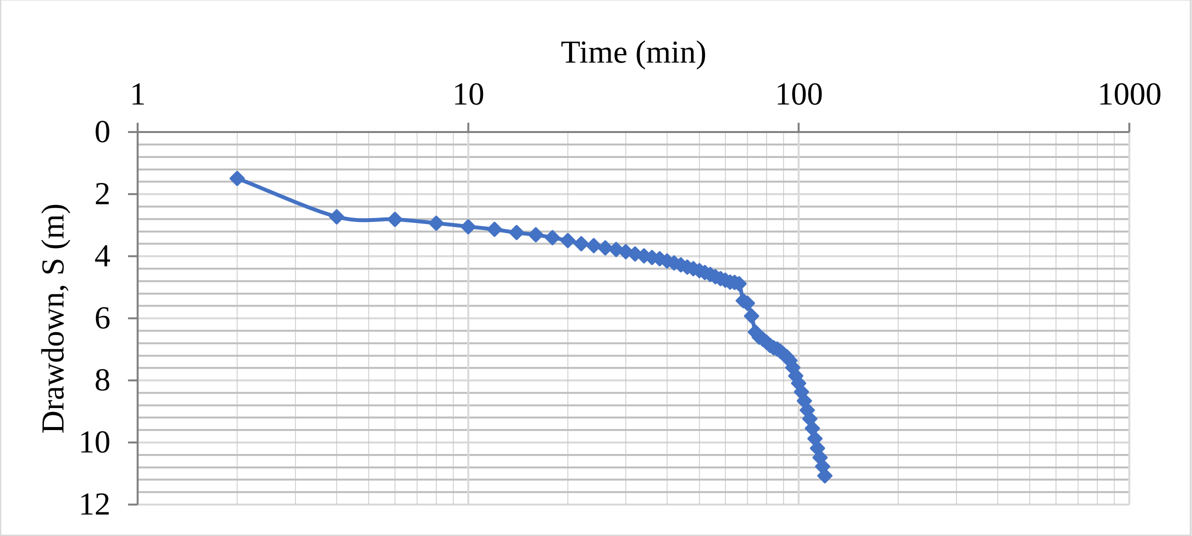


Figure 5.8: Plot of drawdown data for the Moddervlei site (BH 6) indicating the presence of a different permeability formation

The lower transmissivity value of 1.74 m^2/day estimated during the aquifer test is expected at this site which is dominated by the Bokkeveld shale rock. This is because the shale rock, unless fractured, has small pores which are not well connected resulting into slow movement of groundwater even under high hydraulic gradient. However, the transmissivity value at this site is relatively higher than the other sites within the study area (results from the upstream boreholes). The relatively high transmissivity could be due two possible reasons: firstly due to the to the presence of a fracture in this shale rock and secondly due to vertical leakage from the upper alluvial formation which is assumed to have relatively higher permeability. Freeze and Cherry (1979) argued that fractures in shale rock occurring a few hundred of metres below the ground surface can provide an important component of secondary porosity and permeability. They further indicated that even where there are hairline fractures, the created secondary porosity has the ability to provide secondary permeability of larger magnitudes than the primary permeability. Therefore with the presence of fractures relatively higher transmissivity values are likely to be obtained.

Fluid conductivity logging was also conducted to characterise the subsurface around BH6 at Moddervlei site. From the results (Figure 5.9), an EC profile shows varying conductivity gradients from 25 m to 50 m below ground surface, although the depths are within the same shale rock formation. Under this depth profile, EC values range from 3177 to 5100 µS/cm, which is suggested to be as result of fracture zones contributing groundwater of varying chemical compositions and ionic concentrations. The EC anomaly is used to infer the location of the main groundwater flow zones, therefore, it is suggested that BH6 has a fracture which enhances the permeability of the formation. EC logging has been successfully used in studies of groundwater flow in fractured rock aquifers where it was noted that step like increases in EC was as a result of groundwater movement into the borehole and were used to locate major flowing fractures (Cook, 2003; Lasher, 2011; Gomo, 2011). Such fractures are significant in the flow of groundwater and discharge of water rivers.

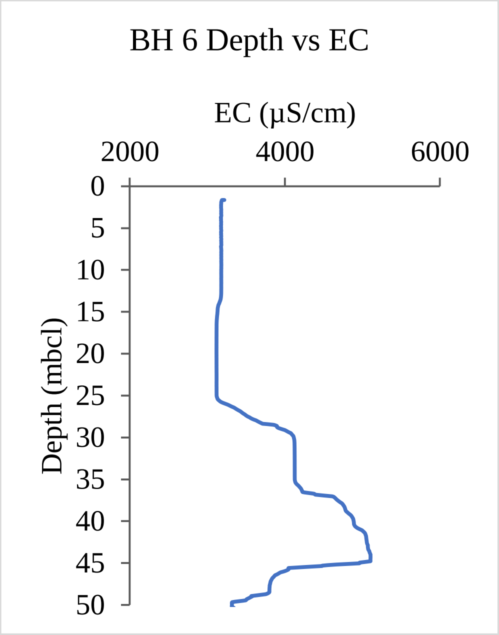


Figure 5.9: EC profile from BH6 suggesting the existence of a fracture

5.5 Role of aquifer characteristics on the flows of non-perennial rivers

The role of groundwater in maintaining river flows looks at characterizing the degree and extent of the subsurface of the area contributing water to the rivers. Results from the study show that during periods of no rainfall, rivers in both the upper, middle and lower parts of the study area are characterised by dry reaches, existence of pools while other sections have flowing water. In aquifers of low permeability, like the one in the study area, its groundwater discharge to streams is expected to originate from various points and such rivers will easily get dry within a season (Winter, 2007). This may result in unreliable and less release of groundwater to the river and river flows are likely to be within a short distance of the river course thereby affecting the downstream reaches of the river. Therefore, groundwater discharge has to occur in a larger area of the river length in order for the river to have persistent flows.

The shallow groundwater levels observed throughout the study area suggests the presence of localized groundwater flow system which are shallow with short flow paths. The groundwater levels in the study area are controlled by the topography and therefore are likely to have a limited regional groundwater flow (Gleeson et al., 2011). The nature of groundwater flow system (regional, intermediate and local) influences the volume of groundwater contribution to rivers and the stability of flow conditions along the river itself. An area receiving a regional groundwater flows would have a relatively stable river flows compared to the river which is contributed from local groundwater flows. The observed shallow groundwater levels allow for a relatively quick groundwater discharge to its nearest discharge point. This means that the aquifer will be able to provide water to the river even in such low permeable formations. This entails the significance of understanding groundwater levels and the aquifer permeability surrounding a river catchment when studying aquifer-river interaction since it will give a quick overview of the hydrological processes occurring in the catchment. For instance, Ivkovic (2009) characterised the potential for hydraulic connection to occur between groundwater and river systems in areas where the measured groundwater levels were within 10 m from the surface. Costigan et al. (2016) identified the lithology permeability, local slopes and groundwater levels as the governing factors controlling flow permanence in non-perennial rivers.

5.6 Chapter summary

This chapter used varying techniques to characterise the different aquifer physical properties in the study area. The chapter argue that discharge of groundwater to the rivers is governed by the aquifer permeability and the nature of groundwater levels, hence the need for thorough aquifer characterization. Based on the porosity, the study area has both primary and secondary aquifers whereby the primary aquifer is present in the downstream areas only while the secondary aquifer is present in both upstream and downstream sites. From the geological map and drilling results, upstream areas are characterised by Table Mountain quartzitic sandstone containing weathered and coarse-grained fractured units while downstream areas are characterised by the Bokkeveld shale with sandy and clay units.

From the borehole drilling results, the weathered units are found to be dry while fractured units are wet indicating the role of fractures in the occurrence and flow of groundwater. Groundwater level monitoring provided the groundwater elevation from where it is determined that the study area has a topographically controlled groundwater levels whereby higher surface elevation have higher groundwater levels. Irrespective of the surface topography, the catchment has shallow depth to water level ranging on average from 3 to 10 m resulting into largely local flow systems. Transmissivity values determined from constant rate pumping tests range from 0.17 to 1.74 m^2/day. The results exhibit that low transmissivity values are associated with weathered nature of the Table Mountain sandstone formation as well as the Bokkeveld shale. Storativity estimates range from 0.16 to 0.26, therefore it can be inferred that the aquifer in the study area is unconfined.

Low hydraulic properties of formation surrounding the river channel would result in slow groundwater movement and eventually slow groundwater discharge to the river. The local flow systems as a result of the shallow depth to water levels would facilitate a relatively quick discharge to the river despite the low hydraulic conductive formation. These findings provide how the physical properties of aquifers influences groundwater flow, its discharge and the interaction with the surrounding surface water bodies. The objective of determining the aquifer characteristics is therefore fulfilled in this study by characterising the geology, estimating the transmissivity values as well as assessing the nature of groundwater levels of the study area. The next chapter presents and discusses the results of the hydrochemical and isotopic analysis which are done to assess the aquifer river interaction in a non-perennial river system.

Chapter 6: Characterising the spatial and temporal variation in aquifer-river interaction

6.1 Introduction

This chapter presents and discusses results of hydrochemical and environmental stable isotope analyses to assess and characterize the interaction between groundwater and surface water in the study area. Hydrochemical and isotopic analyses are a useful tool in assessing the source of mixing between groundwater and surface and may be the only possible tools in arid and semi-arid environments (Aggarwal et al., 2005). The analyses are also conducted to understand the groundwater flow pathways and to evaluate the controls to the groundwater and surface water chemistry. The tools used in this study only provide the qualitative assessment of groundwater-surface water interactions in terms of location and mechanisms of the interactions.

In this study, water sampling for hydrochemistry analysis were conducted in four periods in July 2017, October 2017, March 2018 and July 2018. Drought conditions were prevalent during study period, as such irregular rainfall amounts were encountered during these periods. For this reason, October 2017 and March 2018 were chosen as the major water sampling campaigns representing the wet and dry hydrologic periods respectively. These periods were purposely chosen in order to have representative values for the full hydrological year.

6.2 Electrical conductivity

Electrical conductivity (EC) values are mainly used as a proxy of salinity and the degree of mineralization to describe the hydrochemical characteristics. The run of EC along the river is expected not to change much unless when the river gets contaminated from anthropogenic activities or due to the input of groundwater of different chemical characteristics.

EC measurements were done directly in the field using a multiparameter water quality probe. Meanwhile, total dissolved solids (TDS) values of groundwater were indirectly calculated from the EC values using the relationship TDS (mg/l) = 0.65 x EC (µS/cm) (Hiscock and Bense, 2014). TDS values are used to show the extent of salinization using the classification of Freeze and Cherry (1979) as provided in Table 6.1. Based on the salinity classification in Table 6.1, this study includes the brackish and brine water as being saline as well. Results show that the different water sources have different EC and TDS value ranges in the different seasons.

Table 6.1: Simplified classification of groundwater salinization (Freeze and Cherry, 1979)

Groundwater class	TDS (mg/l)
Fresh water	0 – 1000
Brackish water	1 000 – 10 000
Saline water	10 000 – 100 000
Brine water	Higher than 100 000

Table 6.2: EC values for groundwater during the two major sampling periods

Site	October 2017		March 2018 EC µS/cm		Location
	EC µS/cm	TDS (mg/l)	EC µS/cm	TDS (mg/l)	
BH9	300	195	362	235	Upstream
BH10	348	226	399	259	Upstream
BH11	635	413	712	463	Upstream
BH12	712	463	907	590	Upstream
BH13	388	252	447	291	Upstream
BH14	436	283	466	303	Upstream
F1	516	335	584	380	Upstream
F2	460	299	-	-	Upstream
F3	241	157	336	218	Upstream
F5	274	178	408	265	Upstream
BH1	10230	6650	29900	19435	Downstream
BH2	-	-	60800	39520	Downstream
BH3	-	-	20690	13449	Downstream
BH4	12240	7956	17070	11096	Downstream
BH5	13290	8639	22700	14755	Downstream
BH6	3190	2074	4550	2958	Downstream
BH7	6530	4245	12840	8346	Downstream
BH8	3020	1963	3040	1976	Downstream
PZ 2	27600	17940	31000	20150	Downstream
PZ8	48200	31330	54100	35165	Downstream
PZ14	57400	37310	66200	43030	Downstream
PZ16	28800	18720	33000	21450	Downstream
PZ26	64600	41990	64300	41795	Downstream

In October 2017 (wet period), groundwater EC values range from 274 µS/cm to 64600 µS/cm. There is a clear distinction of groundwater between upstream and downstream areas. The upper high elevation part of the catchment contains fresh waters with the highest EC of 712 µS/cm and an average of 431 µS/cm and TDS of less than 1000 mg/l (Table 6.2). The upstream part of the catchment is dominated by TMG formation with sandstone and quartzite rocks of weathered and fractured units. The lower EC may be attributed to the high velocity of groundwater and lower solubility of the aquifer material units. According to Smart and Tredoux (2002), the low salinity in the TMG formation is due to the less reactive nature of its quartzite sandstone rock as well as the high localised rainfall in the mountainous terrain where the TMG is prevalent. Meanwhile, the middle and lower parts of the study area have the highest groundwater EC with an average of EC of 26 487 µS/cm. The elevated EC could be due to the mineral dissolution as the area is dominated by the Bokkeveld shale and clay formations. The low permeability in these formations coupled with a gentle slope may result in slow groundwater velocities and high residence and contact time resulting in high rock-water interaction and therefore elevated EC. In general, there is a correlation between the potentiometric surface and groundwater salinity such that groundwater in upstream areas is fresh and salinity increases in downstream areas.

In addition, samples from the Nuwejaars River were taken at 7 points along the river, while 2 points were sampled at the outlet of the Voëlvlei and the Soetendalsvlei and further 2 points from the tributaries of the Nuwejaars River. Determination of salinity in rivers was done to assess if there is any noticeable pattern which can be related to the salinity of the local groundwater. Chemical analyses of river data show an increase in the EC values from the upstream to middle lower parts of the catchment. The EC values in the Nuwejaars River range between 598 and 1069 µS/cm with an average of 840 µS/cm which was lower than that of groundwater (Figure 6.1).

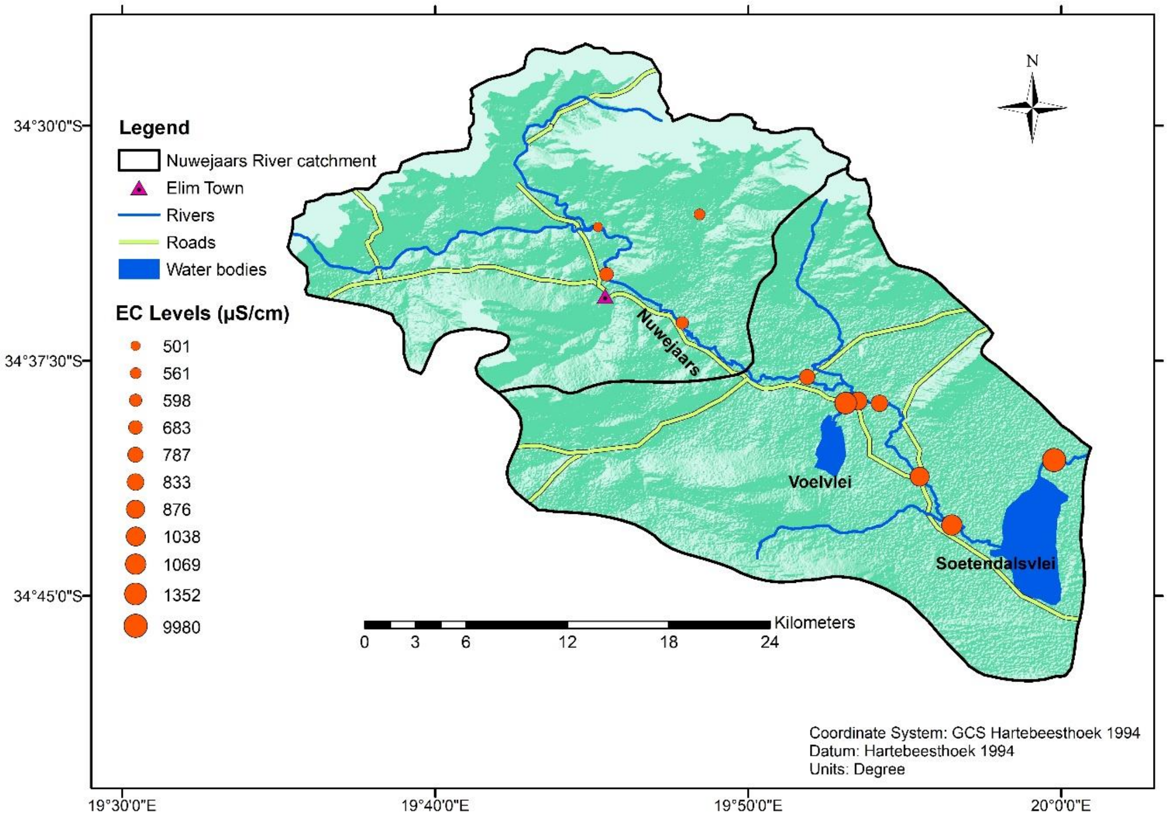


Figure 6.1: River samples EC levels for October 2017 (wet period)

During the wet period, it is most likely that dilution of water from precipitation events across the catchment explains the observed reduced in lower EC data compared to the dry season. Out of all river samples, the lowest EC values are observed in the tributaries (Pietersliekloof and Jan Swartskraal) of the Nuwejaars River located in upper part of the catchment while highest values are observed in the outlets of the Voëlvlei and Soetendalsvlei lakes (Figure 6.1). In a similar study on groundwater-surface water interaction, Moseki (2013) found that higher total dissolved solids values, which are related to electrical conductivity, tend to occur after prolonged periods of low flows or as a result of displaced pool water partly due to concentrating effects of evaporation.

During the March 2018 sampling which falls under the dry period, there is a noticeable difference in the EC values from that in the wet period. The EC values for groundwater range from 336 µS/cm to 66 200 µS/cm with an average of 20 096 µS/cm (Table 6.2), showing an increase in salinity levels during the dry period. Similar to the wet period, salinity levels for the rivers increase from the catchment headwaters to the downstream areas of the river whereby Nuwejaars River tributaries have the lowest EC (355 and 646 µS/cm). Lower EC levels are also observed on the transition between upstream and downstream areas up until the Nuwejaars River Bridge. The general trend within the Nuwejaars River shows again an increase in EC downstream the river as shown in Figure 6.2. Compared to the wet period, salinity levels during this dry period increase with values ranging from 1.5 times in fresh upstream reaches to up to 24 times in pools due to the seasonal wetting and drying cycles. The increase in salinity in the river could be attributed to saline groundwater discharge and partly evaporation. These findings align with results from Bestland et al. (2017) which was done in a similar environment to this study area of Mediterranean climate with cool wet winters and dry hot summers in a non-perennial river system. The study looked at groundwater depending pools and the results showed strong salinity changes of up to 2.5 times during the dry period.

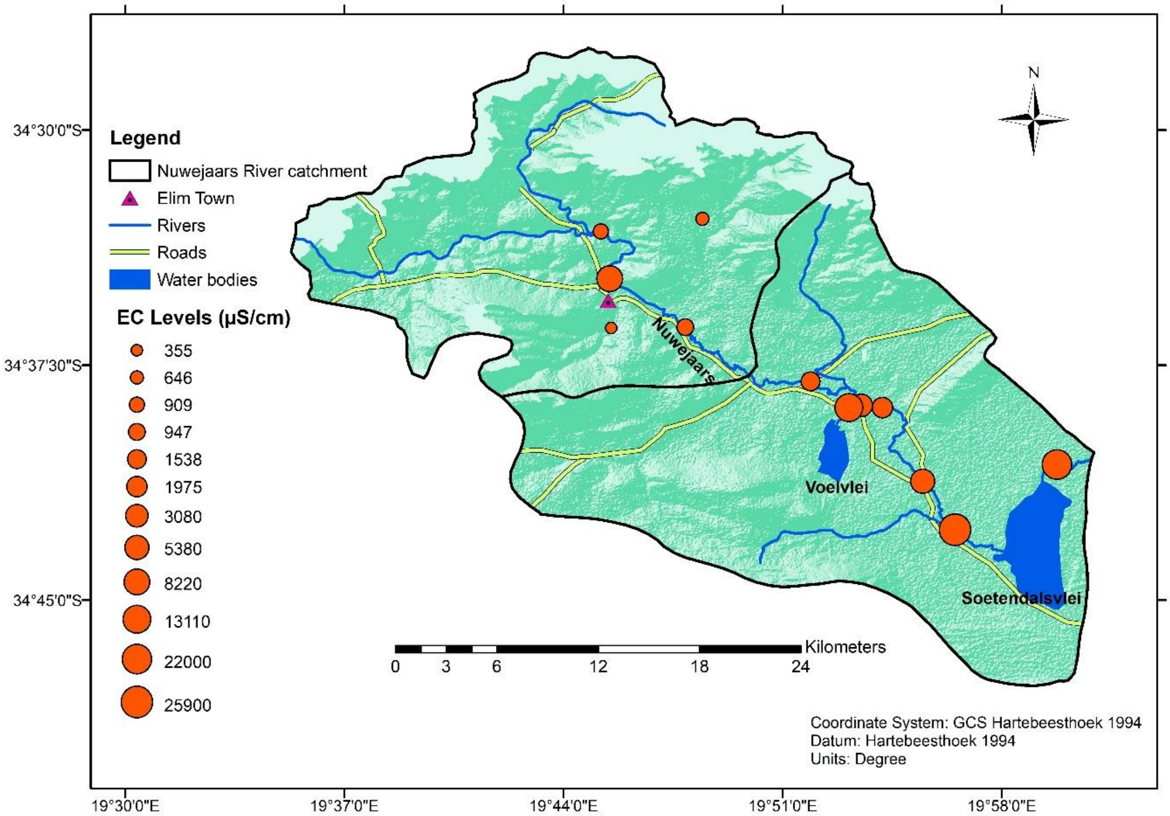


Figure 6.2: River samples EC levels for March 2018 (dry period)

The EC trend of river water is similar to that of groundwater, therefore, it can be suggested that there is a hydraulic connection between groundwater and the river. Groundwater has higher total dissolved solids than surface water and therefore have greater ionic strengths and greater electrical conductivities (Harvey et al., 1997). As such, groundwater discharge zones may be identified by their elevated EC relative to that of surface water. This notion is supported by Li et al. (2017) who argued that with reference to the mass balance, water with higher values of EC should be the sink of that water with smaller values of EC. This is mainly evident during the dry period with low flows where it is expected that groundwater recharges the river. The fresh EC in the upstream could be as a result of fresh groundwater from the upper part of the study area which flows towards the upstream part of the river. This again reflects the different groundwater sources from the upstream to the downstream areas. Meanwhile, the relatively low river salinity (1538 – 1975 µS/cm) observed at the transition between the upstream and downstream area until the Nuwejaars River Bridge is likely to be due to continuous inputs of groundwater fed streams.

One noticeable feature in the study is the elevated EC on one site upstream of the Nuwejaars River close to Elim Town. During the sampling time the water on this part of the river was not flowing which meant the pool was likely to be subjected to high temperatures. Increase in temperature increases the ionic activity and thereby increasing the electrical conductivity (Hiscock and Bense, 2014). However, upstream of this pool was another pool which was also monitored in terms of its EC in which low EC was still encountered. Hence, the possible reason for the elevated EC at this site could be due to the anthropogenic activity. This site is close to a dairy farm in Elim Town (about 400 m) which is located on a higher elevation. Discharge from the dairy farm is likely to enter and mix with the river (pool) and cause the relatively salinity. Therefore, the salinity levels at this site could be related to anthropogenic activities as it is unlikely that mineral dissolution would occur within a short distance compared to closer upstream and downstream sites (which are approximately 5 km apart) and have relatively lower EC values.

The different possible sources of elevated EC in the river including high saline groundwater input, evaporation and anthropogenic activities makes it difficult to use EC only as a tool to assess aquifer-river interaction in a non-perennial river system. Therefore, it is vital to use other tools in addition to EC to provide better and improved understanding of the interaction processes.

6.3 Major ions characteristics

6.3.1 General expressions and statistical summary of major ions data

Major ions analyses during the wet (October 2017) and dry (March 2018) periods are presented and discussed in this section. Average results of the analysed parameters are presented in

Tables 6.3 and 6.4. In this study, a Charge Balance Error (CBE) of ±10% was adopted and such samples having extremely high CBE were omitted for the chemical analysis. Almost 78% of the samples have a CBE of less than 10%. Samples having charge imbalance have mostly negative charges indicating the excess of anions. The possible reasons for the high CBE could be due to analytical errors as well as non-inclusion of minor or trace ions and pollutants in the analysis which could have been present in significant concentrations. However, analytical errors are assumed to be not the main cause true since most of those samples having charge imbalances repeatedly show the imbalances in all the sampling periods.

Table 6.3: October 2017 wet season major ion average results. Units are in mg/l

	Upstream areas		**Downstream areas**	
Species	Groundwater	River samples	Groundwater	River samples
Ca^{2+}	7.4	12.7	140.5	30.4
Na^{+}	70.9	246.7	1447.3	532.1
K^{+}	2.6	5	30.5	9.5
Mg^{2+}	10	35.7	169.1	58.9
Cl^{-}	148.1	469.4	8777.6	1052.6
SO_4^{2-}	18	71.3	841.8	115.5
HCO_3^{-}	23.6	14	182	84.5

Table 6.4: March 2018 dry season major ion average results. Units are in mg/l

	Upstream areas		**Downstream areas**	
Species	Groundwater	River samples	Groundwater	River samples
Ca^{2+}	9.1	20	185.8	65
Na^{+}	66.9	304.8	3269.3	647.1
K^{+}	3.7	4	19.2	17.8
Mg^{2+}	8.6	48	244.8	110
Cl^{-}	119	637	7779.3	3202
SO_4^{2-}	15.3	46.3	1013.2	238.9
HCO_3^{-}	47.1	75.5	260.3	202.8

During both periods, the dominant major cations is in the order of Na>Mg>Ca>K for both groundwater and surface water samples. Meanwhile, major anions data show concentrations range from high to low in the order of Cl>SO_4 >HCO_3 again for both groundwater and surface water during the sampled periods. Generally, there are large variations (Tables 6.3 and 6.4) in the concentrations of parameters in upstream and downstream areas signifying different hydrochemical processes in the study area. Between the two seasons, total average concentrations for groundwater range from 269.7 – 280.6 mg/l in upstream and 12771. 9 – 11588.8 mg/l in the downstream areas. Meanwhile, total average concentrations for river samples range from 854.8 – 1135.6 mg/l in the upstream and 1883.5 – 4483.6 mg/l in the downstream areas.

One noticeable feature is that river samples in upstream areas have higher average concentrations of individual ions ranging from 5 – 469.4 mg/l (wet season) and 4 – 637 mg/l (dry season) than in groundwater which ranges from 7.4 -148.1 mg/l and 3.7 – 119 mg/l in wet and dry seasons respectively (Tables 6.3 and 6.4). This is not expected since the upstream areas are characterised by lower salinity and low mineralization. The higher concentrations in upstream river samples is attributed to the highly concentrated samples close to Elim Town, possibly due to the farming activities which are closer to the river.

6.3.2 Hydrochemical facies

The major ions characterisation of all samples collected during the entire sampling period and a comparison between groundwater and surface water data were made. The conventional Piper diagram was used to classify the water types based on the concentrations of ions in mEq/l. The Piper diagram was chosen because of its ability to graphically show a large number of analyses in a single plot.

Wet period sampling (October 2017)

A Piper diagram (Figure 6.3) shows that there are two groups of similar water chemistry for groundwater samples, which are Na-Cl (86%) and Na-Mg-Cl (14%) type waters. It is shown that Na-Mg-Cl type water comes from shallow groundwaters in piezometers (PZ8, PZ14 and PZ26) which are near the Nuwejaars River. All in all, compositionally the groundwater samples are Na-Cl type water. Meanwhile, during the same wet period, Piper plot for surface water samples (Figure 6.4) are again composed of two similar groups of water chemistry; Na-Mg-Cl (73%) and Na-Cl (27%) type waters. Generally, both groundwater and surface sources have Na^+ and Cl^- as dominant ions with some river samples having a mixture of Mg^{2+}. The similarity in the major ion characteristics for both groundwater and surface water suggests the presence of connectivity between the two water sources.

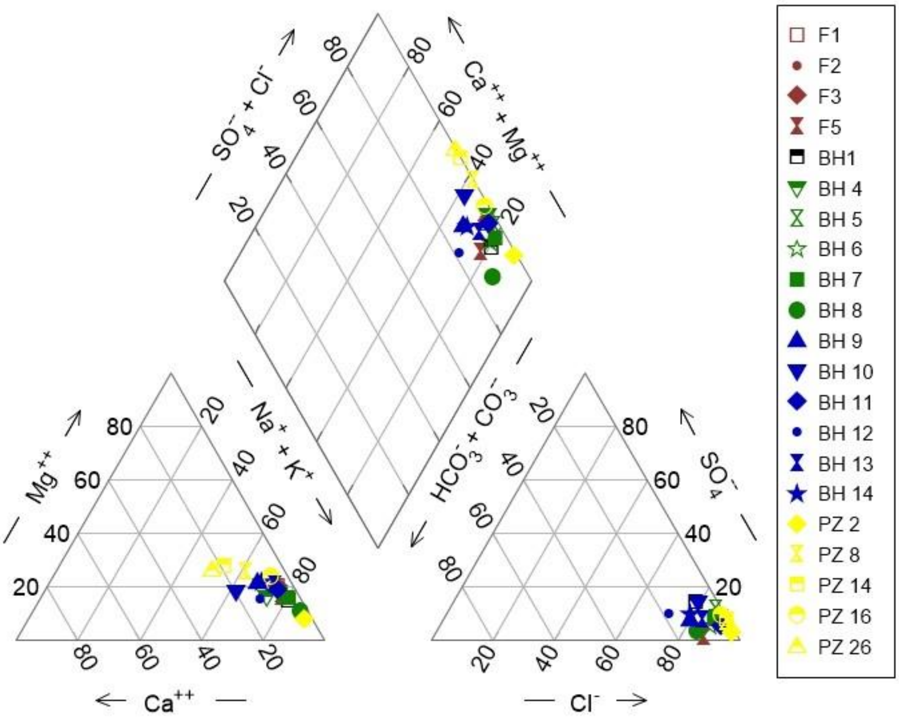


Figure 6.3: Piper for groundwater samples in October 2017 (wet period)

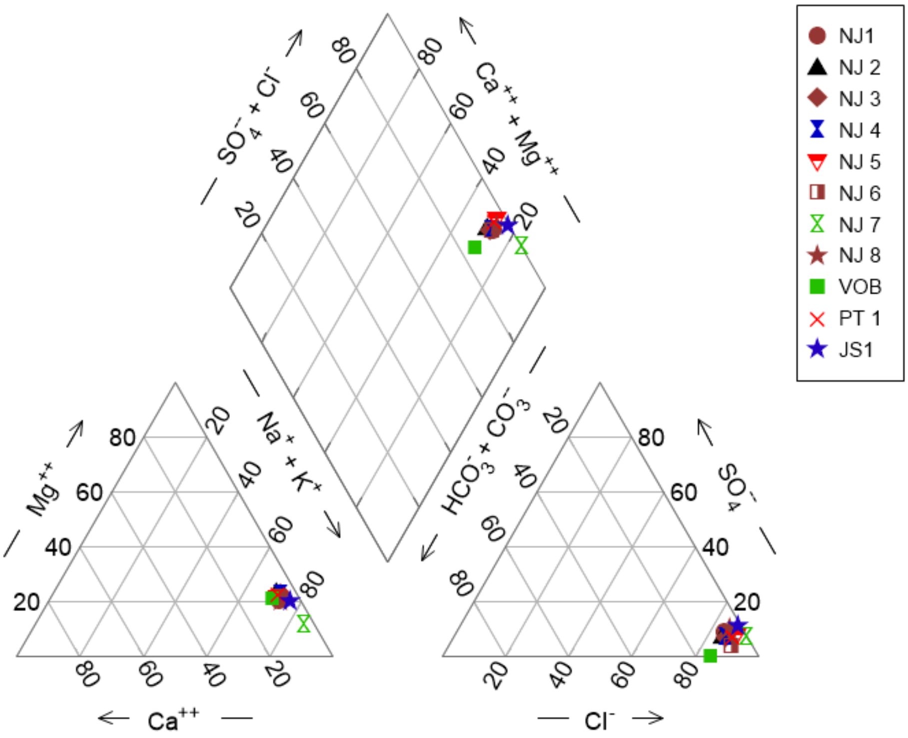


Figure 6.4: Piper for river samples in October 2017 (wet period)

Dry period sampling (March 2018)

The Piper plot for groundwater samples indicate that the samples are dominated by Na-Cl (64%) and Na-Cl-HCO_3 (27%) hydrogeochemical facies while two boreholes have Ca-Mg-Cl water type. The Na-Cl-HCO_3 is dominated in upstream boreholes and in one borehole in the downstream in alluvial sandy aquifer. Meanwhile, Piper plot for surface water samples (Figure 6.6) shows the dominant water type of Na-Mg-Cl (58%), Na-Cl (33%) and Na-Mg-Cl-HCO_3 (8%) during the dry period (March 2018). In general, both groundwater and surface water samples are described as Na-Cl type water. Sodium and chloride contributed to 80% and 81% of the total analysed chemical species in groundwater and surface water respectively. This is an indication of the similar chemical composition of groundwater and surface water in the study area.

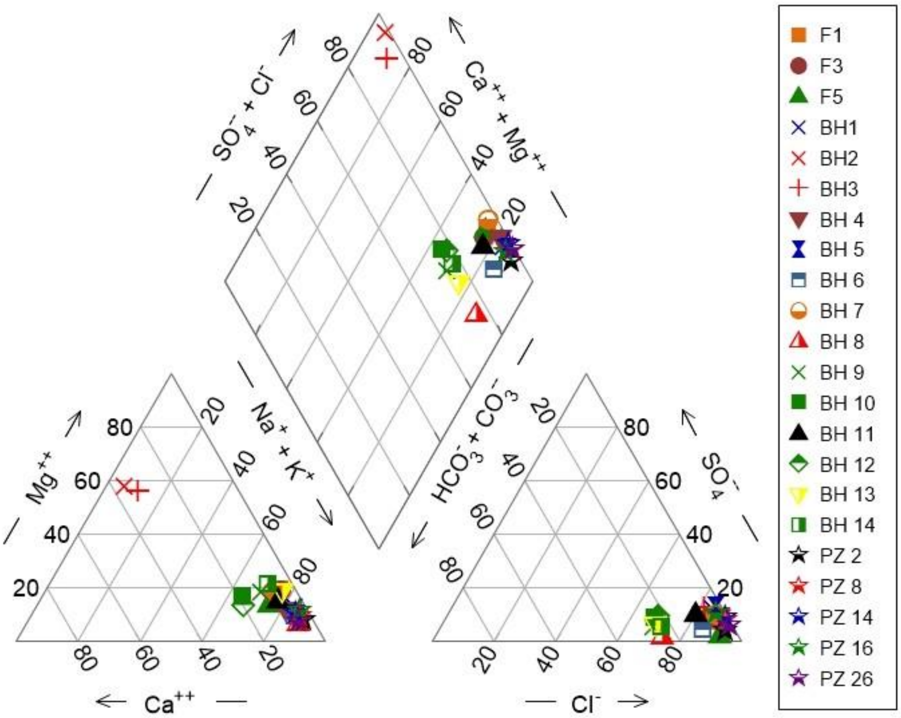


Figure 6.5: Piper plots for March 2018 (dry season) for groundwater

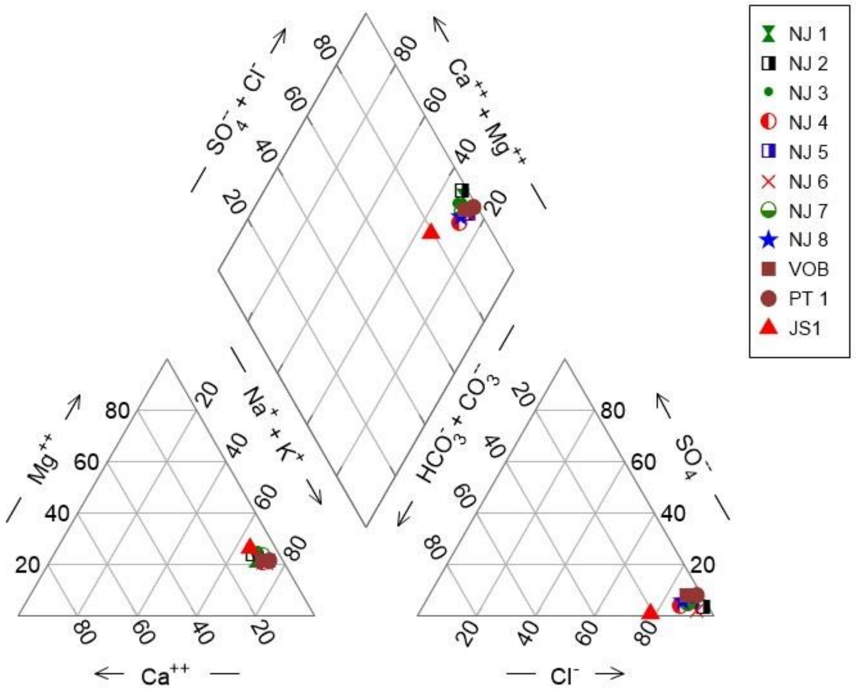


Figure 6.6: Piper plots for March 2018 (dry season) for river water samples

River samples from the outlets of the Soetendalsvlei (NJ1) and Voëlvlei (VOB), the pool close to Elim town (NJ5) and the pool close to SANParks offices (NJ2) are all categorized as Na-Cl type composition. The Na-Cl in these sites would be sourced from both groundwater input, concentrated effects of evaporation, sea sprays as well as agricultural chemicals and animal waste. The Na-Mg-Cl-HCO_3 is from Jan Swartskraal which is located in the upstream area suggesting the contribution of groundwater baseflow during the dry period considering the similar composition of groundwater close to the site. Meanwhile, the Na-Mg-Cl water type in the other 7 samples indicate the possible mixing of fresh river water and that of medium to high saline groundwater. These findings are similar to those by Apedo (2015) where it was found that surface water bodies in the Agulhas plain are characterised by the Na-Cl and Na-Mg-Cl water types. The similarities in the percentage of major ions in groundwater and surface water in March 2018 (dry period) again indicate the hydraulic connection between the two water sources in the study area.

To confirm whether groundwater quality influences the surface water quality and therefore a hydraulic connection between them, Schoeller diagrams were plotted for groundwater (mostly piezometers) and river water samples located closer to each other. The Schoeller plot is a semi-logarithmic diagram representing concentration of major ions in mEq/l. It allows major ions of many samples to be represented on a single graph from which samples having similar patterns can be differentiated. Results from the concentrations of major ions during the wet (October 2017) and dry (March 2018) are shown in Figures 6.7 and 6.8 respectively.

Results indicate that the concentration in major ions are higher in groundwater during both the wet and dry periods. However, wherever there is a rise in concentration of a particular ion in groundwater there is also such a rise of that particular ion in surface water. The fall in the ion concentration is also similar for groundwater and surface water. The same type of variation in major ion concentration between the two water sources therefore imply the possible interaction between groundwater and surface water. In general, both water sources have high concentrations in Na and Cl. Therefore, the chemical characteristics of river water is generally influenced by the groundwater characteristics.

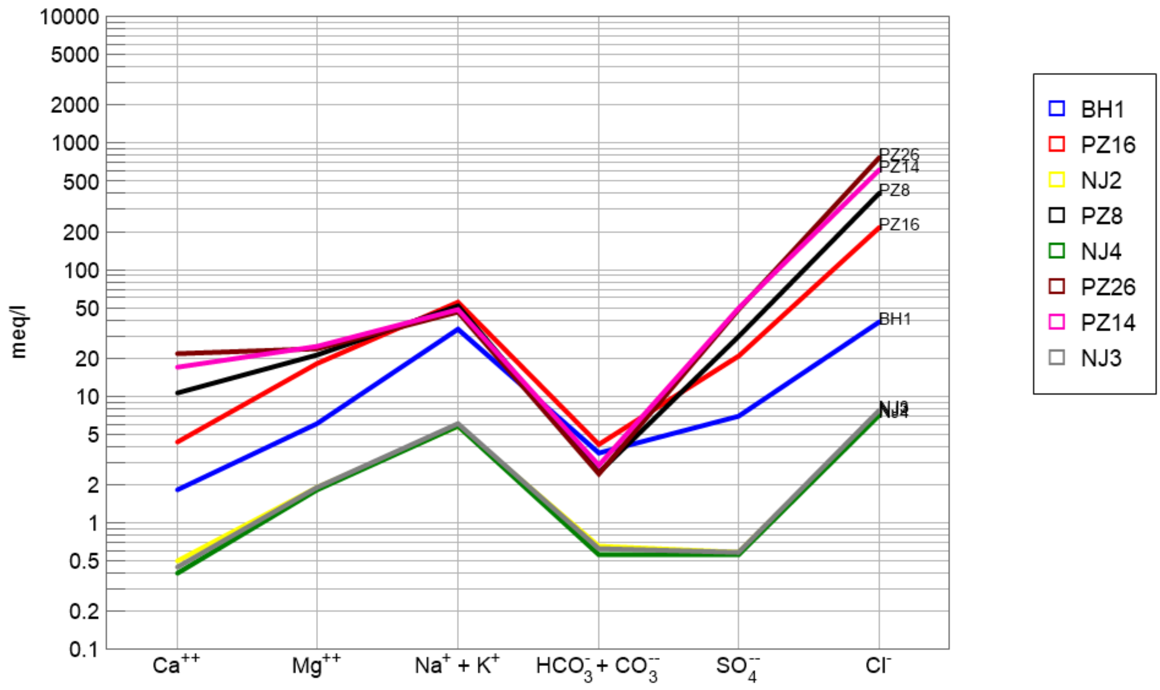


Figure 6.7: October 2017 Schoeller showing relationship between groundwater (BH1, PZ8, PZ14, PZ16 and PZ26) and surface water (NJ2, NJ3 and NJ4) at various locations

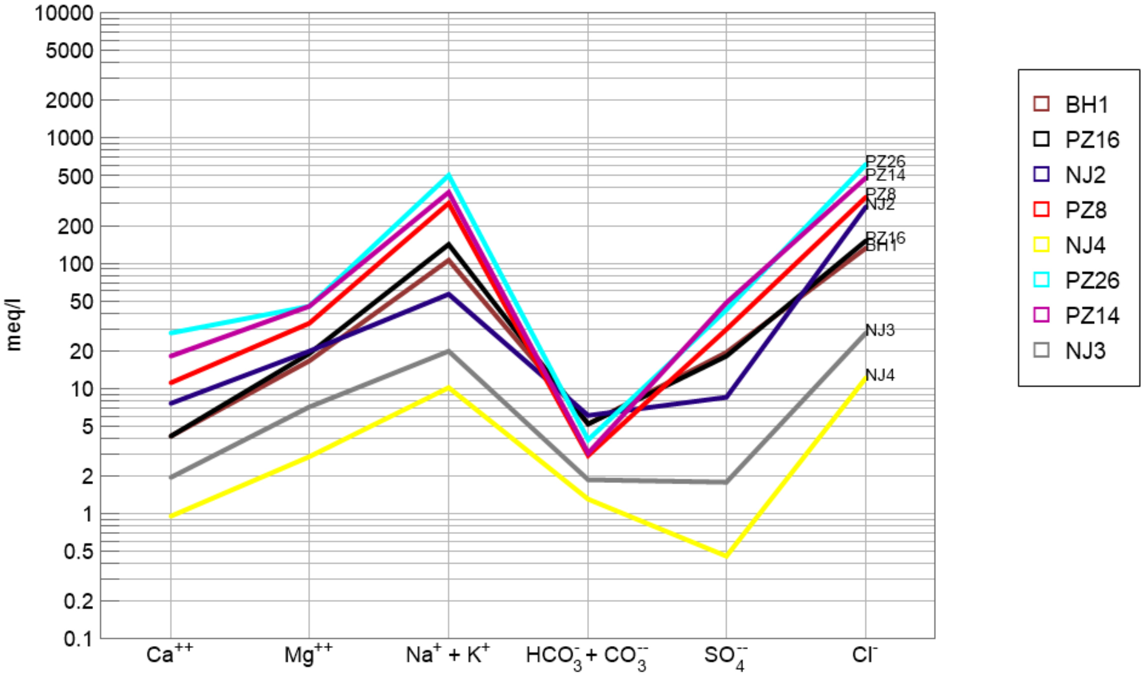


Figure 6.8: March 2018 Schoeller showing relationship between groundwater (BH1, PZ8, PZ14, PZ16 and PZ26) and surface water (NJ2, NJ3 and NJ4)

Using hydrochemical data, a report by Bestland et al. (2017) from a study in a Mediterranean climate in Australia indicated that majority of the pools were almost wholly dependent on groundwater as their source of water while only a few of pools were from a mixing of groundwater and surface water. Moseki (2013) also conducted different case studies of groundwater-surface in temporary rivers from different catchments where pools were of focus. The study found that hydrochemistry data was crucial in determining the existence of connectivity between pools water and the alluvial aquifer. It was found that Mokolo River and Shot Belt Pool were mostly losing water to the aquifer while in the Seekoei River the pools were sustained by groundwater flux from the channel aquifer.

6.4 Environmental stable isotopes

6.4.1 Introduction

The composition of stable isotopes in water are considered conservative under normal temperatures (up to 60 – 80°C) since they are rarely affected by rock water rock interactions unless under such elevated temperatures (Gat, 1996). Considering the groundwater temperatures in the study area (an average of 18 °C), the stable isotopes can be therefore be considered as a conservative.

The stable isotopes of δ^2H and δ^{18}O are used to infer the potential interaction between groundwater and the Nuwejaars River and its tributaries. When characterising the isotopic composition of water, it is important to have a local precipitation data in order to identify the relative depletion or enrichment of the sampled water. The results are plotted relative to the Cape Town local meteoric water line (LMWL), which is the closest LMWL to the study area (approximately 200 km), as well as relative to the global meteoric water line (GMWL). The GMWL is defined by the equation $\delta^2H = 8\ \delta^{18}O + 10$ (Craig, 1961). For the purposes of local investigations which is the case with this study, it is important that the groundwater and surface water data are compared with the LMWL. The GMWL can be a suitable reference for determining the possible rainfall compositions in cases where there is not enough local data to create a representative LMWL (Mengistu et al., 2015). However, Cape Town and the Heuningnes catchment both experience Mediterranean climate with cold rainy winters and dry summers. They are both located along the coast with similar elevation ranges as well as within the same latitude (34° S), hence the possibility of using the Cape Town LMWL.

6.4.2 Results and discussion for March 2018 sampling

During the dry season in March 2018 (Figure 6.9), the δ^{18}O values of groundwater range from -5.48 ‰ to -1.7 ‰ while δ^2H values range from -24 ‰ to -5.9 ‰. Meanwhile, δ^{18}O values for surface water (rivers) range between -5.12 ‰ and -7.08 ‰ while δ^2H values range between -22.9 ‰ and -38.8 ‰. The LMWL for Cape Town is given by the equation: $\delta^2H = 5.3\delta^{18}O + 5.3$

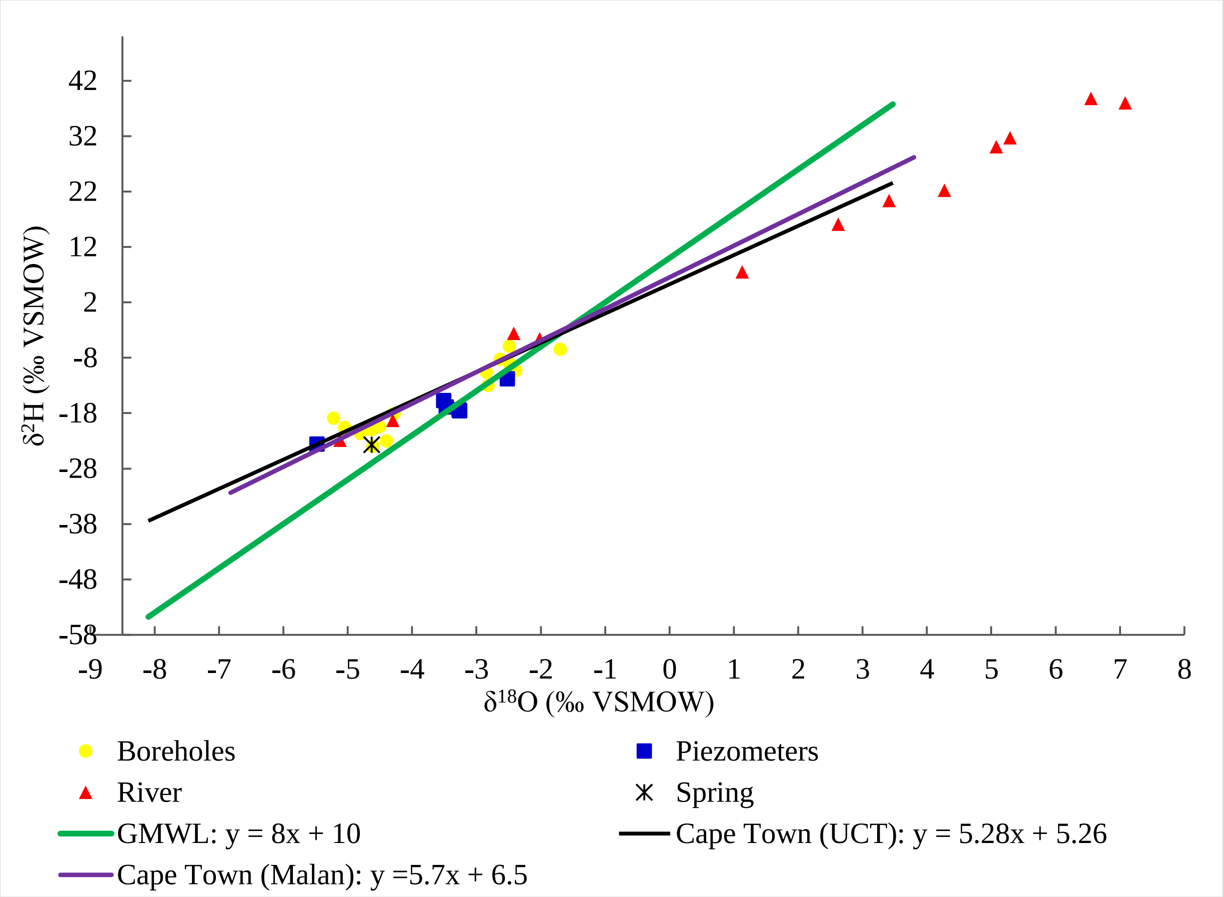


Figure 6.9: Stable isotopes of water showing groundwater and surface water samples in relation to the LMWL and GMWL

All the groundwater samples plot at the depleted (negative) potion of the LMWL in comparison to the surface water samples. This confirms that groundwater in this study area is as a result of recharge from winter rainfall since rainfall during winter period tend to be more depleted than summer rainfall (Guan et al., 2013). The plot shows most of the groundwater samples (shallow from piezometers, relatively deeper from boreholes and spring water) experience less evaporation during or before recharge as the samples plot slightly below the LMWL. Although winter periods which bring rains in the study area are usually cold, drought conditions were encountered during the study period in which temperatures were high hence causing evaporation before recharge. The flat surface topography would also enhance ponding and slow recharge which would expose the water to evaporation during or before recharge. Meanwhile, a few of groundwater samples including one shallow from a piezometer plot on the LMWL, suggesting no or less fractionation from the meteoric water.

Results also indicate that most of the river samples were enriched (more positive) with heavy isotope indicating evaporative signatures. Exception for river samples are sites JS1, ETS, PT1 and NJ7 which both are depleted with oxygen and hydrogen isotopes. Both of these sites are located in the upstream part of the study area. Samples from these sites plot close to groundwater samples indicating the contribution (input) of groundwater to the river considering that the samples were taken during the peak dry period. Similar results were found by Mencio et al. (2017) in a study on stream-aquifer relationships in a Mediterranean area where samples were taken from a pool remaining in a river during the summer period. They found that there is no clear shift of isotopic signatures from the meteoric line that could be attributed to evaporation and the pools are thought to be originating from groundwater. Meanwhile, all groundwater samples from shallow piezometers including those close to the river show depleted signatures. This indicates no evidence of recharge from the river water, which are characterised by heavily enriched isotopic signatures.

Isotopically, it is difficult to quantify the contribution of groundwater to rivers if the river water is exposed to evaporation since the isotopic signatures would change. Evaporation results in the removal of lighter isotopes and a concentration of heavier isotopes in water (Mazor, 2004). Therefore, only such river samples which were not exposed to higher evaporation, for example, due to canopy cover or reduced temperatures, would provide a better indication for groundwater contributing to such rivers. The enriched samples from the Nuwejaars River could signify such high evaporation as a result of higher temperatures as well as limited flows in pools and due to low topography in which all of enriched samples are located. Therefore, it is important to use other tools in addition to isotope data when interpreting and recognizing the sources of water in such dry environments.

6.4.3 Results and discussion for July 2018 sampling

Isotope analyses were also done in July 2018 which was characterised as the beginning of the rainfall period in the study area. During this period there is an increase in groundwater levels and some river reaches were flowing while other reaches were either still dry or only had pools. Rainfall and sea water samples were also collected in addition to the groundwater and river waters. The rainfall sample has an δ^{18}O of -5.49 ‰ and δ^{2}H of -25.8 ‰. All groundwater samples show depleted signatures which is also the case during the dry period with δ^{18}O ranging from -4.76 to -2.2 ‰ and δ^{2}H ranging from -12.5 to -24.5 ‰ (Figure 6.10). Most of the groundwater samples from boreholes show signatures similar to that of the rainfall sample indicating recharge before fractionation. However, all water samples taken from piezometers are all plotting below the LMWL suggesting the influence of evaporation in the shallow groundwaters. Although some groundwater samples are close to the rainfall signature, variations in the measured values are observed which suggests the actions of different local processes such as selective infiltration, evaporation prior to infiltration, direct percolation through preferential channels and probably, surface water contribution mixes (Londoño et al., 2008). The signature of the groundwater samples in the downstream areas are different during the dry and wet periods, which indicates that the aquifer is not large enough to mask the seasonal isotopic variation caused by rainfall.

River samples, which show depleted values during the dry period again exhibit, as expected, depleted signatures during the rainy period. Some samples showing enriched values (δ^2H of 16.1 ‰, δ^{18}O of 2.62 ‰) during the dry period have depleted signatures during the wet period (δ^2H of -8.4 ‰, δ^{18}O of -2.69 ‰), suggesting the influence of rains flushing out the enriched water and replacing it with the fresh unevaporated water. The isotopically enriched river samples during the wet period (δ^2H of 9 ‰, δ^{18}O of 0.92 ‰) are relatively less enriched compared to the dry season sampling (δ^2H of 20.4 ‰, δ^{18}O of 3.41 ‰) indicating the influence of recent precipitation and reduced evaporation as the temperatures get reduced during the winter period. During this sampling period (July 2018), the rainfall had not reached its peak hence the fresh rain water did not completely flush out the old evaporated waters.

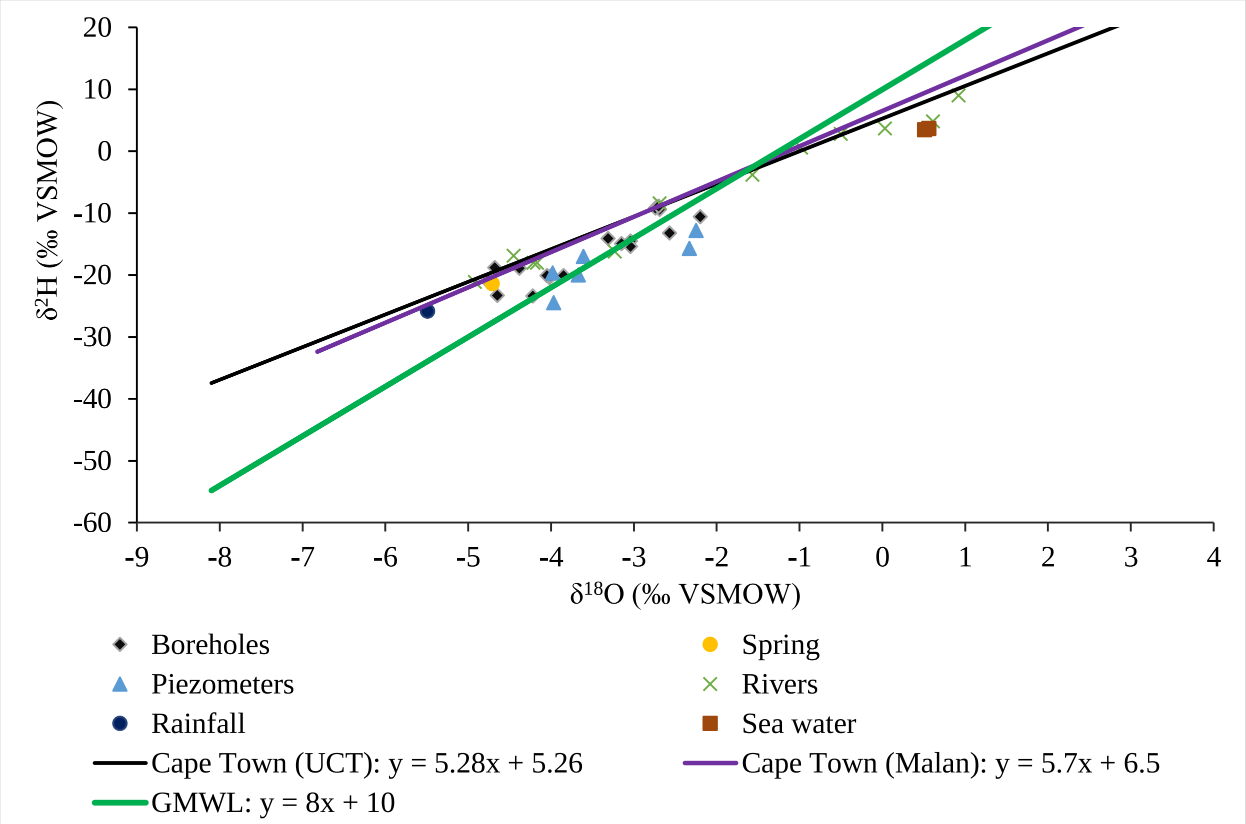


Figure 6.10: Stable isotope composition for various water sources during the beginning of the rainfall period

Isotope signatures for river samples in the upstream part of the catchment are all similar to the dry period. This again suggests the dominance of groundwater input in these parts of the catchment. According to Lambs (2004), seasonal variations in isotopes will be smaller in streams where groundwater is the dominant source, and larger in streams where recent precipitation is the main source of flow.

6.5 Processes governing groundwater quality

6.5.1 Introduction

This section identifies the hydrogeochemical processes and investigates the origin of groundwater type found in the study area. Na-Cl is the dominant water type in most rain, groundwater, spring and river samples regardless of site conditions. The relationship between different dissolved species were used to evaluate the origin of solutes and the associated processes leading to such concentrations. Precipitation as the input to the hydrologic system contains only small amounts of dissolved ions as it reaches the surface water and eventually groundwater. Therefore, the main processes affecting groundwater quality include, evaporation, ion exchange, silicate weathering and mixing processes (Carrillo-Rivera et al., 2007).

6.5.2 Groundwater in upstream areas

Groundwater in upstream sites, characterised by the TMG quartzitic sandstone formation, have Na-Cl and Na-Cl-HCO_3 as the dominant water types. Boreholes in upstream portions of the study area exhibit relatively low TDS (a maximum of 590 mg/l), hence its water is characterised as fresh. These findings provide an opposing view from the general assumption that Na-Cl type composition are mostly saline waters. The probable source of the sodium-chloride in the upstream groundwater could be from atmosphere which is brought in during the recharge process. Salts derived from the sea spray contain sodium chloride which when mixed with rainfall find its way into groundwater during the recharge process.

The amount of sea derived sodium-chloride deposited depends on the distance of the sites from the sea. Furthermore, air masses containing sodium chloride may move inland and drop out the salts as dry deposition (Hem, 1985). Therefore, atmospheric chloride is the main source of chloride considering that the sites are only 30 – 40 km from the seashore. The data demonstrates that chloride values from the rain sample collected in July 2018 at an altitude of 22 m amsl is 67.8 mg/l. This value is higher than those reported by van Wyk et al. (2011) for chloride values in rainfall surrounding the coastal regions of South Africa indicating that the chloride in the boreholes of the study area is of meteoric origin.

The findings in this study are similar to the findings by Smart and Tredoux (2002) who showed that TMG aquifers typically have a low salinity Na-Cl dominated groundwater. Xu et al. (2009) also found Na-Cl water type for the chemical analysis of boreholes in the TMG formation. Work from Demlie et al. (2011) in Sandspruit catchment in Western Cape Province of South Africa again indicated the Na-Cl type including in fresh groundwaters. Furthermore, van Wyk et al. (2011) agreed that rainfall compositions in coastal and immediate inland areas would retain most of its Na-Cl maritime composition.

To test that the Na-Cl waters in these upstream sites are from precipitation, a relationship for Na^+ and Cl^- was established. Chloride is a conservative ion and therefore its concentration will only be affected by mixing and evaporation while sodium is highly soluble which keeps on dissolving in waters resulting in wide range of concentration (Carrillo-Rivera et al., 2007). Therefore, if Na-Cl is from precipitation, then the concentration of Na^+ and Cl^- will be in almost equal amounts with their ratio being close to 1. The Na/Cl ratio for the rainfall sample collected in July 2018 is found to be 0.987. A plot of Na^+ against Cl^- for upstream boreholes is shown in Figure 6.11. The plot shows that there is an excellent relationship between Na^+ and Cl^- with their ratio ranging from 0.7 to 1 with an average of 0.8 during both the wet ($R^2 = 0.71$) and dry ($R^2 = 0.97$) periods suggesting that the Na and Cl are of meteoric origin.

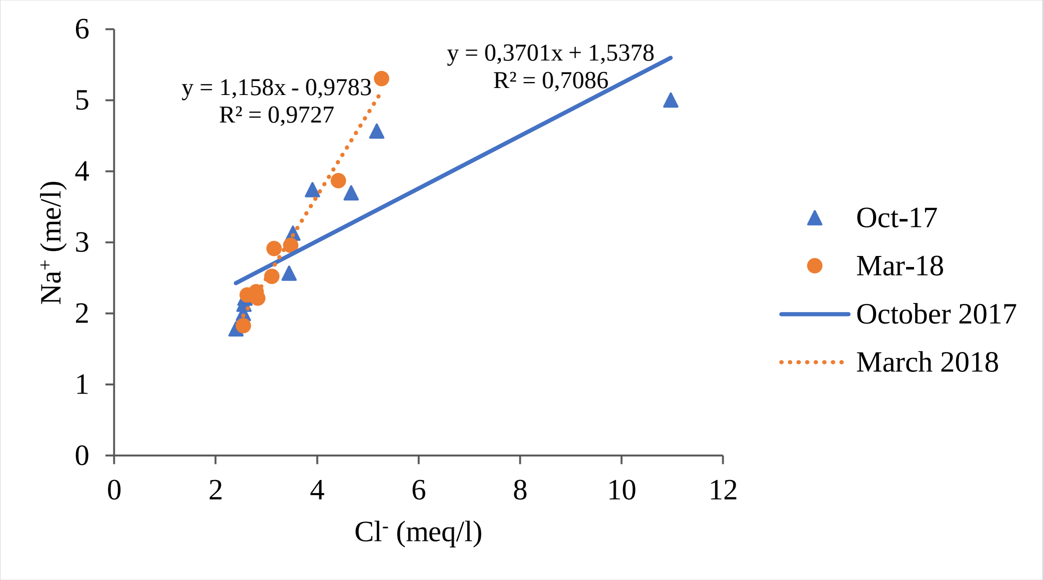


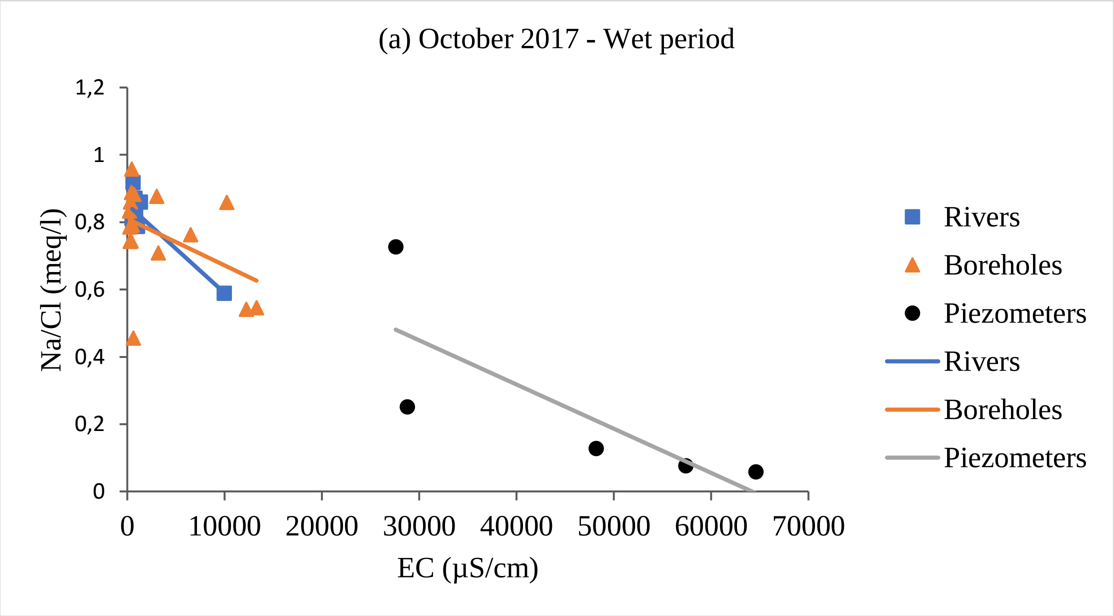
Figure 6.11: Relationship between Na^+ and Cl^- for the upstream boreholes

6.5.3 Groundwater in downstream areas

Almost all the groundwater in the downstream areas are characterised by the Na-Cl type composition with high concentrations Na^+ and Cl^- and highly saline samples. The source of Na^+ and Cl^- and the high salinity was investigated using different ionic relationships. It was hypothesised that the salinity would come from effects of evaporation, sea spray resulting in saline recharge water as well as rock water interaction.

Considering that the depth to groundwater levels in the study area are shallow (less than 10 m) and the prevalent drought conditions during the sampling periods, the influence of evaporation and evapotranspiration on the salinity of water samples were investigated. This was achieved by producing a plot of sodium-to-chloride ratio against EC, which is based on the notion that evaporation would result in an increase in the total dissolved solids and increased EC. Surface water samples were also included considering that they are the most evaporative systems. According to Jankowski and Acworth (1997), concentrations by evaporation or evapotranspiration would leave the ratio of sodium to chloride unchanged with increasing EC which would produce a horizontal line for the sodium-chloride ratio against an EC plot. An assumption is made that there are no minerals being precipitated (Jankowski and Acworth, 1997).

Results from the analysis are presented in Figures 6.12 (a) and (b) for the wet and dry period respectively. During both seasons there is a decreasing trend in the ratio of sodium to chloride against the increasing EC. In addition, there is no constant ratio between sodium and chloride with increasing EC. This indicate that evaporation is not a major process controlling the chemistry of the waters in the study area neither contributing to the increased salinity. However, for samples from piezometers (shallow groundwater to about 1-2 m deep), the slope of the plot which relate to the Na/Cl ratio is higher during the wet season compared to the one during the dry season. This suggests that as much as evaporation is not a major process, it still plays a role in the concentration of the ions and salinity for shallow groundwater sites during the dry season. During this period, the study area has higher evaporation rate than precipitation (refer to Figure 2.3). Evaporation leads to an increase in ionic concentration as the water levels decline.


(a) October 2017 - Wet period

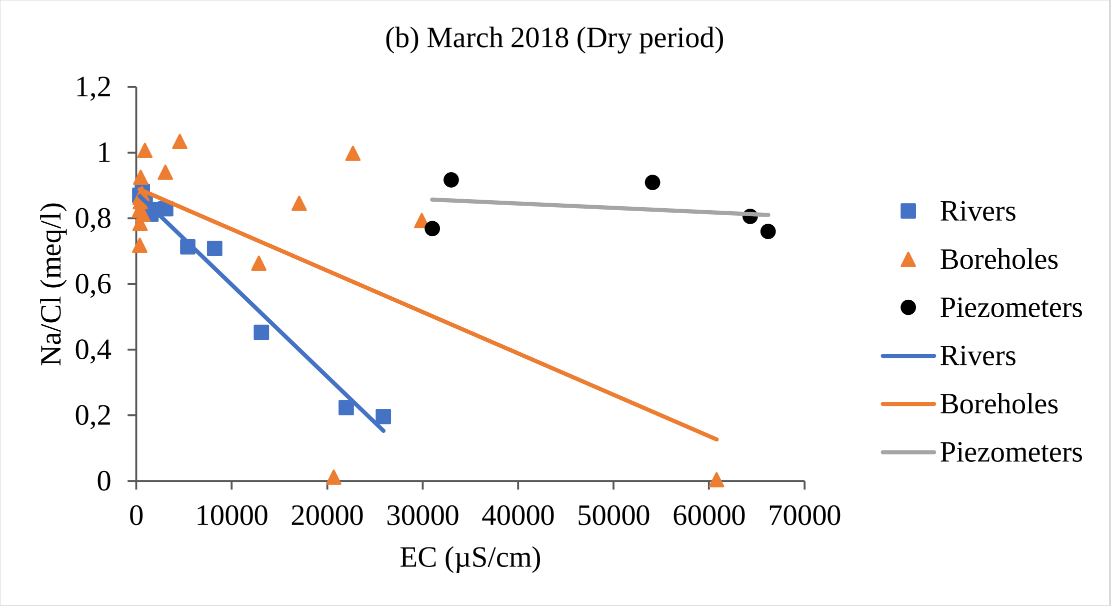


Figure 6.12: (a) Na/Cl vs EC during October 2017 and (b) during March 2018 (dry period)

The source of higher concentrations in groundwater from low lying areas was also investigated by analysing the correlation of Na^+ and Cl^- since they are the most dominant ions giving out a Na-Cl water type. Kumar and James (2016) indicated that a sodium-chloride ratio approximately equal to one is mostly attributed to halite dissolution because there will be equal mixing of sodium and chloride. Results (Figure 6.13) show that groundwater samples are plotting on and below the 1:1 line with a clear seasonality effect. During the high rainfall periods (October 2017) there is more chloride than sodium in most samples suggesting the dilution of sodium due to groundwater recharge, considering that chloride is largely a conservative ion. However, a good correlation scenario is observed during the dry period (March 2018) in which the ratio ranges from 0.66 to 0.99 with an average of 0.86, indicating the influence of host rock dissolution for the increased salinity. Due to the differences observed between the main seasons, data was also analysed for the July 2018 sampling campaign to represent the transition between dry and wet season as the rains had just started. During this period most samples plot along the 1:1 line indicating the same origin while few samples are slightly below the line indicating less sodium probably due to dilution.

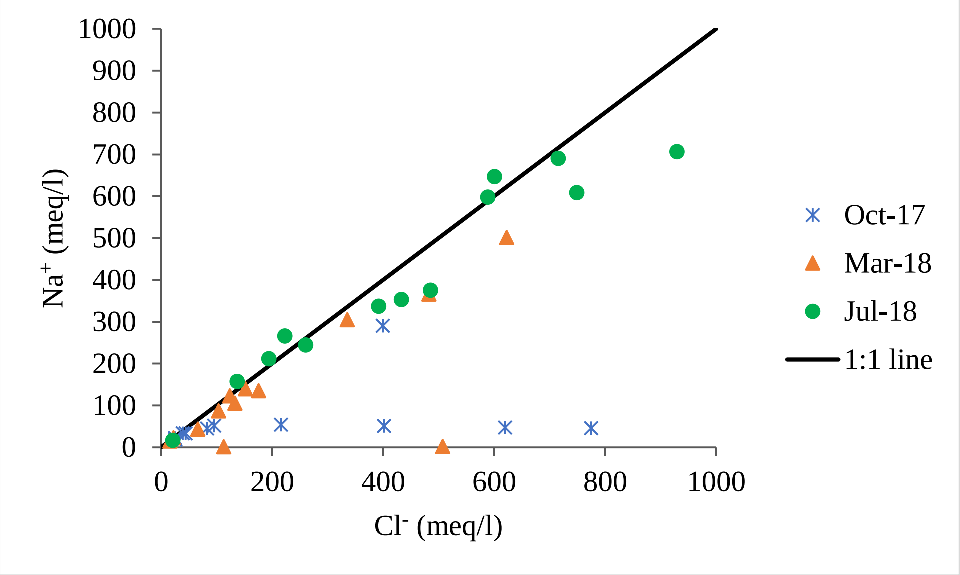


Figure 6.13: Bivariate plot of Na$^+$ against Cl$^-$ for the downstream boreholes

The dissolution of halite would be a probable source in the study area as the low lying is dominated by Bokkeveld shale and clay formations. With respect to rock water interaction, halite becomes the main source of chloride in groundwater whereby a maximum saturation of 180,000 mg/l can be reached (Mazor, 2004). Furthermore, most groundwaters contain chloride in the concentration range of 50 – 2000 mg/l which may be two to three orders of magnitude below the halite saturation concentration (Mazor, 2004). Results from this study show that most of the groundwater samples in the downstream areas have chloride values above 2000 mg/l reaching a maximum of 25,000 mg/l which suggest halite contribution.

Leaching of marine shale and sediments especially in the downstream areas is also suggested to be one of the causes for the Na-Cl water type. In the Western Cape Province of South Africa, shales from the Bokkeveld Group are well known for having saline groundwater (Weaver et al., 1999). In the downstream parts of the study area Bokkeveld shale rock dominate with clay and sandy clay top layers. It must also be noted that the concentration of chloride in groundwater is higher in the piezometers (shallower groundwater) than in boreholes. The high chloride concentrations in such areas is expected since the system act as a closed drainage basin with poor hydraulic conductivity and low gradient resulting into less flushing of old water from fresh rainwater. As such, the chloride deposits are not being completely leached thereby elevating its concentrations. This explanation is supported by Hem (1985) who stated that fine grained marine might retain the chloride built up in such a way for very long periods. Furthermore, all the piezometers are within the clay and sandy clay formation therefore high salinity in these waters could also be due to salt filtering which can happen in compacted clay and shale layers. Although groundwater does percolate through such layers, the dissolved larger ions are not permitted to pass through causing high build-up of salts near the inflow side of the membrane (van Weert et al., 2009).

Another kind of geochemical reactions which alters the chemical composition of groundwater is ion exchange, which can occur during flow through both the unsaturated and saturated zones. In ion exchange process, ions adsorbed on surface of fine-grained aquifer materials are replaced by ions in solution. The exchange of calcium and magnesium with sodium ions has been widely documented in ion exchange processes. In this process, the mineral surfaces exert more electrostatic attraction for Ca^{2+} and Mg^{2+} ions than for Na^{+} or K^{+} since Ca^{2+} and Mg^{2+} have a higher atomic mass (nearly twice) than that of Na^{+} or K^{+} (Younger, 2007). This result in Ca^{2+} or Mg^{2+} being taken up into the mineral surfaces while Na^{+} or K^{+} ions are released into the solution thereby reducing Ca^{2+} or Mg^{2+} and increasing Na^{+} in the solution. Ion exchange is prevalent in clay formations since clays are negatively charged hence they are effective at adsorbing cations.

As previously mentioned, the downstream sites are dominated by shale and clay formations with its groundwater being characterised by high Na^{+} concentration. To test if ion exchange has an effect on the groundwater chemistry in the study area, a plot of Ca^{2+} + Mg^{2+} against HCO_3^{-} + SO_4^{2-} was created for the downstream boreholes (Figure 6.14).

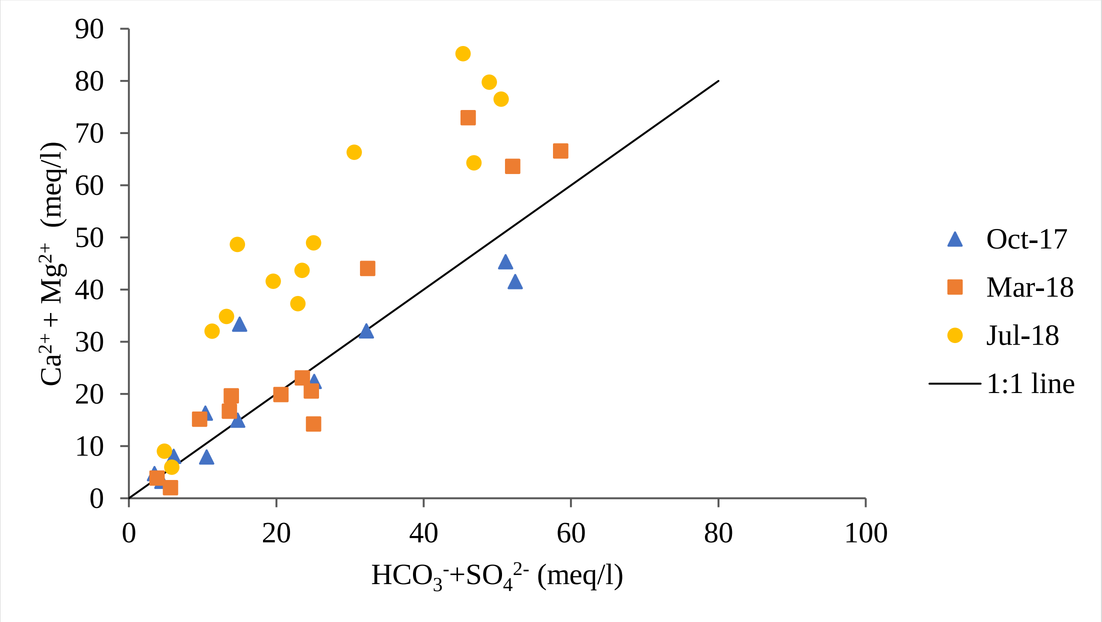


Figure 6.14: Bivariate plot of Ca^{2+} + Mg^{2+} against HCO_3^{-} + SO_4^{2-}

According to Fisher and Mullican (1997), if ion exchange is a dominant process the samples will be shifted towards the right of the 1:1 mixing line, which is the $HCO_3 + SO_4$ region. The shift will be to the right so that the negative charges of HCO_3 and SO_4 must balance with Na^+ as the only other major cation. Results show that most of the samples plot above and along the 1:1 line towards the Ca + Mg region, suggesting that ion exchange is not the dominant process controlling the water chemistry.

Sodium in groundwater may also be produced from the weathering of primary silicates containing sodium. With all conditions being constant, the concentration of dissolved components is proportional to the duration of the water–rock interaction. The concentration of sodium depends on the length of the contact time as it is a kinetically controlled process (Varsányi et al., 2015). Fisher and Mullican (1997) indicate that a Na-Cl molal ratio greater than one would typically reflect sodium from silicate weathering reactions. They further indicate that silicate weathering results in waters having HCO_3^- as the abundant anion. However, all groundwater samples have a Na/Cl ratio of one or close to one in both sampling periods. Furthermore, HCO_3^- is not the dominant anion in the two sampling periods. These scenarios suggest that silicate weathering does not control the sodium amount and groundwater type (Na-Cl) of the study area.

6.5.4 Environmental stable isotopes and salinity

The use of ion ratio relationship to identify the source of ions in water can be difficult since the chemical composition of water may undergo secondary changes such as ion exchange, oxidation and reduction and evaporation (Gibrilla et al., 2010). As earlier discussed in the above sections, most of the groundwater samples especially in the lowlands are compositionally as saline having Na-Cl type waters. To confirm that the origin of saline groundwaters is from the dissolution of the Bokkeveld shale and clay host rocks, a relationship between salinity (EC) and isotope ($\delta^{18}O$) is plotted. Analysis is made from the dry period sampling in order to clearly see the effect of evaporation. If water salinity is due to the salinity of host rock, the stable isotopic composition is not changed with an increase in salinity of groundwater (Payne, 1988). Furthermore, groundwater that has undergone evaporation will have a positive correlation between EC and $\delta^{18}O$ (Gibrilla et al., 2010). Results from the analysis are presented in Figure 6.15.

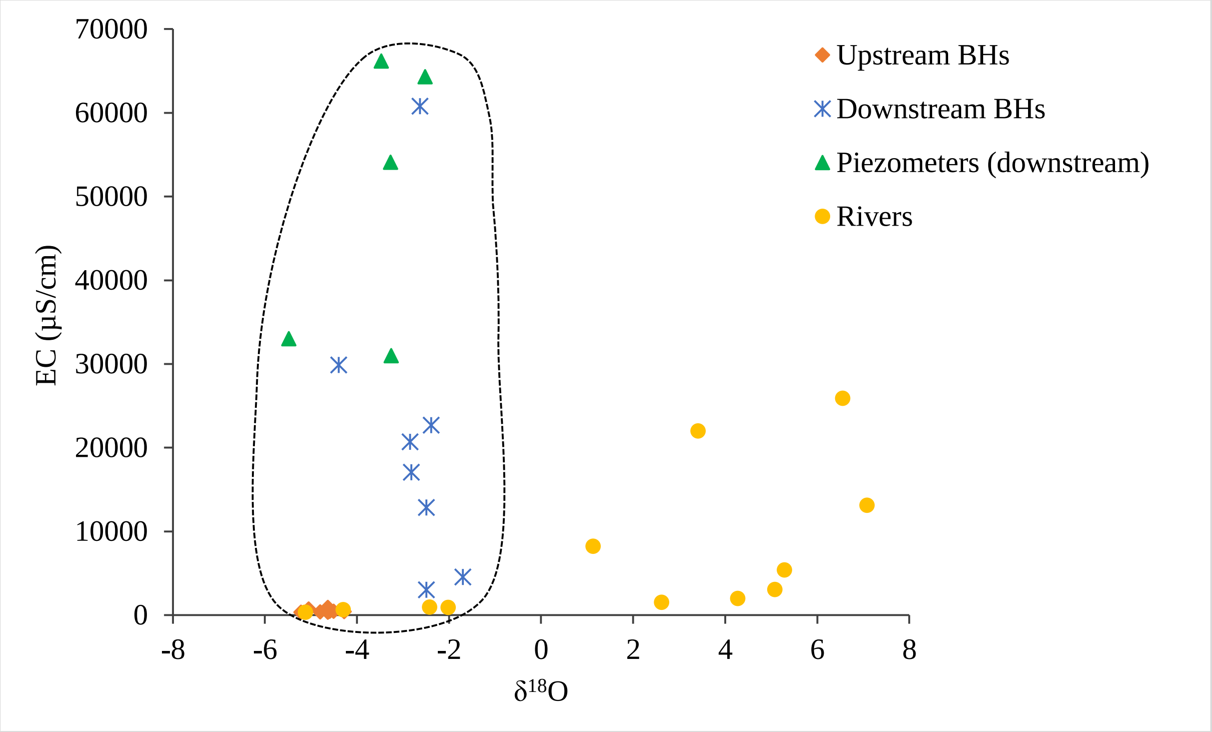


Figure 6.15: Plot of EC against oxygen-18 values for March 2018

Results show that all the groundwater samples do not show major $\delta^{18}O$ changes with increasing EC showing poor correlation. The samples cluster within the same area confirming that the salinity which is mostly from Na^+ and Cl^- is from the dissolution of halite lithology common in the area. Although the EC and $\delta^{18}O$ correlation is weak in piezometers with $R^2 = 0.35$, a positive correlation is observed. Meanwhile, negative correlation is observed in the boreholes with $R^2 = 0.11$. This suggests that the shallow groundwater from piezometers undergoes some evaporation, although it does not largely influence the groundwater quality. In general, the post-meteoric and pre-infiltration evaporation is minimal.

For the river samples, the increase in EC is associated with a notable change in $\delta^{18}O$ indicating the evaporation effect with a positive correlation and $R^2 = 0.3467$. However, the poor correlation indicates that the salinity is not only from evaporation. The probable explanation for this could be the contribution of saline groundwater discharging into the river, hence the salinity is as a result of combined effects of evaporation and mineralization. This shows the importance of using different tools in assessing aquifer-river interaction, for instance, using EC alone (Section 6.2) raised questions if the elevated EC in rivers were due to evaporation only or other factors.

6.5.5 Environmental stable isotopes and chloride

A relationship between isotopes of water (either $\delta^{18}O$ or $\delta^{2}H$) and chloride is used to investigate the origin of salinity in groundwater. According to Payne (1988), if salinity is due to the enrichment of salts by evaporation, then the $\delta^{18}O$ or $\delta^{2}H$ signature would have a low slope reflecting kinetic fractionation. Furthermore, a plot of chloride content against either isotope ^{18}O or ^{2}H will be positively correlated, as increased evaporation would result in isotopic enrichment as well as an increased chloride concentration (Payne 1988). Being a conservative element, the concentration of chloride can be elevated due to evaporation and its concentration may increase along its flow paths from recharge to discharge (Xie et al., 2010). Throughout the sampling periods, chloride is found to be the dominant ion in both upstream and downstream areas hence the need to investigate its source. A plot of $\delta^{18}O$ against chloride is presented in Figure 6.16.

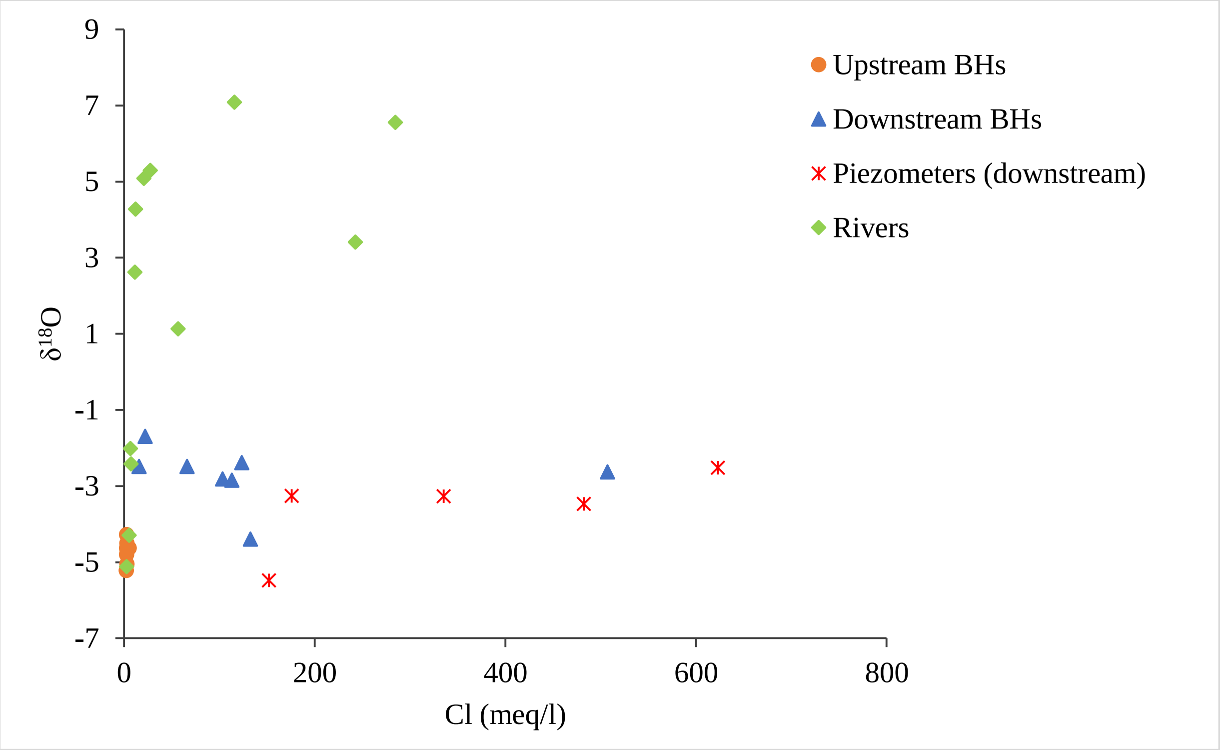


Figure 6.16: A plot of $\delta^{18}O$ against Cl^{-} showing the role of mineralization in the water salinity

Results show that there is almost no correlation between $\delta^{18}O$ and chloride for groundwater samples, although there appears to be a slight positive correlation for shallow groundwater in piezometers. The lack of correlation again suggests that the source of salinity is localized coming from chloride bearing minerals. As expected, the $\delta^{18}O$ in river samples show a positive correlation with the chloride concentrations indicating contribution of evaporation to salinity. However, in line with the $\delta^{18}O$: EC above, the correlation is weak in river samples with R^2 = 0.275 further suggesting that the salinization is not only due to evaporation.

6.6 Implication of aquifer-river interaction on non-perennial river ecosystems

Exchange fluxes between aquifers and rivers are important processes for the ecological health of rivers. Groundwater discharge becomes an important component to the water balance of most rivers especially in semi-arid environments where evaporation can be higher than the rainfall input. Thus, the influence of groundwater discharge into rivers including non-perennial is significant mostly during the period of no rainfall when there are low flows. In the study area, the Nuwejaars River characterised by dry and flowing reaches with few portions of the river course having pools during the dry period. The river reaches having water are characterised by the high hyporheic exchange, mainly controlled by groundwater discharge which is key for nutrient cycling and contaminant transport (Caluso et al., 2016). Such an environment is important for most biogeochemical and ecological processes as well as for the provision of habitats for various plant and animal species.

In most circumstances at a local catchment scale, the focus on interactions between aquifers and rivers is on the hydrological changes to determine whether the river is either gaining or losing water. However, from the ecological point of view, the most important water resource attribute is the period of time water is available in the river (Bertland et al., 2014). Findings from the study show that during the dry period the Nuwejaars River and its tributaries are largely gaining water from groundwater. As such, groundwater input plays a major role in ensuring that the hydroperiod is long during period of no rainfall especially in arid and semi-arid environments. Groundwater discharge zones identified in this study are ecologically one of the main features of aquifer-river interactions.

6.7 Chapter summary

The chapter has provided the usefulness of using hydrochemical and environmental tracers in assessing aquifer-river interaction in non-perennial river systems. Results from the study area indicate that there is a close hydraulic connection between the aquifer and the rivers in both upstream and downstream areas. This is observed by the similar patterns and trends in the major ions, salinity as well as through the use of isotopic signatures data for groundwater and surface water.

The upstream part of the study area is characterised by low EC values in groundwater and surface water samples. Meanwhile, EC is higher in the downstream sites such that the EC increases with a decrease in surface topography towards the sea. In this study EC is used to assess the aquifer-river interaction based on an assumption that the run of EC along the river would not change much unless where there is input of groundwater of different chemical characteristics or when the river gets contaminated from the farming activities. The similar pattern of EC in the groundwater and river samples suggest a hydraulic connection between the two water sources.

Major ions trends again show similar characteristics for groundwater and river samples. An increase and decrease in either ion in groundwater is accompanied by a corresponding increase and decrease in that particular ion in river samples further suggesting the interaction. Groundwater in the region is mainly characterised by Na-Cl, Na-Cl-HCO_3 and Na-Mg-Cl water type while river samples are characterised by Na-Mg-Cl and Na-Cl water types. The Na-Cl waters which dominates the groundwater samples are understood to have originated from the same source based on the good correlation between Na^+ and Cl^- in both upstream and downstream areas. The use of major ions shows that there is a connection between groundwater and the river despite the initial assumption that connectivity would be limited due to the low hydraulic conductivity. Major ion characteristics are also used to predict the hydrogeochemical processes controlling groundwater quality which eventually influences the quality of surface water. The various ions analyses in this study concludes that Na-Cl type composition is derived from the sea spray as well as dissolution and leaching of host rock mostly the Bokkeveld shale.

River samples in upstream areas show depleted $\delta^{18}O$ and $\delta^{2}H$ signatures similar to groundwater samples. It is conceivable of high evaporative enrichment of $\delta^{18}O$ and $\delta^{2}H$ from surface water bodies in the downstream areas during the dry period. During the rainy seasons, depleted river samples are observed indicating the influence of recent rains flushing out enriched water and replacing it with new water which has $\delta^{18}O$ and $\delta^{2}H$ magnitude close to the local precipitation. Meanwhile, the data demonstrate that during the dry period with high evaporation in rivers it is difficult to ascertain the groundwater contribution to rivers using isotope data as the water ends up being exposed to evaporation hence the isotopic signatures change. However, isotope data would work in such cases where there is high groundwater input to the river to keep on flushing the evaporated river water. Results also show that groundwater samples have lower stable isotopic values including during the dry season, indicating that there was no groundwater recharge from the highly enriched river samples. The use of major ions as well as environmental isotopes in conjunction with EC data in pool or less flowing river samples helps to rule out in few cases where elevated EC could be the result of evaporation.

Findings from the current chapter fulfil the second objective of the thesis where the spatial and temporal variation in the interaction between aquifers and river water is characterised. However, the contribution of groundwater to the river water is not quantified in this study, therefore, future work in this study area needs to focus on addressing this gap. Based on the understanding on the hydrochemistry in the current chapter as well as on the groundwater levels, local geology and aquifer hydraulic characteristics a hydrogeological conceptual model which explains the influence of groundwater on the river systems of the study area is constructed in the next chapter.

Chapter 7: Summary of main results, conceptualization of groundwater flow system and study recommendations

7.1 Introduction

This chapter integrates different hydrogeological data to create a hydrogeological conceptual model for the study area. Geology, hydrogeology, recharge/discharge, groundwater flow and hydrology data are used to construct the conceptual model whereas chemistry and environmental data are used to improve and verify the conceptual understanding of the model (Mengistu et al., 2015). The conceptual model provides information on how groundwater flows within the aquifer system. In the current chapter, hypotheses on the dominant groundwater flow paths which govern the extent of water interchange between the aquifer and the river are tested with relevant data analyses. The chapter also discusses how the different hydrogeologic settings affect the generation and maintenance of streams which also determines the nature (perennial or non-perennial) of a river. It is important to point out that the continuity of river flows is affected by different factors such as evaporation from the river, transpiration from riparian vegetation and human influences such as abstraction. However, this study focuses only on the influence of hydrogeologic characteristics in sustaining or reducing flows in a river. Developing an accurate conceptual model is essential step in the process of a groundwater numerical groundwater model (Izady et al., 2014). The conceptual model forms the aim of this study thereby assessing the influence of groundwater on non-perennial systems.

7.2 Aquifer parameters

Constant rate pumping tests were conducted in three sites across the catchment, two sites in the upstream area and one site in downstream area. The purpose of the tests were to estimate the aquifer parameters which influences groundwater flow system. Results show that the study area is characterised by low transmissivity (T) values both in upstream and downstream areas, with T values of 0.17, 0.24 and 1.74 m^2/day. Secondary porosity is dominant in the study area, as such the occurrence and movement of groundwater is largely controlled by the extent of fractures. From the drilling, pumping tests and electrical conductivity borehole logging it is found that there is less occurrence of fractures in the sites which signify the relatively slow rate of groundwater flows in the study area.

7.3 Hydrogeochemical zones and isotopic data

The chemical composition of groundwater indicates the different processes and reactions the groundwater encounters as it flows through the different geological materials (Appelo and Postma, 2005). Therefore, differing groundwater flow systems can be distinguished using the characteristics of the water chemistry. In this study, patterns in the chemical and isotopic data were therefore used to delineate groundwater zones from which 3 groundwater zones were defined.

In the upstream part of the study area, groundwater from artesian boreholes, boreholes close to faults and spring water have Na-Cl waters. The water type from upstream areas do remain compositionally unchanged during the wet and dry periods. Therefore, it is argued that groundwater is likely to come from deep regional flows. Meanwhile, in the same upstream area are the boreholes having Na-Mg-Cl water type composition during the wet period which is indicative of groundwater originating from localized flows and relatively shallow groundwater. One of such sites is the artesian borehole which stops flowing during the dry period further confirming the localization of flows.

It must be noted that different data types show that there is mixing between waters from the deeper and shallow boreholes, hence the shallow boreholes are likely to have the Na-Cl type characteristics. The Na-Mg-Cl type during the wet period is therefore due to the freshening effect of recharge rainfall water. Meanwhile, during the dry period, the water type from the shallow boreholes in the upstream area change to Na-Cl-HCO_3 type composition. The HCO_3 could be due to the atmospheric gases available in the soil or in the unsaturated zone between the land surface and water table (Hem, 1985). The Na-Cl-HCO_3 type would indicate the recently recharged water from the rains. This is in agreement with the rainfall sample collected in July 2018 which also show the Na-Cl-HCO_3 type composition. Overall, groundwater in upstream sites is characterized by low pH (below 7 with an average pH of 5) and an average EC of about 400 µS/cm and 500 µS/cm during the wet and dry seasons respectively. The low pH in the upstream areas is due to the quartzitic and poor buffering nature of the TMG lithology (Smart and Tredoux, 2002).

In the downstream areas of the study area, water chemistry exhibits Na-Cl water type composition, which do not change during the wet or dry seasons. It is interesting to observe that there is an exception for one borehole (BH8 at Moddervlei) in the alluvial/sand formation, which evolves from Na-Cl to Na-Cl-HCO_3 demonstrating the influence of recharge rainfall water. The dominant geology in downstream areas is the Bokkeveld shale and the sandy clay layers. Groundwater in these downstream parts is deemed to have lower flow rate and a relatively longer contact time making some samples have salinity reaching 60,000 µS/cm. Considering that surface topography in the downstream areas ranges from the sea level to about 30 m, the high salinity is likely to be as a result of limited flushing with fresh water. Highest mineralized waters of 40 000 mg/l are in shallow groundwater from piezometers which are within the clay formation. The membrane properties of clays may lead to the exclusion of ions from water flowing across the membrane thereby raising the concentration of ions (Back, 1988).

The influence of saline fractured shale bedrock on the alluvial sand aquifer is seen in BH8 (at Moddervlei) which is 8 m deep and drilled only in the sandy formation. The borehole has a relatively elevated EC with an average of 3000 µS/cm which signifies that there is high likelihood of connectivity between the shale bedrock and alluvial aquifer probably via the fractures as confirmed from the EC borehole logging.

With regards to isotopic composition, groundwater samples from sites close to regional faults including springs and artesian boreholes are relatively lighter in their isotopic composition than in the downstream sites within the same sampling period. Isotopic composition of precipitation at higher altitudes are depleted due to the lower average temperatures (Mazor, 2004). This suggest that such samples are recharged from higher altitude surrounding catchments. This is regardless of the differences in the hydrochemical composition of the boreholes, for instance deep and shallow boreholes. Clark and Fritz (1997) indicate that the depletion in isotopic composition will be in the range of -0.15 to -0.5 ‰ for $\delta^{18}O$ and a corresponding depletion of about -1 to -4 ‰ for $\delta^{2}H$ isotopes per every 100 m rise in altitude. One interesting feature are samples from groundwater sites close to SANParks Offices (BH1 and PZ16) in the downstream area which show depleted isotopic signatures ($\delta^{18}O$ of -4.4 ‰ and $\delta^{2}H$ of -23 ‰) close to those in the upstream areas in both March and July 2018. This site sits at a lower elevation compared to many other sites at higher elevation close to the upstream area which are characterised by relatively high isotope values. The possible reason for the low isotopic values at this downstream site could be the sites being supplied by upstream groundwater through the North West – East trend fault.

In general, there are differences in isotopic signatures in the upstream and downstream areas controlled by small topographic differences and geological structures. According to Folch et al. (2011), lightest isotope values indicate that the fault zones are acting as barriers to regional, large scale flow systems. The differences in isotopic values between the upstream and downstream boreholes therefore suggests the discontinuity in flows.

Shallow and deeper boreholes in both upstream and downstream sites have similar isotopic signatures with an exception of a slight difference observed in boreholes at Spanjaardskloof site. The deeper borehole aquifer (over 60 m) shows relative depletion in δ^2H than a shallow (of roughly 20 m) one. The variations in isotopic composition at the same site would reflects the presence of different recharge flow systems as well as absence of connectivity between the deeper and shallow hydrogeological units. Thus, the deeper borehole at this site is likely to be recharged by deeper regional flows while the shallow one is mostly recharged by rainfall falling in the local area. The deuterium excess at this shallow borehole in Spanjaardskloof was higher than all groundwater sites and it was close to deuterium excess of rainfall sample indicating quick preferential recharge before evaporation. This agrees with groundwater level data at Spanjaardskloof where the shallow borehole responds quickly to rainfall event. Hydrochemical data also shows characteristics of shallow recently recharged water in the shallow borehole.

7.4 Groundwater recharge area, flow and discharge

Groundwater recharge occurs in most parts of the study area, although it may occur relatively quicker in some sites than others. This is noted by the response of boreholes to rainfall in all parts of the study area. Based on the groundwater level, chemistry and isotope data high recharge rates are understood to be in the upstream parts especially in the Spanjaardskloof area where the bedrock outcrops exposing the fractures from which rapid infiltration would occur. The Department of Water Affairs Groundwater Resource Assessment (GRA) II (DWA, 2004) shows the recharge rates of 3.5 and 4.1% of mean annual precipitation in the G50B and G50C Quaternary Catchments respectively. G50B Quaternary Catchment is mostly covering the upstream areas while G50C Quaternary Catchment mostly covers the downstream areas (Figures 2.1). The slightly higher recharge in G50C Quaternary Catchment could be due to reduced runoff which is in response to flat topography while the presence of dense vegetation in the G50B Quaternary Catchment could reduce groundwater recharge. The GRA II dataset is based on the chloride method and adjusted to account for factors such as depth to groundwater, landcover, variation of MAP and slope (Holland, 2011). Therefore, there is a need to do the recharge estimates at a local catchment scale and use other methods to validate such findings since the GRA II results are based on a regional assessment and the chloride method was applied in a coastal area.

The available data on groundwater levels is used to construct a contour map to be used as a platform where general groundwater flow direction is deduced. Figure 7.1 shows groundwater level contours and the general groundwater flow direction for March 2018. Closely spaced contours are found in the upper high elevation parts of the study area indicating a relatively higher hydraulic gradient of 0.0126 while widely spaced contours are found in the lower elevation areas of the catchment indicating a relatively low hydraulic gradient estimated to be 0.000843.

Generally, the map shows groundwater flow mimicking the surface topography. It shows that the local groundwater flows from the North and North-West in the higher recharge areas towards the Nuwejaars River as the discharge area. This is mainly evident at Modderlvlei and around Elandsdrift Farm sites in the middle part of the study area, where the contours are pointing up the river suggesting dominance of groundwater flow.

Theoretically, groundwater discharge to the rivers is shown by the upstream bending of contours and contours nearly parallel to the river. In the present study, on the upstream part of the river groundwater level contours are approximately perpendicular to the river suggesting that there are hydraulically neutral conditions where there is no clear losing or gaining conditions. It must be noted that according to Darcy’s Law groundwater flow occurs not only when there is a hydraulic head gradient but also the hydraulic conductivity of the formation. Therefore, the potentiometric surface maps presented in this study only indicates the potential groundwater flow direction due to the fact that the sites in the study area are characterised by low conductive formations.

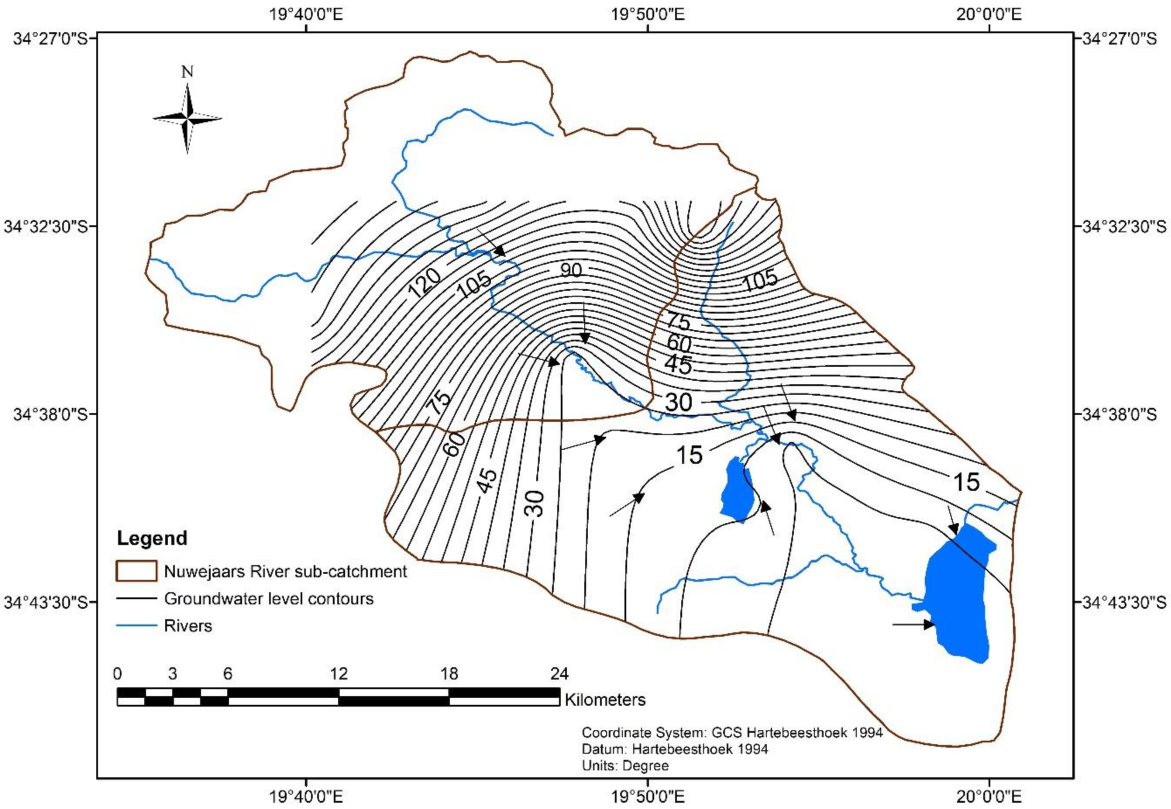


Figure 7.1: Potentiometric surface map for March 2018 showing the potential groundwater flow direction

When the seasonal potentiometric surface maps are compared, there is no variations between the wet and dry periods. This is in agreement with the small changes in the hydraulic head observed in the boreholes/piezometers between the two seasons. Hence, in this study one potentiometric surface map is produced.

The East-West fault in the northern part of the study area seem to act as a barrier to groundwater flow at a regional scale. This is apparent in Boskloof boreholes which are drilled close to the fault zone whereby there is significant drop in the hydraulic head compared to other boreholes in the study area. The fault systems occur in the boundaries between the fine grained (cataclastic) sandstone quartzite and the shale rock suggesting that the faults would impede lateral groundwater movement. This suggests that at this regional scale there is a discontinuity of groundwater flow towards the south thereby directing the flow towards the east or west direction. This results in the localization of groundwater flows within the study area. The low yield boreholes available in the study area suggests of the isolation of such sites from the regional flows.

There is also an evidence of the North East – South West fault in the north east part of the study area acting as a conduit of flow. It is highly likely that the groundwater flow along the fault connects with the Pietersieliekloof River (PT1) which is a tributary to the Nuwejaars River. Pietersieliekloof River, although small usually flows throughout the year thereby supplying water to upper reaches of the Nuwejaars River. During the dry season, Pietersieliekloof River show depleted isotopic signatures similar to those of all upstream boreholes. Meanwhile, site NJ7 is the only surface water sample along the Nuwejaars River having depleted stable isotopic signatures indicating the contribution of groundwater connected through the Pietersieliekloof River. Wolwegatskloof River close to Elim town (ETS) also has lowest stable isotope values similar to the upstream boreholes. The stream originates from an area close to the fault and it flows continuously throughout the year.

7.5 Conceptual modelling

The main source of recharge water to Nuwejaars River is the winter rainfall occurring between May and October, the groundwater fed tributaries as well as groundwater discharge in the alluvial plains. The shallow groundwater in the study area appears to flow to the nearest discharge point.

In the downstream areas, there is a prevalence of clay intercalation in areas long the Nuwejaars River. These are mostly of low conductivity which would restrict vertical groundwater movement to the shale bedrock. This would result into greater lateral groundwater movement towards the river (Banks et al., 2011). The exchange fluxes not only influence the quantity but also quality of water in the river. Due to the geologic heterogeneity, it is hypothesised that the shallow water table in the lowlands may be disconnected from the regional groundwater flows forming a perched groundwater. Perched groundwater can act as a partial substitute for regional groundwater by limiting seepage loss, providing base flow and bank storage (Niswonger and Fogg, 2008) thereby maintaining the ecosystem functioning of rivers.

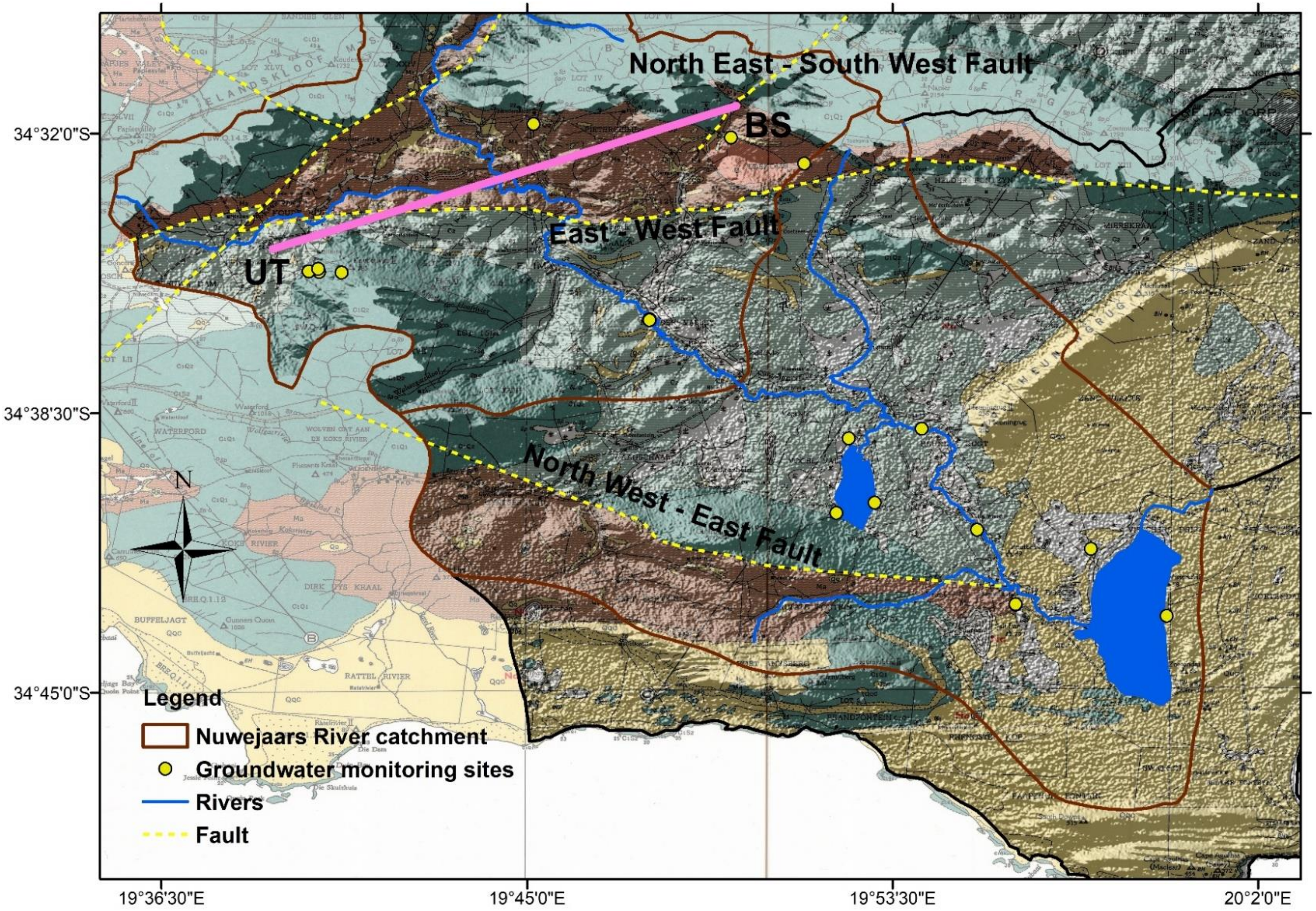


Figure 7.2: Map of the study area showing the geological cross section from Uitsig (UT) to Boskloof (BS) sites passing through Jan Swartskraal and Pietersieliekloof Rivers. The conceptual model for groundwater flow in the upstream areas is developed from this cross section.

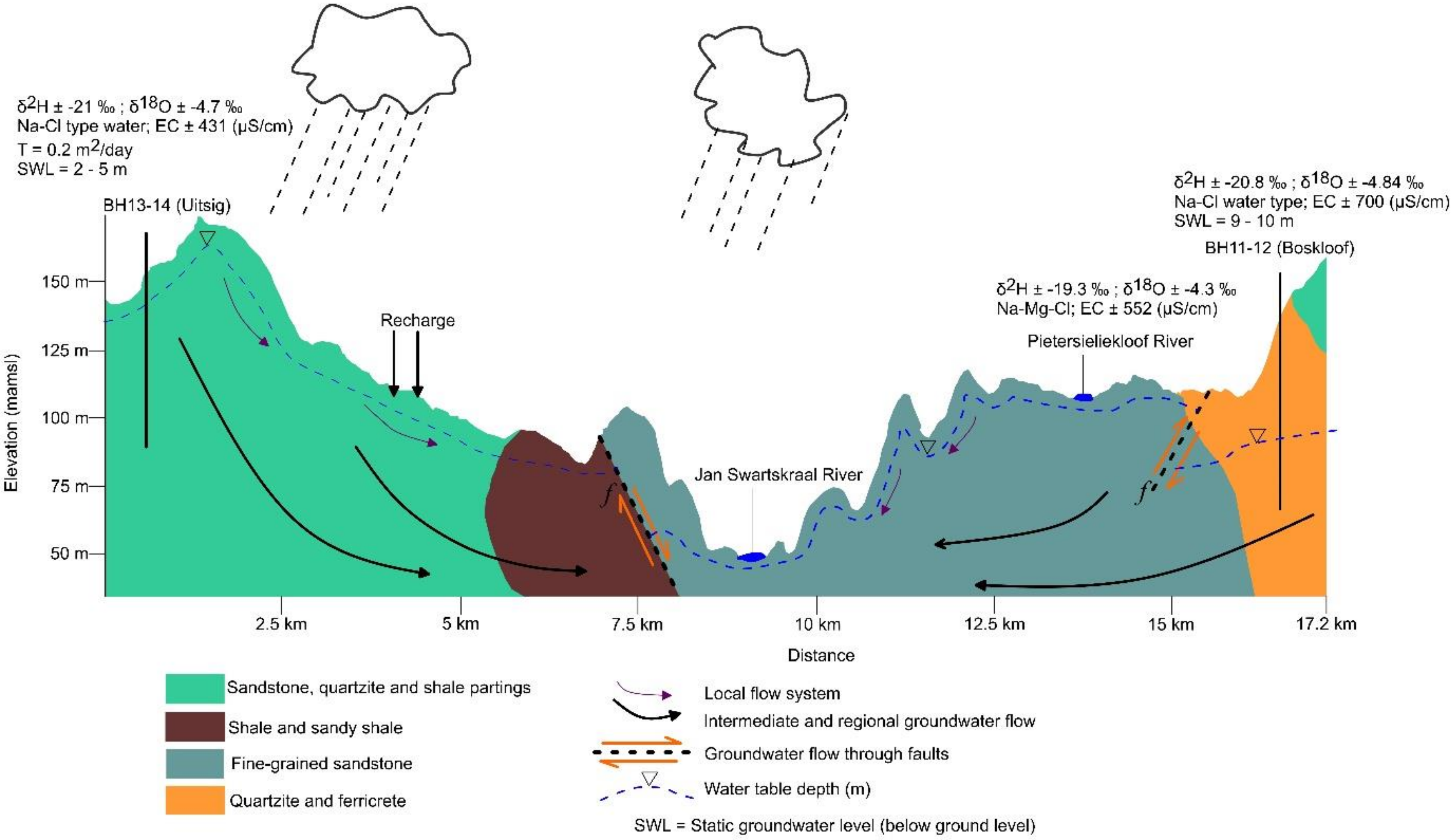


Figure 7.3: Conceptual model of groundwater flow in the upstream areas through Uitsig and Boskloof

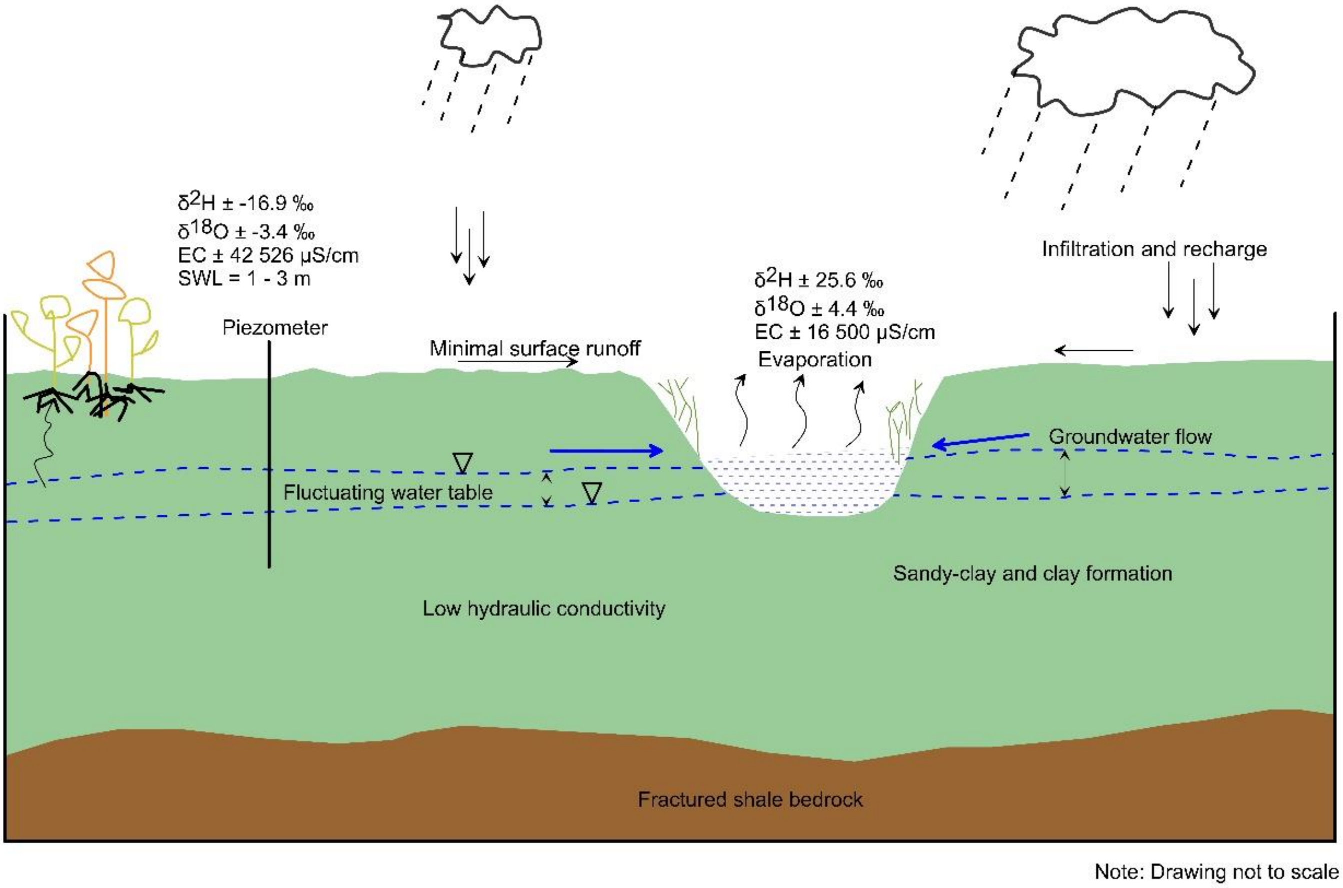


Figure 7.4: Conceptual model of aquifer-river interaction in the downstream area

7.6 Proposed optimised management of non-perennial river systems

In semi-arid regions like the study area, rainfall is highly variable and sometimes become significantly less than the evaporation. Therefore, groundwater discharge to the rivers becomes an important part of the water balance by providing flows to rivers. The amount of water in a river and the sustainability of streamflow from headwaters to downstream reaches usually depend on contributions from groundwater (Winter, 2007). On the other hand, high groundwater abstraction would contribute to the drying up of rivers by lowering the water table. In the study area, groundwater use is prevalent in the upstream areas where the groundwater is relatively fresh. One noticeable feature closer to sites where groundwater abstraction is happening is the decline in spring discharge and some artesian boreholes stopped flowing during summer. However, it is yet to be known if this was due to the abstraction, or natural decline or as a result of drought which occurred during the study period. Meanwhile, in the downstream areas the saline nature of groundwater makes it less suitable for different uses. In general, groundwater use can have negative implications on the hydraulically connected surface water bodies and eventually impact on its ecosystems. Therefore, the allocation and management of groundwater resources has to take into account the occurrence, recharge, flow and discharge of groundwater to sustain the river ecosystems.

It is been observed that despite the downstream areas having low permeable sandy clay formations, there is still groundwater discharge towards the river during the dry season. This could be due to the shallow or perched aquifer systems which might not be in contact with the regional or immediate groundwater flow systems. Perched groundwaters cause fluctuations of river water levels thereby determining the onset of flow in non-perennial rivers but also the chemistry of temporary pools (Niswonger and Fogg, 2008). Aquifers in such shallow systems are sustained only by the winter rainfall since they are disconnected from the regional and intermediate flows. This means that the groundwater and its associated flow systems are susceptible to exploitation and climate change, for instance, the drought conditions experienced during the current study period resulting in disconnected river flows. In order to ensure river connectivity, it is therefore important to maintain the river flows in the upstream areas (catchment headwaters). For a river which is connected to a groundwater system, controlling groundwater withdrawal by humans and riparian vegetation in the upstream areas is crucial in maintaining the river flows. Managing such losses in the headwaters would result in the river flowing longer distances to its downstream segments thereby providing reliable supply of water to the aquatic organisms throughout the course of the river.

7.7 Conclusion

This study demonstrates the efficacy of using an integrated approach of combining different data sets for assessing the role of groundwater in non-perennial rivers. Aquifer hydrology, hydrochemical, isotopic and geological data are used to describe the hydrogeological system of the Nuwejaars River sub-catchment. North East – South West fault in the north eastern part and the North West – East fault in the western part of the study area play an important role in the groundwater flows. The faults act as a conduit to groundwater flow by supplying water to the upstream rivers which feeds into the Nuwejaars River. The conceptual model for the aquifer river interaction in the study area has been supported by the following evidence:

- The study area has a shallow water table (less than 10 m) both in upstream and downstream areas thereby promoting a relatively quick discharge to the rivers

- The Table Mountain Group (TMG) formation dominant in upstream areas has low transmissivity values suggested to be due to effects of fault development which result in development of low permeable fine-grained materials (fault breccias). This reduces the occurrence of fractures and eventual occurrence of groundwater. Generally, the Bokkeveld Group formation has low hydraulic conductivity values, however, in this study it is found to have a relatively higher hydraulic conductivity in some localized areas probably due to the presence of fractures as shown by the EC borehole logging
- Deeper groundwater and spring water in the upstream parts of the study area exhibit the isotopic signatures of rain water indicating direct recharge without significant evaporation
- Vertical mixing occurs in the TMG quartzite formations in the upstream areas as demonstrated by the similar chemical and isotopic signatures of water samples
- On a catchment scale, upstream areas are deemed to have high groundwater recharge rates and the downstream areas are discharge zone. Groundwater recharge is mainly from rainwater infiltration with no evidence of river seepage
- Low surface elevation (gradient) and poor hydraulic conductivity in the downstream portion of the study area cause slow groundwater flows resulting in less flushing and high salinization in the downstream areas
- The slow Darcian flows would result in slow and minimal groundwater discharge to the river resulting into groundwater failing to maintain the flows or pools in such cases

7.8 Recommendations of the study

The major limitation for the study is the inability to quantify the water fluxes between the aquifer and the river. It is difficult to use quantitative techniques at first attempt to assess the aquifer-river interaction in rivers which are non-perennial since some river segments are characterised by non-flowing water. However, this study has provided qualitative information on aquifer-river connectivity at catchment scale and identified river segments where interaction is occurring so that such areas are targeted for more detailed quantitative assessments.

It is also critical to have more boreholes and piezometers close to the river in different physiographic features in order to properly explain how different hydrogeological characteristics can be used to explain the influence of aquifer-river interaction in non-perennial rivers. Although this is the case, results from some of the study sites provide significant information on the groundwater characteristics of the study area to explain varying site-specific scenarios. Groundwater in upstream areas of the catchment, where some of the boreholes are located, plays a major influence on streamflow generation as well as influencing the hydrochemistry of the rivers.

Based on the findings and limitations, the study has put in the following recommendations for future research:

- Improve groundwater monitoring sites both in upstream and downstream areas as well as close to the rivers in order to have a better distribution of groundwater level patterns and aquifer hydraulic parameters as influenced by the sub-surface heterogeneities
- Redo some components of the study in a normal period without the drought conditions which were experienced during the current study. Water sampling for both hydrochemical and isotopic samples need to be done during a period of average or high rainfall period which describes the average dry and wet periods for the study area in order to make better conclusions. Furthermore, there is need to conduct a long monitoring of environmental isotopes from precipitation and groundwater in both upstream and downstream areas to add on to the existing water level monitoring
- Apply appropriate tracer techniques for quantifying the contribution of the water sources (groundwater, river and precipitation) to each other using the mass balance approach
- Estimate groundwater recharge rates from data obtained at site specific catchment scale in order to improve an understanding of the catchment water balance.

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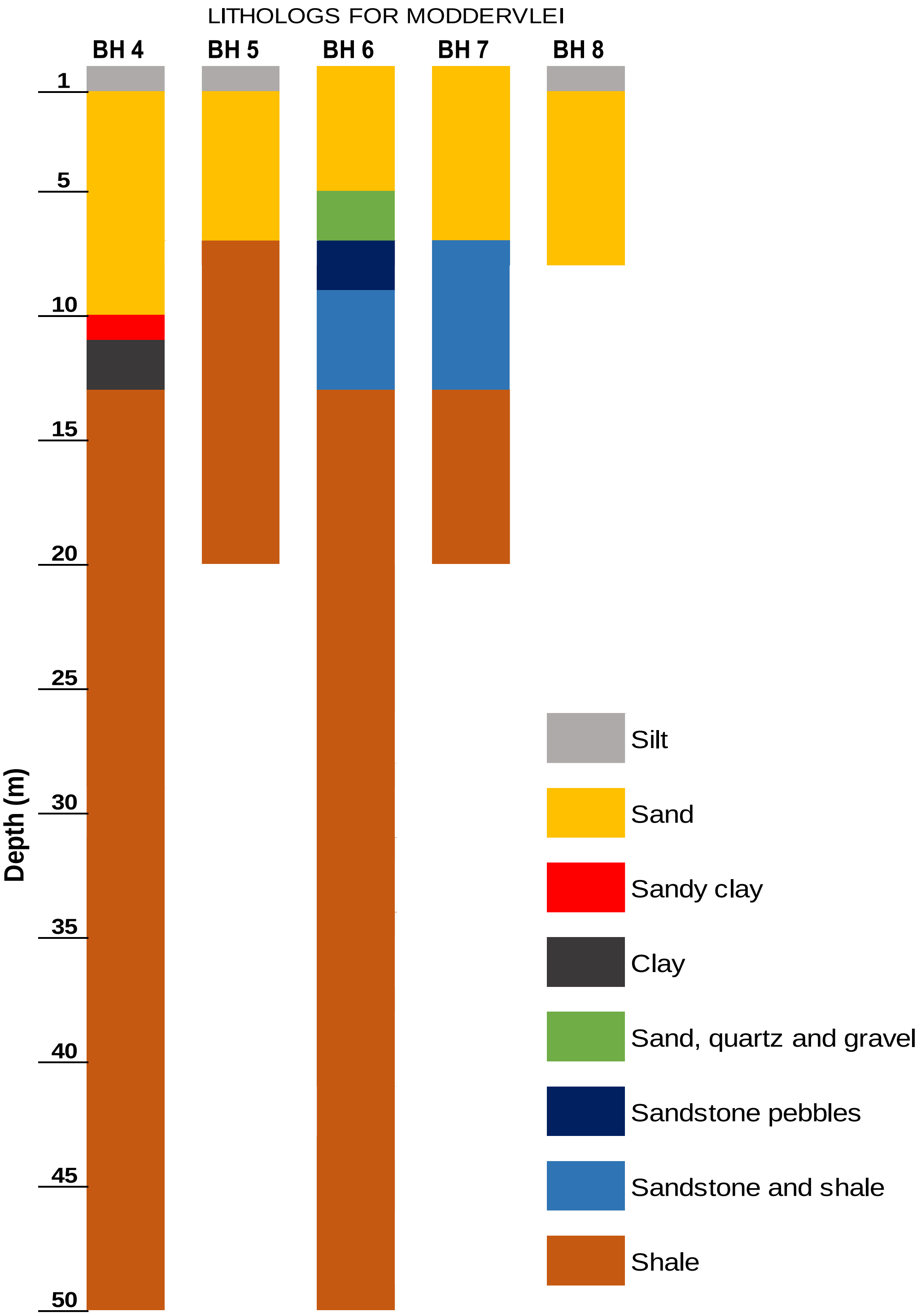
Appendix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Depth (m)
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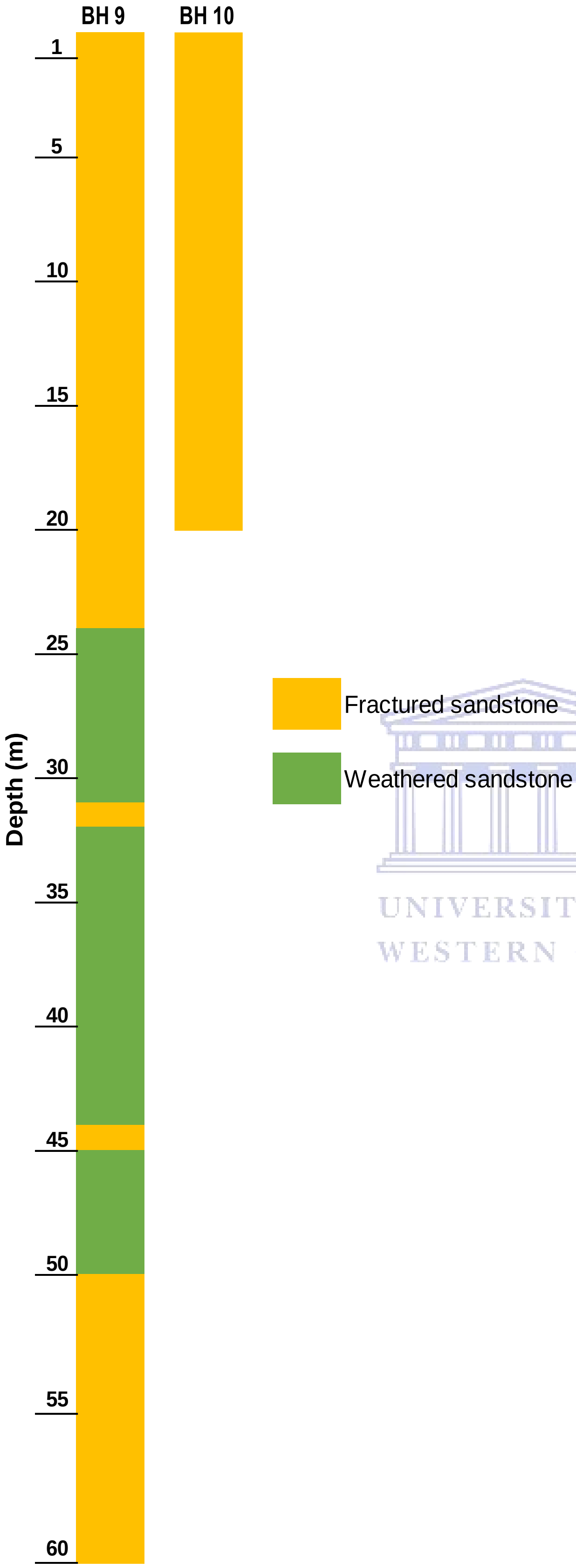
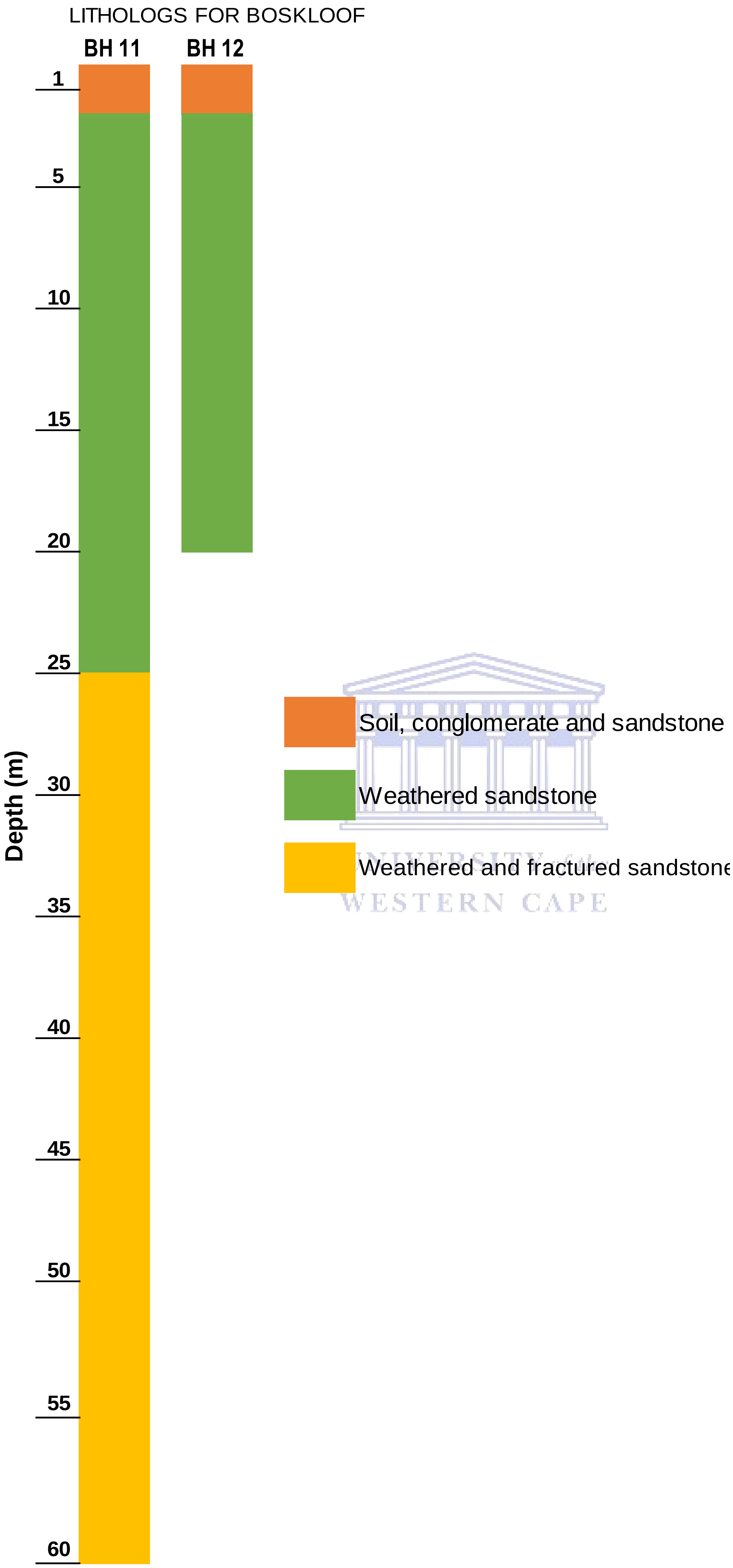
40
45
50
Silt
Sand
Sandy clay
Clay
Sand, quartz and gravel
Sandstone pebbles
Sandstone and shale
Shale

LITHOLOGS FOR SPANJAARDSKLOOF




LITHOLOGS FOR BOSKLOOF
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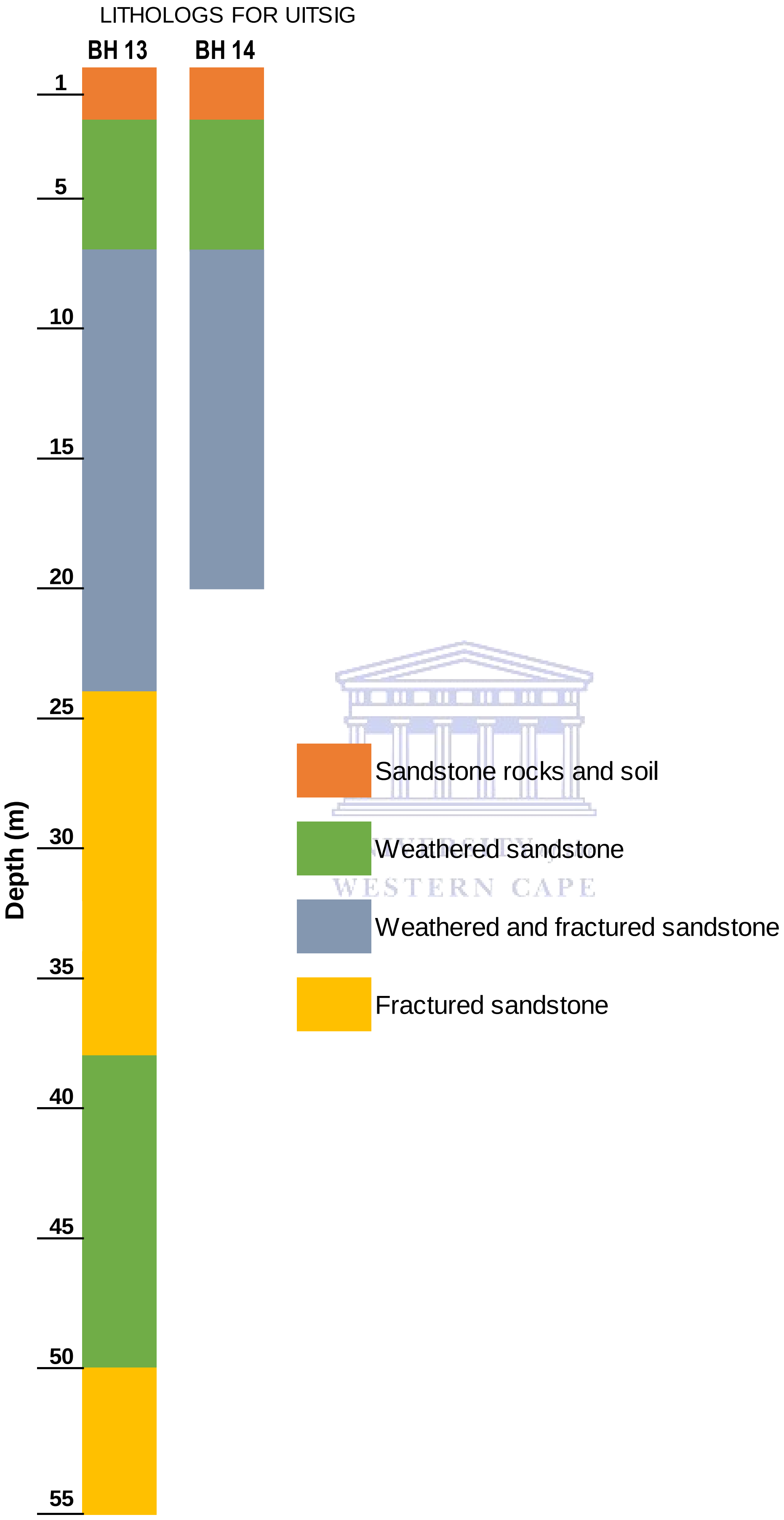
Soil, conglomerate and sandstone
Weathered sandstone
Weathered and fractured sandstone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Sandstone rocks and soil
Weathered sandstone
Weathered and fractured sandstone
Fractured sandstone