Assessing the influence of groundwater recharge mechanism on non-perennial river systems, Tankwa Karoo, South Africa

RESPICE PROSPICE

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In

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DECLARATION

I, Phumlani Mqondeki, declare that *Assessing the influence of groundwater recharge mechanism on non-perennial river systems, Tankwa Karoo, South Africa* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Phumlani Mqondeki

Date:…………………

Signed:…………………………..

DEDICATION

This work is dedicated to my beloved parents, Mr. Dododo and Mrs. Nolusindiso Mqondeki.

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I would firstly like to thank God for giving me the strength and courage to complete my studies. To the Institute for Water Studies at the Department of Earth Science and the National Research Foundation (NRF) for their financial assistance, without which any of this research would have not been possible. To my supervisors from the Department of Earth Science, Dr. Thokozani Kanyerere and Dr. Kevin Pietersen for your continued assistance throughout this research, I thank you. I would also like to thank Dr. Jaco Nel, from the Institute for Water Studies, from whom I have benefited from his expertise. To the technical staff at the Department of Earth Sciences, Mr. Evan Swaartbooi, for assisting me with laboratory analysis. To my fellow students at the Department of Earth Sciences, for assistance with field and laboratory work. To the South African National Parks (SANParks), for granting me access to Tankwa-Karoo National Park. The South African Weather Services (SAWS), for providing climatological data. The Department of Water and Sanitation staff, Mr. Ashton Van Niekerk and Mr. Brian Dyason, for providing me with secondary data and assisting me with fieldwork. Finally, I would like to thank my parents, my wife and my son for their continued moral support and encouragement during my studies.

ABSTRACT

In South Africa and neighbouring countries such as Zimbabwe, Botswana, Angola, and Namibia, most river systems are non-perennial due to semi-arid or arid climatic characteristics. In such river systems, the interaction between groundwater and surface water is of significance in terms of developing appropriate methods for determining ecological water requirements among others. However, the interaction is not well understood in terms of the influence on the volume and quality of water on the gaining and losing water bodies. In past research, the importance of non-perennial rivers (NPRS) was neglected because these river systems were considered as systems of low ecological importance and economic value. However, an improved understanding of these systems illustrated that they provide habitat for diverse and unique flora and fauna. Therefore, the main research question that was posed for the study was what is the influence of river-aquifer interactions in non-perennial river systems in the semi-arid environment?

The central argument was that unless we assess the interaction between surface water and groundwater in NPRS, we cannot improve on understanding of the role of groundwater on the NPRS. The aim of the study was therefore, to assess surface water-groundwater (river-aquifer) interactions in non-perennial river systems to provide an insight regarding how these water resources interact in semi-arid environments. To achieve the aim, three specific objectives were formulated, namely, to establish the groundwater contribution to the river system, to investigate the role of the river in recharging the underlying aquifer, and to develop a regional hydrogeological conceptual model of recharge mechanisms. To achieve the objectives of the study, samples were collected from boreholes, a dug well, springs, surface water and cumulative rainfall collectors during the summer and winter seasons. The samples were analysed for hydrochemistry and stable isotopic signatures (δ^2H and δ^{18}O). The intention was to identify where and when do river-aquifer interactions occur in the study area. Secondary data from records review and field data from hydrometric methods, ERT geophysical surveys and tracer techniques were also used to address the third objective.

The hydrochemical analyses showed that during the dry season, four distinct water types in the study area were characterised. These were Ca-HCO_3, Ca-SO_4, Na-Cl, and Na-HCO_3. The dominant water types were Na-HCO_3 and Na-Cl, on the lower lying flat areas of the study area. These water types were associated with discharge zones thereby confirming the role of aquifers in recharging rivers. In addition, the $Ca\text{-}HCO_3$ and $Ca\text{-}SO_4$ were associated with recharge zones on the escarpment and foothills. The groundwater chemistry evolved as it travelled from the recharge areas of the escarpment to the discharge areas on the lower lying flat areas, as expected, through rock-water interactions. The same four water types were characterised during the wet seasons. The evidence from the wet season in the discharge areas of the lower lying flat areas also provided evidence that aquifers recharged rivers. The stable isotopes results revealed that the majority of groundwater samples were similar to the rainfall isotopic signature during both winter and summer seasons thus indicating recently recharged water of meteoric origin, with or without some evaporation taking place before infiltration. This suggested that recharge occurred rapidly, most likely through preferential pathways that prevent any significant evaporation. Therefore, the conclusion was that the results possible show rivers contributing to groundwater recharge through preferential pathways. However, there were limited surface water sampling points in the study area to conclusively state that the rivers recharged the aquifers. The isotopic signatures of springs were similar to that of some of the springs, as expected, during both dry and wet seasons. Therefore, the conclusion was that groundwater contributes to surface water through spring discharges further confirming the role of aquifers in recharging rivers.

The developed hydrogeological conceptual model revealed that spatially, the groundwater flow direction extends from the northeastern higher lying areas of the escarpment towards the southwestern lower lying areas, thus mimicking the topography. Deeper groundwater levels were measured on the escarpment and become shallower towards the lower lying areas. Therefore, a topography-controlled water table was observed in the TKNP. Groundwater recharge in the higher lying areas occurred mainly as direct recharge through preferential pathways. In the lower lying, flat areas recharge occurred as slow diffuse recharge. Recharge through the streambeds of the non-perennial rivers is largely episodic, only occurring in response to large rainfall events. The methods that were chosen to assess the interaction were effective; however, there were limited surface water sampling points to conclusively determine the type of interaction. Hence, it was recommended that a combination of different approaches should be implemented for settings similar to the study area. However, using different methods in a study results into interpretation challenges of the findings because different methods tend to have different principles, assumptions and theories.

Keywords: Groundwater-surface water interactions, hydrochemistry, stable isotopes, geophysics

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Chapter 1 : General introduction

1.1 Introduction

In South Africa and neighbouring countries such as Zimbabwe, Botswana, Angola, and Namibia, the majority of river systems are non-perennial due to semi-arid/arid climatic characteristics (Rossouw, *et.al*, 2005). Non-perennial river systems (NPRS) represent a significant but yet understudied and particularly vulnerable portion of river networks around the world (Mcdonough *et.al,* 2011). Perennial river systems are those that flow throughout the year but only cease to flow under extreme drought conditions (Rassam *et al.*, 2013). Whereas, NPRS are classified into three broad categories based on their runoff characteristics, as proposed by (Skoulikidis *et al.*, 2017), as being: intermittent, ephemeral and episodic. Intermittent rivers cease to flow on seasonal or occasional bases (usually for weeks to months), ephemeral rivers flow only in response to the occurrence of precipitation or snowmelt, and episodic rivers carry surface water during very short periods (hours to days) immediately or during heavy rainfall.

Ephemeral rivers are more common in Southern Africa, with some experiencing flow very rarely and others experiencing flow more frequently but still intermittently or episodic due to extended periods, up to nine months, without significant rainfall events (Rossouw, *et.a*l, 2005; Gomo, 2011). In some parts of South Africa, ephemeral rivers experience extended periods of still water ponds/pools within their channels with significant water-sediment interactions (Rossouw, *et.al*, 2005; Seaman *et al.*, 2010; Bestland *et al.*, 2017). This could be attributed to very slow groundwater discharge that is sufficient to maintain pools but insufficient to overcome evaporation losses and to generate channel flow (Hughes, 2005). The vast majority of river-aquifer interactions research studies have been focused mainly on perennial river systems because available methods for assessing the interactions are often reliant on flowing water (Bestland *et al.*, 2017). It is often acknowledged that groundwater abstractions have led to a reduction of baseflow in different semi-arid catchments worldwide, however, a broader understanding of the river-aquifer interaction in these environments is still lacking (Mccallum *et al.*, 2013).

Furthermore, water issues such as over-allocation, environmental flows, and river salinity are all influenced by the connectivity between streams and aquifers (Mcdonough *et.al*, 2011; Brodie *et al.*, 2007; Seaman *et al.*, 2010). Thus river-aquifer interactions should be assessed and incorporated into management responses to a range of water quantity and quality issues (Brodie *et al.*, 2007). Therefore, the current study is evaluating the influence of groundwater recharge mechanism on non-perennial river systems, in terms of the quantity and quality of water in these river systems, using the Tankwa-Karoo as a case study.

1.2 Background of the study

Under the South African National Water Act of 1998 (NWA), water use licenses, including groundwater, should only be issued once a reserve/environmental flows are set aside. Environmental flows describe the quantity, timing, and quality of water flows that are required to sustain aquatic ecosystems and supply basic human needs (Levy and Xu, 2011). However, in South Africa and abroad, the methods that are currently available for determining ecological water requirements/environmental flows were developed on perennial river systems and are not always applicable to non-perennial rivers (Rossouw *et.al*, 2005). In past research, the importance of NPRS has been neglected because these river systems were considered as systems of low ecological importance and economic value (Skoulikidis *et.al*, 2017). However, these systems have been found to provide habitat for diverse and unique flora and fauna (Seaman *et al.*, 2010).

Seaman *et.al,* (2010) noted that the interaction between groundwater and surface water is of major importance in terms of developing appropriate methods for determining ecological water requirements, water quality, and quantity of water in non-perennial river systems and probably in perennial river systems as well. The groundwater aspect in river systems is a key component of environmental flows that support many aquatic, hyporheic, and riparian ecosystems especially during dry periods (Rassam *et al.*, 2013). The importance of the groundwater component becomes increasingly important when moving from perennial to non-perennial rivers (Rossouw *et.al,* 2005). It is therefore essential to place emphasis on the groundwater component when developing methods for the assessments of ecological water requirements in non-perennial rivers. This thus suggests that more research is required to further improve understanding of the interaction between groundwater and non-perennial river systems.

1.3 Problem statement

1.3.1 Research problem

In non-perennial river systems, the interaction between groundwater and surface water has been reported to be of major importance in terms of developing appropriate methods for determining ecological water requirements among others (Seaman *et al.*, 2010). However, there is still a lack of a broader understanding of the river-aquifer interaction in these river systems in terms of the influence on the volume and quality of water on the gaining and losing water bodies (Mccallum *et al.*, 2013). The interaction between surface water and groundwater resources has implications on the quantity and quality of the two interlinked resources and thus they require focused attention in terms of research. Lack of an understanding of the interaction of groundwater and non-perennial river systems has negative implications on the proper management of water resources in semi-arid environments.

1.3.2 Research question

What is the influence of river-aquifer interactions in non-perennial river systems in the semi-arid environment?

1.3.3 Thesis statement

Although groundwater and surface water resources were often evaluated as separate components of the hydrologic cycle in the past, they interact and the interaction varies both spatially and temporally. The central argument for the current study is that unless we assess the interaction between groundwater and surface water in NPRS, we cannot improve on our understanding of the role of groundwater on the NPRS. An improved understanding of the influence of groundwater on the flow regimes of non-perennial river systems and vice versa is essential for determining appropriate measures to better utilise water resources in the semi-arid environment in a sustainable manner.

1.4 Study aim and objectives

1.4.1 Research aim

The aim of the study is to assess surface water-groundwater (river-aquifer) interactions in non-perennial river systems to provide an insight as to how these water resources interact in semi-arid environments.

1.4.2 Research objectives

The specific objectives for the current study are to:

1. Establish the groundwater (aquifer) contribution to the surface water (river) system.
2. Investigate the role of surface water (river) in recharging groundwater (aquifer).
3. To develop a regional hydrogeological conceptual model of recharge mechanisms.

1.5 Significance of the study

The study improves on knowledge of how groundwater and non-perennial river system interact in semi-arid environments. The knowledge gained from the study will inform the basis for developing appropriate measures to better utilise water resources in semi-arid environments in a sustainable manner. Furthermore, an improved understanding of groundwater-surface water interactions is essential for the development and implementation of water allocation plans such as developing methods to determine environmental flows. It is therefore essential to understand the connectivity between the two water resources for informed decisions.

1.6 Study conceptualisation, scope and nature of the study

1.6.1 Study conceptualisation

The current study forms part of a bigger project, the Environmental Sustainable Management of Non-Perennial Rivers Project. The overall aim of the project is to improve:

1. Understanding of the relationships between river flow, ecosystem characteristics and services provided by non-perennial rivers, and
2. Prediction, decision-making and management related to the ecological and social consequences of flow modifications of non-perennial rivers.

The research components of the project include geomorphology, groundwater, hydrology, water quality, riparian vegetation, and aquatic fauna. The current study focuses on the groundwater component of the Environmental Sustainable Management of Non-Perennial Rivers Project. The groundwater component aims to establish the influence of groundwater on the non-perennial river system, using selected catchments as case studies.

1.6.2 Scope and nature of the study

Within the scope of hydrogeology, which deals with the movement and distribution of water in the rocks and soils of the earth's surface, the current research study focuses on the recharge and discharge components of hydrogeology. These include the natural recharge of aquifers from precipitation and surface water bodies such as rivers, streams, and ponds, and the discharge of groundwater to rivers (groundwater recharging surface water bodies). The study focuses on establishing the groundwater contribution to the river system, investigates the role of the river in recharging the underlying aquifer, and describes groundwater recharge mechanisms in the system through a regional hydrogeological conceptual model.

The current study uses quantitative approaches to address the three objectives. The quantitative approach involved the process of measuring water levels, water quality, and environmental isotopes in the field to achieve the first two objectives of the study. A desktop design approach involved the collection of secondary data, such as water levels, climatological, geological, and hydrogeological data from various sources to address the objective on developing a hydrogeological conceptual model of recharge mechanisms.

1.7 Research Framework

The research framework that guides the current study is presented diagrammatically in figure 1-1. It shows the relation between the study topic, aim and objectives of the study and the processes that followed to address the research study.

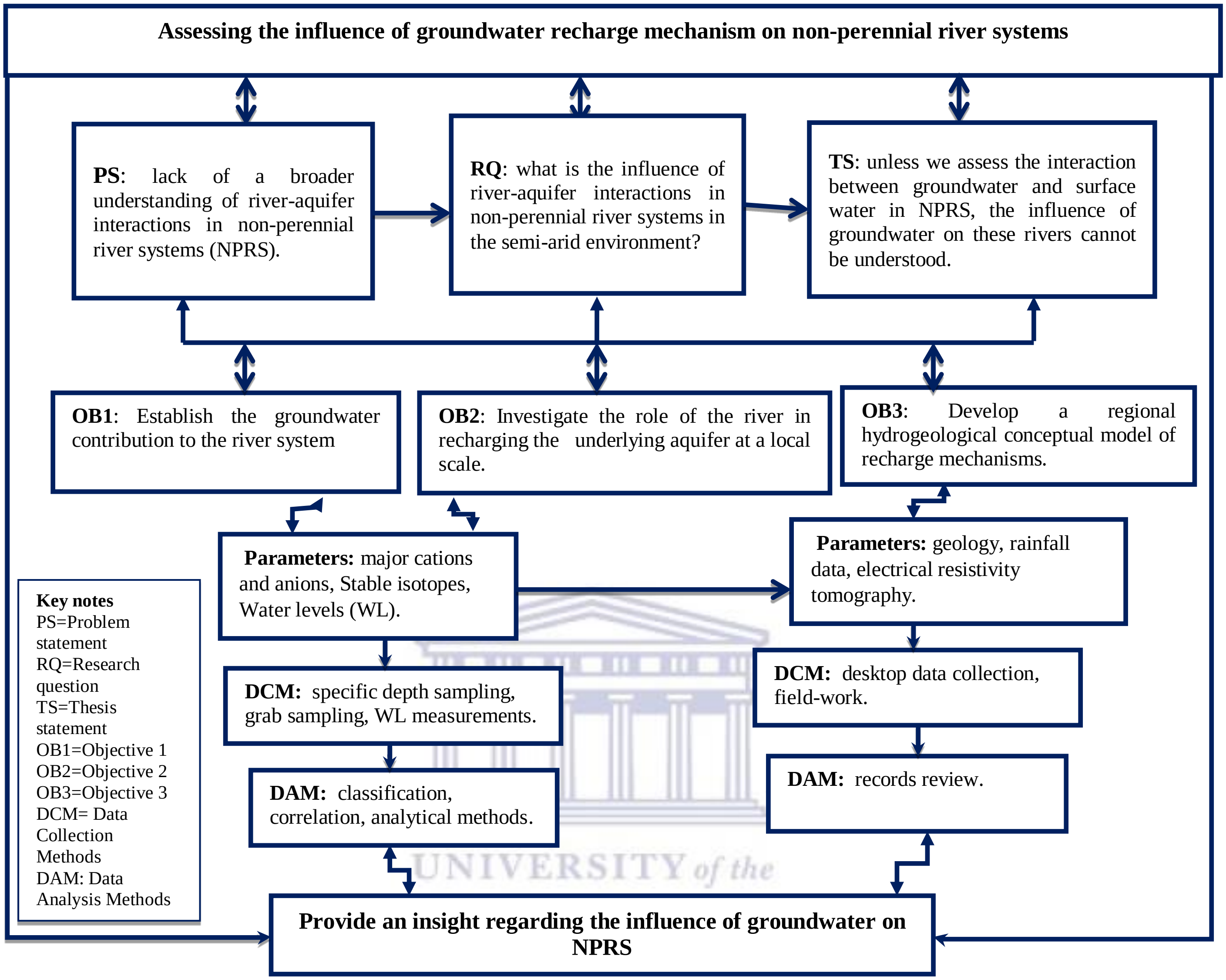


Figure 1-1: Research framework

1.8 Outline of the thesis

The thesis consists of six chapters, and these chapters are as follows:

Chapter 1 is a general introduction to the study. Where the research problem, research question, thesis statement, aim, objectives, significance, study conceptualisation, scope and nature and research framework of the study are included. Chapter 2 provides a setting where the research is applied. The chapter describes the physiographic features of the study area and assesses the potential influence of such features on the results. These include the climate, geology, topographic and hydrogeological characteristics of the study area. Chapter 3 presents a review of the literature on groundwater recharge in the semi-arid environment in the global and local context to understand the current discussions related to the study topic. A discussion of surface water-groundwater interactions, losing streams, and gaining streams is provided in a systematic and analytical manner to show a gap in previous studies. The conceptual and theoretical frameworks guiding the current study are included in the chapter. Chapter 4 provides the research design and methods used to collect and analyse the data to address the research question of the study. Chapter 5 presents the key findings of the study and discusses the findings to address the research question. Chapter 6 provides the conclusion of the study, the main findings, and recommendations for future studies.

Chapter 2 : Description of the study area

2.1 Introduction

This section of the thesis presents a description of the study area where the research study was performed. The description includes the main physiographic features in the study area that can potentially influence interactions between groundwater and surface water.

2.2 Description of the study area

2.2.1 Location and extent of the study area

The study area, Tankwa-Karoo National Park (TKNP), is located within the boundary of the Northern and Western Cape Provinces of South Africa (figure 2-1), under the Namakwa District Municipality. The TKNP was proclaimed in the year 1986 and covers land that is more than 145,000 hectares in size. Vegetation in the TKNP is still recovering from years of over-grazing when the land area was mainly used for farming. The TKNP is within the Olifants/Doring Water Management Area (DWS, 2005). The water management area includes the non-perennial Tankwa River, which is a tributary of the Doring River. Tankwa River traverses the TKNP with some of its tributaries such as the Renoster and Sandlaagte Rivers and, is impounded upstream by a dam called the Oudebaaskraal Dam, which was developed for irrigation purposes (SANParks, 2017).

The Oudebaaskraal Dam, built in 1969, was the largest privately owned farm dam in South Africa, with a storage capacity of 34 million m^3 before it was handed over to the TKNP in 2007. The dam rarely fills completely and it previously supplied water irregularly to approximately 320 ha of land irrigated by farmers on an opportunistic basis (DWS, 2005). The Tankwa River flows a north-westerly direction towards the Doring River. The main tributary to the Tankwa River, Renoster River, originates from the Roggeveld Escarpment east of the catchment area. As in many arid and semi-arid regions around the world, the scarcity of rainfall events and the lack of perennial rivers mean that groundwater is the main water source for potable water, game and livestock watering in the Tankwa Karoo.

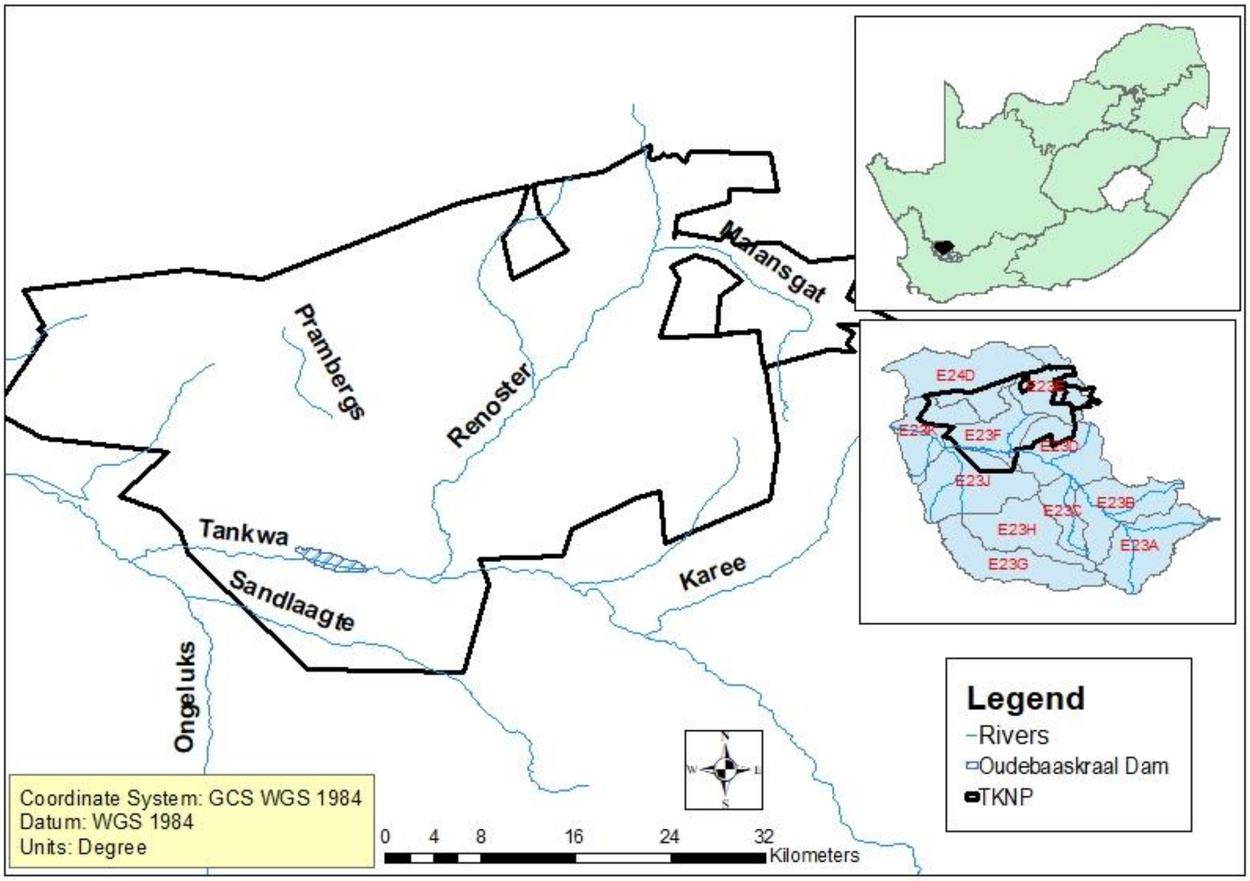


Figure 2-1: Tankwa-Karoo National Park. Data Source: Water Resources, WR (2012).

2.2.2 Topographic characteristics of the study area

The Roggeveld Escarpment to the east, the Cederberg Mountains to the west and the Klein Roggeveld Mountains in the south surround the Tankwa-Karoo (figure 2-2). The area is underlain by generally gentle dipping strata of the Dwyka Formation, Ecca Group, and lower Beaufort Group, affected by mild folding in the south. Younger alluvial deposits occur in restricted areas around the Tankwa River system (DWS, 2005). The land surface topography plays an important role in both direct and indirect recharge mechanisms. Steep slopes along the mountainous areas tend to have low infiltration and high runoff rates. Such conditions tend to be more favourable for indirect and localised recharge mechanisms through small depressions, cracks and fissures. Whereas, the flat, lower lying areas surfaces have poor drainage and tend to be more conducive for direct recharge mechanisms (Petersen, 2012). In the study area, the relatively flat areas most likely serve as groundwater discharge zones and the mountainous areas of the escarpment are most likely to be major groundwater recharge zones. The altitude within the TKNP ranges from 316 to 1640 m (Niekerk and Dyason, 2017).

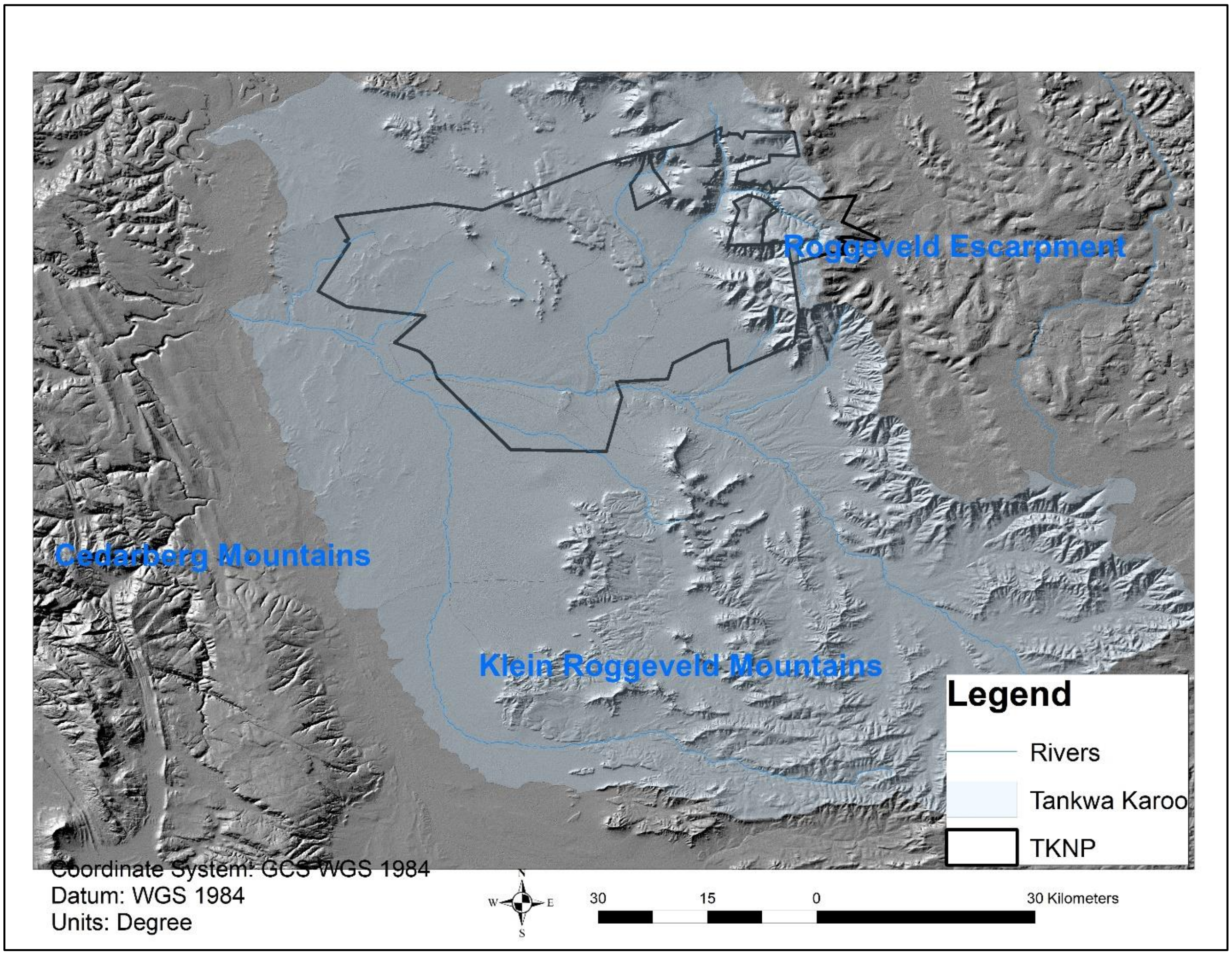


Figure 2-2: The topography of the study area

2.2.3 Hydrogeology of the Main Karoo Basin

Most boreholes in the Main Karoo Basin are at depths of less than 300 m deep. The communities in the Karoo are solely dependent on these shallow aquifer systems for domestic and agricultural use (Maceba, 2017). Groundwater levels generally lie within a weathered aquifer zone, which is usually between 10 and 50 m and below this is a deeper fractured zone that is usually present to depths of about 100 – 160 m (Murray *et.al*, 2001). The aquifers in the Main Karoo Basin can be divided into three zones, as proposed by Van Tonder (2012): a shallow aquifer zone (approximately <300 m), an intermediate zone down to about 1000 m and a deep zone down (>1000 m) to the basement with pockets of hot water, saline, confined groundwater. The groundwater is unlikely to occur as a continuous aquifer zone to the deep aquifer formations and may be separated from the deeper groundwater (Dwyka group and below) by zones of effectively impermeable rocks (Rosewarne *et.al*, 2011).

The electrical conductivity of the shallow groundwater generally ranges between <70 – 370 µS/m throughout the Basin. Groundwater quality of the Main Karoo Basin changes throughout the area from local to regional scale and is predominantly a function of soil type, host rock lithology, rainfall, and climate. The regional pattern, which is similar to that of precipitation, indicates that salinity increases towards the west of the Main Karoo Basin (Murray *et.al*, 2015). Warm springs in some areas of the Basin indicate groundwater circulating from depth in the intermediate zone (300 -1000 m) and possible to the deeper of >1000 m, with the exception of the Southern Oil Exploration (Soekor) boreholes drilled in the 1960s and a few other deep mining exploration boreholes. Little is known about the deep zone, as there are few boreholes that have been previously drilled to explore them (Murray *et.al*, 2015). According to DWS (2005), groundwater recharge is estimated to be 63 million m^3/a on the Main Karoo Basin, however, the water quality is generally poor, and the yields are very low.

2.2.4 Climate characteristics of the study area

The Tankwa Karoo lies within an arid to the semi-arid environment with isohyets of mean annual rainfall in the range of 0-500 mm. About 25 % of the rainfall in the region occurs in the summer season, with a mean July minimum temperature of 6°C and a mean January maximum temperature of 38°C (Van Niekerk and Dyason, 2017). The highest average maximum temperatures occur from November to March, with the hottest months being January and February. The highest wind speeds occur from October to March (SANParks, 2016). The climate of the Tankwa Karoo is characterised by very cold winters and very hot summers. Tankwa Karoo lies within a winter rainfall region, with the majority of the rainfall occurring between May and August each year (figure 2-3). The mean annual rainfall recorded at the Tankwa-Karoo National Park weather station (-32.2400, 20.0950, situated at 494 m) in figure 2-3 (a) for the period from 2006 to 2016 was 29 mm. At the Agterkop weather station (-32, 1100, 20.1220 at 1267 m) in figure 2-3(b), a longer rainfall period was recorded from the year 1996 to 2016. The mean annual rainfall for the period was 31.21 mm.

The data for the weather stations were obtained from the South African Weather Services (SAWS, 2017). The Agterkop weather station is located on the Roggeveld escarpment thus a slightly higher mean annual rainfall was observed. Rainfall patterns in the catchment are such that infrequent flood events recharge the aquifers. Because of the low rainfall and high evaporation rates in the Karoo region, there expectation is that there will be low groundwater recharge from direct precipitation and low or no river flows for some time during the year. The seasonal nature of the rainfall in the study area imply that groundwater recharge will mainly occur during the wet period (May to August) and very little to none during the dry period (September to April). The year-to-year and long-term trends in rainfall, as well as the frequency, duration and intensity of individual storm events, will have an effect on the recharge mechanisms and river flow.

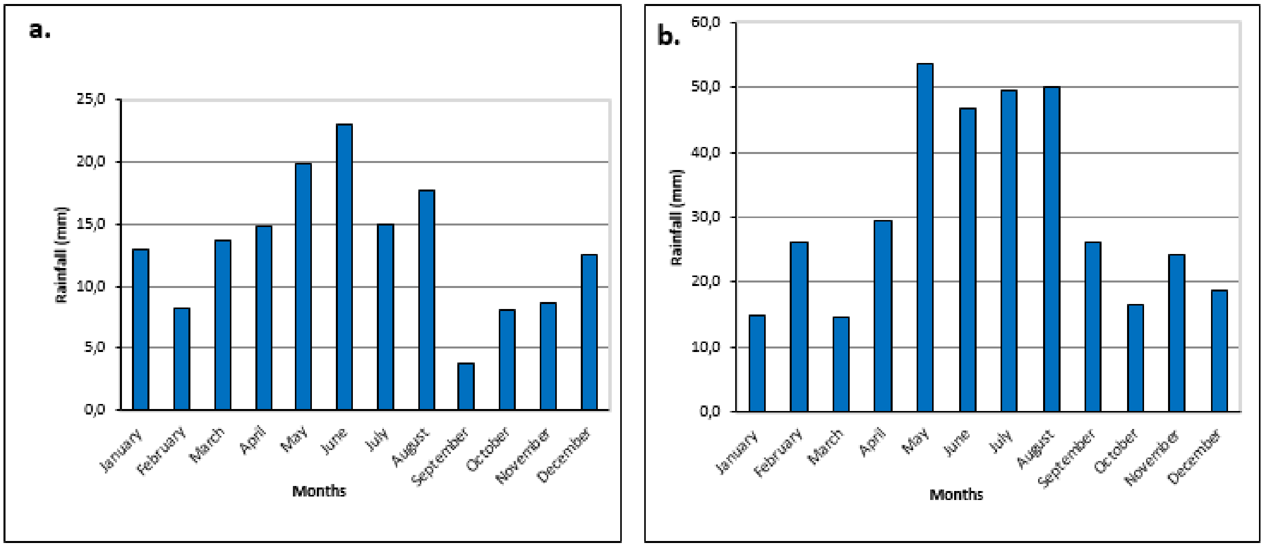


Figure 2-3: TKNP (a) Weather Station (2006-2016) and Agterkop (b) Weather Station (1996-2016). Data Source: SAWS, 2017.

2.2.5 Regional geology of the Main Karoo Basin

The Karoo Supergroup was deposited during the late Carboniferous to the Middle Jurassic period and consists mostly of marine glacial to terrestrial deposits of sandstone and shale. These sediments were deposited in two major basins, the Kalahari and the Main Karoo basin. The Kalahari basin stretches across Botswana, Namibia, and central north South Africa. The bulk of the Karoo strata occur in the Main Karoo Basin (Figure 2-4), which covers an area of approximately 700 000 km^2 but was much more extensive during the Permian age (Mbiko, 2016). The Main Karoo Basin stretches across most of central South Africa (Murray *et al.*, 2015). The

Karoo Supergroup attains a cumulative thickness of approximately 12 km in the south-eastern portion of the Main Karoo basin towards the eastern end of the Karoo Through. The Basin is bounded along the south by a fold-thrust belt called the Cape Fold Belt (CFB) and along the east by a monoclonal downwarp (Johnson *et.al,* 1997). Geological strata in the Karoo are generally horizontal to very gently dipping, except in areas adjacent and sub-adjacent to the CFB (Rosewarne *et.al*, 2011). The lithology in the Basin consists of Tillite, diamictite, and subsidiary shale of the Dwyka, with shale and siltstone of the Tierberg, Prince Albert and Whitehill Formations representing the Ecca Group (Murray *et.al*, 2015). Dolerite dykes, rings and sills of variable thickness occur throughout the basin (Rosewarne *et.al*, 2011; Murray *et.al*, 2015). The dolerite intrusions can have the effect of baking, deforming and fracturing the sedimentary rocks thereby allowing transmissive zones to develop along the geological contacts (Murray *et.al*, 2015). Therefore, the areas of high permeability are those that are associated with dolerite intrusions, thick alluvial deposits, folded and faulted formations.

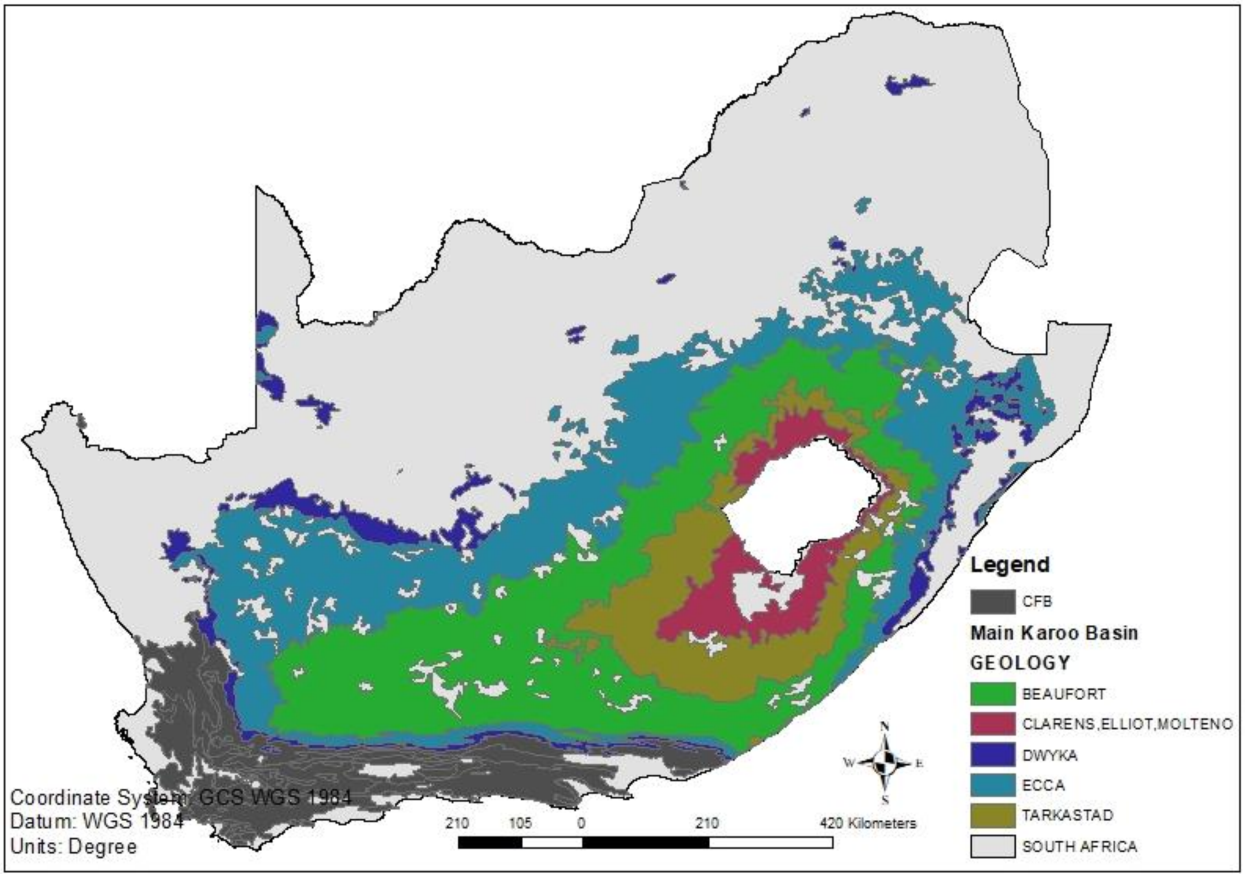


Figure 2-4: Extent of the Main Karoo Basin. Data Source: WR, 2012.

2.2.6 Geology of the Tankwa Karoo

In the study area, Tankwa-Karoo National Park (TKNP), only the Karoo Supergroup occurs (figure 2-5). The lithological groups range from the oldest, the Dwyka Group which occupies the western edge of the TKNP, to the Ecca group, that occupies most of the park, to the youngest, the Beaufort Group capping the Roggeveld Mountains on the eastern edge which forms the Great Escarpment (Figure 2-6). The Dwyka Group only has one formation within the park, the Elandsvlei Formation, with sediments deposited in a glacial environment. The Ecca group is represented by four formations within the TKNP, from oldest to youngest: The Prince Albert Formation, followed by the Whitehill Formation, then the extensive Tierberg Formation and the Waterford Formation (Rogers and Smith 2012). The rock types in the area include Tillite, diamictite, and subsidiary shale of the Dwyka, with shale and siltstone of the Tierberg, Prince Albert and Whitehill Formations representing the Ecca Group (Murray *et.al*, 2015). Mudstone, siltstone, and sandstone of the Beaufort Group, as well as alluvium and colluvium, are also found in some places (Van der Merwe, *et.al.*, 2015). The different geological formations have a common attribute within them, and this is a high level of fracturing. This thus indicates the potential for water movement and groundwater recharge through the fractures. The fractures also increase the spatial extent upon which groundwater and surface water can interact and increases the potential of interaction (Madlala, 2016).

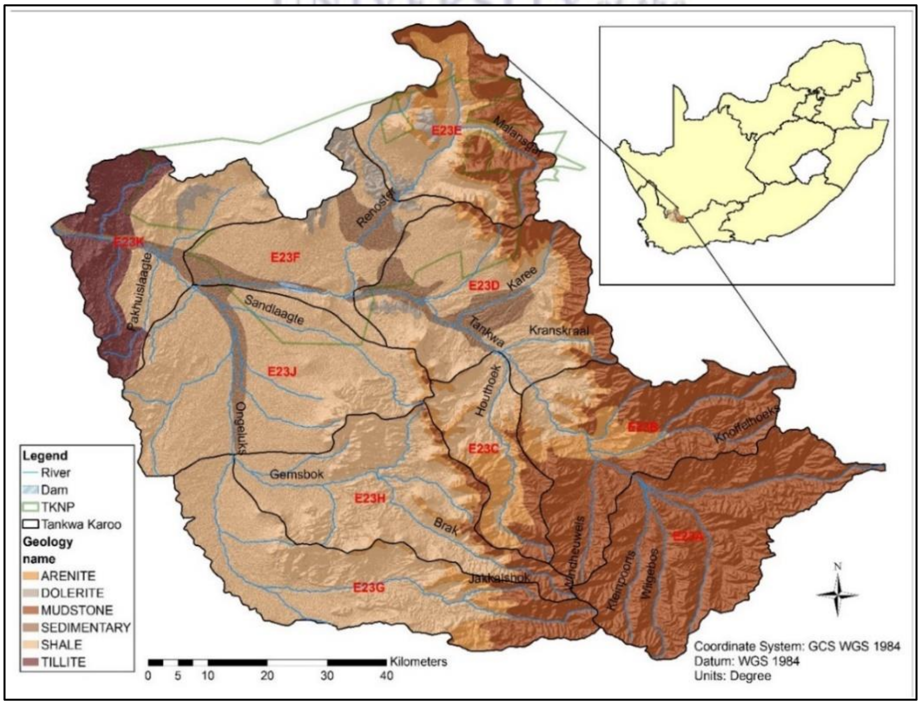


Figure 2-5: Geology of the Tankwa-Karoo. Data source: WR, 2012.

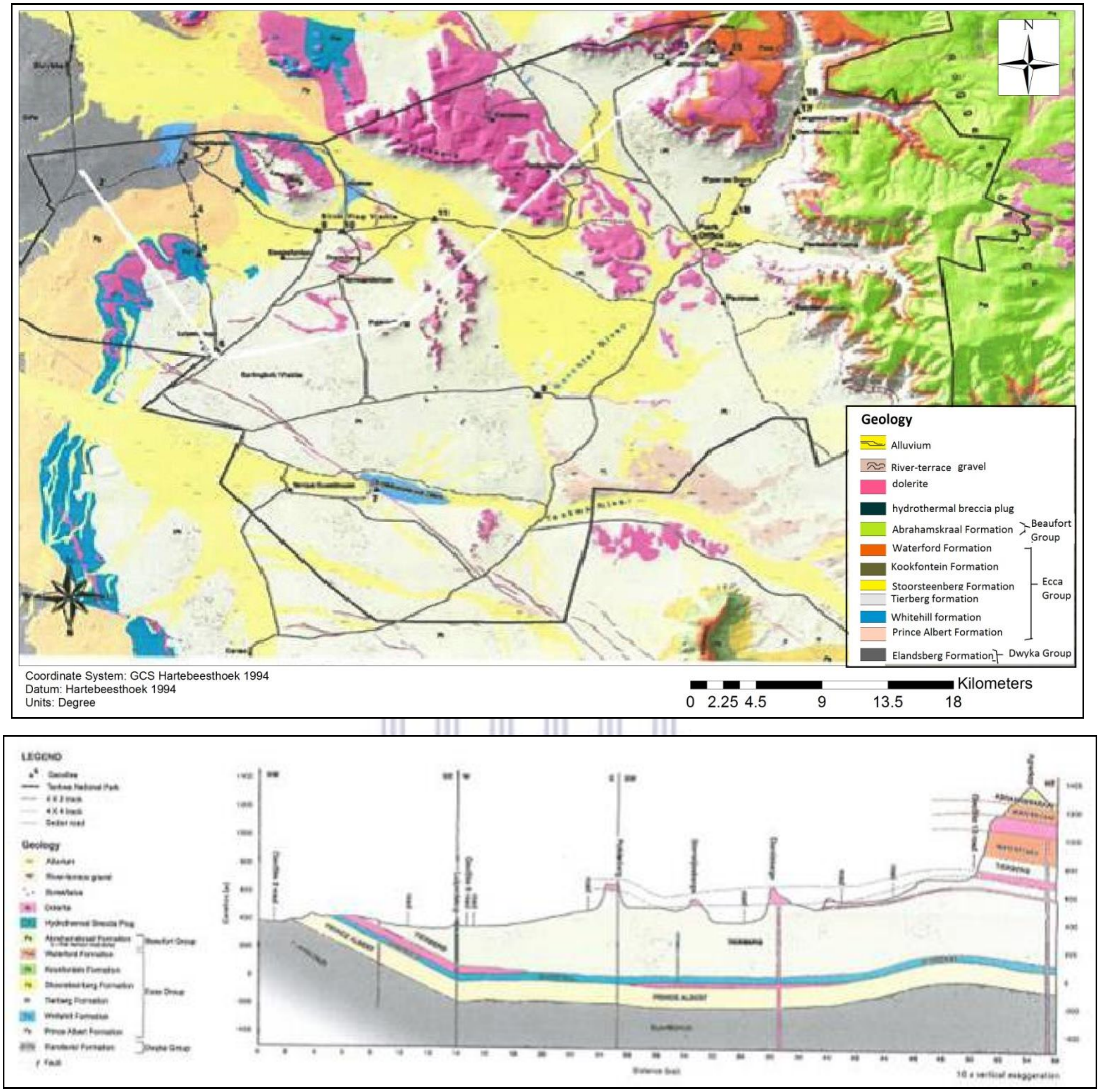


Figure 2-6: Geological representation and cross-section. Adapted from Rogers and Smith (2012)

Chapter 3 : Literature review

3.1 Introduction

Chapter 3 presents a review of peer-reviewed journal articles and reports on groundwater recharge assessment studies in the global context and the local context of Karoo aquifers in South Africa with the purpose of identifying current knowledge and gaps concerning the study topic. A discussion of surface water-groundwater interactions, losing, and gaining streams research studies is presented. Groundwater recharge mechanisms, the conceptual and theoretical frameworks of groundwater recharge in semi-arid environments form part of the review.

3.2 Global context on groundwater recharge

Globally, groundwater recharge studies have been carried out by various researchers using numerous approaches, with a relative explosion of recharge studies being reported in the literature since the mid-1980s (de Vries and Simmers, 2002). Groundwater recharge is broadly defined as the vertical flow of water from precipitation passing through the surface vegetation, the soil zone, the vadose zone, the capillary zone and into the water table (Conrad and Munch, 2006). Although it is one of the basic components of the hydrological cycle, assessing and quantifying recharge is difficult because it cannot be directly measured at the spatial scale of most relevance (Martinez, *et.al.*, 2015). In arid and semi-arid environments, the assessment of groundwater recharge is considered to be one of the key challenges in determining the sustainable yields of aquifers as recharge rates are generally low in comparison with average annual rainfall or precipitation (Sukhija *et al.*, 2003; Martinez *et.al.*, 2015). Understanding groundwater recharge mechanisms can provide fundamental information for water resource management (Li *et al.*, 2017).

In the United States of America, Stephenson and Zuzel (1981) evaluated the characteristics of natural groundwater recharge using precipitation data, soil depth, and groundwater observations in the semi-arid south-west Idaho. The researchers noted that groundwater recharge is complex and is a function of climate, physiographic characteristics and the type of geologic material through which it flows. Three types of natural groundwater recharge mechanisms were identified, and these were recharge from precipitation events as water flows down basalt outcrops, through shallow soil zones, and through bedrock channels during runoff and channel flow. A conclusion for the study was that the spatial and temporal variations of water table elevations generally reflect the seasonal characteristics of precipitation. Melki *et.al*, (2017), reported similar findings and suggested that the natural recharge in semi-arid environments is highly variable in time and space as is the rainfall thus this complicates the estimation of recharge.

In China, Li *et al.*, (2017) determined the groundwater recharge mechanisms in a deep loessial unsaturated zone using environmental tracers. Soil samples were collected from seven sites within the Heihe watershed during the years 2012-2013 to determine soil water contents, chloride concentrations, and the stable isotopes composition. Precipitation data were collected at two sites using rain gauges located at the upper and lower reach of the Heihe River to incorporate the impacts of climate and elevation on isotopic composition. Groundwater samples were taken twice a month and analysed for isotopic composition. The stable isotopes, tritium, and chloride in precipitation, groundwater and soil water concentrations were then used as inputs to mass balance methods. Results of the study revealed that the isotopic compositions of groundwater were different from those of deep soil water but were similar to that of precipitation. The chloride concentration in soil pore water was much greater than in groundwater and precipitation; groundwater had detectable tritium concentrations. This thus suggested that recharge occurred likely via the rapid infiltration of precipitation through preferential flow.

In central Tanzania, Onodera *et al.*, (1995) evaluated the groundwater recharge mechanisms of a confined aquifer in the tropical semi-arid Makutapora Basin, using stable isotopes (deuterium and oxygen-18) in natural waters of the basin during December to April 1991. An analysis of the relationship between Deuterium (δD) and Chloride (Cl^-) suggested that groundwater recharge was restricted to a part of the hill slopes, rivers and upland areas underlain by fractured bedrock and the recharge was rapid without any significant evaporation. The isotopic ratios of the confined aquifer were found to be lower than the weighted mean δD and $\delta^{18}O$ values of local rainfall collected from a rain gauge thus suggesting that rainwater with low isotopic ratios from heavy rainfall events infiltrated more rapidly and preferentially than rainfall with high isotopic ratios from small rainfalls. The results for the isotope analysis did not clearly show seasonal isotopic variability, however, there was variability in $\delta^{18}O$ which may have resulted from the variation in rainfall amount during the rainy season.

In the arid western Rajasthan India, Chandrasekharan *et.al,* (1998) carried out investigations on natural recharge mechanisms using isotope techniques. Radioactive (^{3}H and ^{60}Co) and stable isotopes (δ^2H and $\delta^{18}O$) methods were applied to different parts of the study area to determine the natural recharge mechanisms from rainfall over three years beginning in the year 1982. Groundwater recharge was estimated based on the soil moisture movement of a tagged layer by radioactive tracer, tritium (^3H). Two tube wells were sampled for ^{14}C analysis and dug wells samples for ^3H and stable isotopes δ^2H and $\delta^{18}O$ analyses. It was found that the stable isotopes composition was highly depleted in relation to the corresponding rainfall values thus indicating that recharge of the present-day rainfall was negligible. However, the authors noted that it is possible that the groundwater may have also been recharged once in several years either by infiltration of local intense precipitation or by episodic floods. The conclusion to the study was that arid regions receive very little contributions to groundwater from local precipitation, with a few exceptions. Analysis of the stable isotopes suggested that artesian flowing wells and other deep dug wells in the study sites have ancient water and that recharge to the fractured rock aquifers occurred during a moister and cooler period than the present. Furthermore, the wells were most likely recharged remotely through distant outcrops.

Crerar *et.al*, (1998) undertook a research project to establish which of the factors that affect groundwater recharge represent the major control on an alluvial aquifer in the semi-arid Namibia. The hypothesis for the study was that antecedent silt conditions are important at inhibiting recharge. An experimental site was set up at the Gross Barmen on the Swakop River, which is an ephemeral system. A detailed survey of the study site was first carried out through geophysics (resistivity depth probing), and topography survey. Field installed equipment included: a flood gauge, pumping and observation boreholes to determine the aquifer hydraulic characteristics, and neutron probes installed at 3 m. Analysis of the results over two flood events indicated that the variation in recharge was not directly linked with flood volume. However, for the first flood in each season, a much higher recharge percentage occurred. Determination of the initial recharge rate from the time lapse between flood peak arrival and groundwater table reaction gave higher than expected values. The apparent recharge rate taking place through preferential pathways invalidated the hypothesis of the study. However, a laboratory experiment to investigate the effects of varying silt loads and flood flow velocities along a simulated river section, using alluvium collected at the Gross Barmen site, revealed that at low velocities clogging of the top sand layer by silt occurred and infiltration was significantly inhibited than at higher velocities. The study effectively showed that the formation, during flood events, of an impermeable silt layer is a significantly important factor in the determination of recharge to unconsolidated alluvium underlying ephemeral rivers.

In the semi-arid Botswana, Selaolo *et.al*, (2003) carried out moisture transport studies in the unsaturated zone as part of a Groundwater Resources Monitoring and Recharge Study (GRES) over a ten-year period (1987-1997). Multiple tracer profiling studies were carried out along a southeast-central Botswana transect to determine the moisture fluxes and to explain groundwater recharge mechanisms using Chloride, the stable isotopes deuterium ($\delta^{2}H$) and oxygen-18 ($\delta^{18}O$), and the radioactive isotope tritium (^{3}H). It was noted that moisture fluxes only represent potential recharge and the actual recharge can only be determined when the saturated zone is included in the analysis. The moisture fluxes were calculated based on the Chloride Mass Balance Method (CMB), Isotope Displacement (ID) and tritium (^{3}H) methods. Results from the study indicated that moisture fluxes generally decrease with decreasing rainfall from south-eastern Botswana to the central Kalahari. The moisture fluxes were shown to highly vary spatially, with slow diffuse through the top soils and of an essential multimode nature with relatively fast preferential flow through soil cracks, root channels, and fractures. Analysis of the results obtained from the CMB method revealed that moisture fluxes in fossil valley systems are lower than fluxes in higher topographic interfluves areas. However, there were uncertainties of regionalization of moisture fluxes and the recharge rates of the study.

3.3 Previous studies on Karoo aquifer systems

The groundwater contained within the weathered and fractured rock aquifer systems in the Karoo is an important resource for local communities for domestic, livestock, and irrigation water supply (Adams *et al.*, 2001). In the past, there have been several research projects conducted in the Karoo region related to the assessment of the groundwater to understand the system for better management practices of the water resource. The large dependence on groundwater in the Karoo is driven by the fact that the vast majorities of rivers that drain in the region are non-perennial in nature and only flow during periods of peak rainfall. The Karoo is situated in one of the driest parts of South Africa thus effective management of water resources in the region is an important issue.

Van Tonder and Kirchner (1990) undertook a three-year project to study the natural groundwater recharge of fractured rock Karoo aquifers in the semi-arid regions of Dewetsdorp and De Aar using the Saturation Volume Fluctuations (SVF) method. The recharge in the Karoo formations was found to vary between 2 and 5 % of mean annual rainfall. In areas underlain by a thick soil cover, the recharge was less than 3% while recharge in hilly areas with a thin soil cover was of the order of 5%. The researchers argued that groundwater balance methods are the only methods that yield reliable estimates of groundwater recharge in the Karoo. Furthermore, methods that used unsaturated zone data were unsuitable for calculating the natural recharge of Karoo formations of South Africa. The conclusion for the study was that the main groundwater recharge mechanism in the Karoo formations of South Africa is flow along preferential pathways.

Adams *et al.*, (2001) undertook a research study to establish, interpret and map the chemical composition of groundwater in the semi-arid western Karoo, in Sutherland. A total number of 110 boreholes were sampled for chemical and stable isotopes (δ^{2}H, δ^{18}O) analyses. Descriptive statistics, correlation matrices, R-mode factor analysis were used in the study to understand the hydrochemical processes of groundwater. Six water types based on the major cations and anions were characterised in the area. The major processes that influenced the groundwater chemistry were salinisation, mineral precipitation: dissolution, cation exchange, and human activities. Analysis of the isotope data indicated that groundwater recharge of partially evaporated water took place in some places, however, recharge in other areas seemed to have taken place rapidly, most likely through preferential pathways thus preventing any significant evaporation. Natural groundwater recharge occurred over most of the area. The effects of localized topography were one of the factors responsible for the variation in groundwater chemistry and as well as in the stable isotope composition. The climatic variability of the area complicated the interpretation of the chemical and isotopic composition of groundwater.

Chavellier *et.al,* (2001) assessed the occurrence of groundwater associated with Karoo dolerite sills and ring structures using morpho-tectonic models. On a regional scale, the spatial variability of the large structures in terms of morphology, geometry, shape, size, fracturing, tectonics and mechanisms of occurrence was assessed on three 1/50 000 scale maps of Victoria West, Middelburg, and Queenstown. The occurrence of groundwater associated with the dolerite sills and ring intrusions was assessed. A single dolerite sill and ring complex was selected for a geohydrological investigation based on information obtained from the regional study. From the regional study, the dolerite sills and ring complexes of the Western and Eastern Karoo were classified into three basic morpho-tectonic models. A spatial analysis of regional borehole information over the three maps indicated that terrain slope, controlled by the occurrence of dolerites sills and ring complexes, has a significant control on groundwater occurrence, as well as the intersection of dolerite dykes and sills.

A detailed local study was then carried out at Victoria West to determine the occurrence of groundwater with the associated structures through geological field mapping, remote sensing, hydrocensus of all water points and exploration drilling. The analysis of the hydrocensus data indicated that most of the more productive boreholes are those that tap the shallow (<30 m) weathered Karoo sediments alongside dolerite dykes. In the study, Karoo dolerite sills and ring complexes proved to structure conducive to the formation of deep-seated fractured rock aquifers. There was an increase in yield with depth, which could have indicated even higher yielding fractures could exist with depth.

Murray *et al.*, (2012) developed transmissivity maps for the main Karoo Basin. The areas of high permeability for the Karoo were those that are associated with dolerite intrusions, thick alluvial deposits, folded and faulted formations. Two methods were developed from the study to determine aquifer yields for water supply and they are the Aquifer Assured Yield Model (AAYM) and the Aquifer Firm Yield Model (AFYM). The AAYM statistically analyses the long-term time-series data of inflow versus reservoir storage. Whereas the AFYM uses historical data of monthly rainfall along with groundwater recharge estimates, evapotranspiration and baseflow to determine the storage of an aquifer in a given month. The methods were tested in areas with data and were found to provide reasonable estimates. Other tools that were developed in the study include groundwater quality maps, the Copper-Jacob model which assists in estimating borehole spacing for a firm yield and a Wellfield Model.

Dennis *et.al.*, (2013) undertook a research project to predict any future change in recharge rates because of climate change for Karoo aquifers of South Africa. Vulnerability to climate change profile was created and assessed by developing a method called DART, with the parameters: D = depth of water level change, A= aquifer type (storativity), R= recharge and T = transmissivity. The DRASTIC methodology was also developed to express aquifer vulnerability to the threat of pollution. The vulnerability assessment of the study considered two scenarios, current precipitation patterns and future patterns based on a selected global climate model. Initial findings from the study indicated that no significant difference between the current and future average water levels thus groundwater recharge does not change that much in the future. Indices over dry months seemed to not change much due to the fact that the recharge model showed very little recharge over the same months. This was worst-case-scenario, as episodic recharge events will occur, and if the recharge is significant, a higher recharge index is expected. The results of the study provided a method of mapping the vulnerability to climate change which can be used at both regional and national scale.

According to Rosewarne *et al.*, (2013), much is known about the relatively shallow aquifers (<300m) in the Karoo formations of South Africa, following decades of research, however there is a gap in knowledge about the deeper formations (>500m) and associated groundwater occurrence and its possible interconnections with the shallow aquifer zone. The possibility of large reserves of shale gas underlying the Karoo and their exploitation resulted in focused attention on the groundwater resources and aquifers in the Karoo region. This is because many environmental concerns were raised regarding hydraulic fracturing in the Karoo, such as the possible mixing of water from shallow aquifers with the deep groundwater. Another concern raised was that the exploration could result in undesirable groundwater for water supply if the deep water is of poor quality.

Murray *et.al* (2015) thus undertook a research project for the Water Research Commission to characterize the deep-seated aquifers in the Main Karoo Basin. Eight study sites were selected ranging from the central to the south-western portions of the Main Karoo Basin. In the study sites, water samples were collected from warm springs, deep boreholes suspected to contain deep groundwater and from shallow boreholes near the sites for comparison. The samples collected were analysed for their hydrochemical composition and isotopic signatures. The results of the study suggested that the deep aquifers have distinct characteristics from the shallow groundwater. Analysis of the hydrochemical and isotopic data using stiff diagrams indicated that the deep groundwater formed a Y-shape, had low ^{14}C values, and temperatures greater than 25°C in some sites. Whereas the shallow groundwater data formed a hexagonal-shaped stiff diagram, had high ^{14}C values and were characterized by cold water with temperatures less than 25°C.

Some other major characteristics of the deep-seated aquifer system were that it contains older water with low tritium, low $^{36}Cl/Cl$ and $^{3}He/^{4}He$ ratios and very low nitrate because of denitrification. The stable isotope composition of the deep groundwater was greater than those of shallow groundwater, had low alkalinity, low uranium and vanadium due to anoxic (depletion of dissolved oxygen) conditions amongst others. More studies were recommended to further characterise the deep aquifer systems as it was not possible to obtain groundwater samples from the deep-seated shale that are being considered for shale gas exploration and development because no suitable deep boreholes exist. The assumption was that samples obtained from the warm springs were from deep sources of unknown depths thus, there was an uncertainty in the interpretation.

3.4 Surface water-groundwater (river-aquifer) interactions

The interaction between surface water bodies such as streams, lakes, and wetlands with groundwater occurs in all types of landscapes (Sophocleous, 2002). As such, surface water bodies are an essential part of groundwater flow systems. Even in cases where the surface water body is separated from a groundwater system by an unsaturated zone, seepage from the surface water body may recharge groundwater (Winter *et.al.*, 1999). This can occur as a flood flows down a river, infiltrating into the sandy and alluvial deposits of the channel beds (Banks, 2010). In most physiographic and climatic settings, groundwater discharge is the main contributor to streamflow not only in dry periods but also during floods (Chen *et.al*, 2013).

The groundwater contribution to streams is termed baseflow and defined, from a hydrogeological perspective, as the proportion of the stream flow that is from groundwater outflow/discharge (Bruskova, 2007). The transition zone between surface water bodies and groundwater bodies is called the hyporheic zone (Vogt *et al.*, 2010). Due to the exchange of water between the two systems, the development of either of these resources affects the other in terms of quantity and quality (Winter *et.al*, 1998). Therefore, understanding the factors that influence the interaction and how such an interaction occurs is required for the effective management of the two interlinked resources (Winter *et.al.,* 1999; Gomo, 2011).

There are three basic ways in which streams interact with groundwater. A river/stream can gain water from inflow of groundwater through the streambed (i.e. gaining stream), lose water by outflow through the streambed (i.e. losing stream) thus recharging the underlying aquifer, or do both, gain in some reaches and lose in other reaches. In some environments, streamflow gain or loss may be a persistent occurrence whereby a stream is always gaining water from the aquifer or continuously lose water to the aquifer (Winter *et.al,* 1999). For a stream to gain water from groundwater, the water table should be at or higher than the surface water level, as in figure 3-1A, thus groundwater moves towards or into the stream. Gaining streams or effluent streams are usually perennial and have a flow that increases in a downstream direction (Kalbus *et.al.*, 2006).

In losing streams, the water table is lower than the surface water level (figure 3-1B), therefore, the river is recharging the underlying aquifer (Winter *et.al*, 1999; Chen *et.al*, 2013). Losing streams or influent streams lose a significant amount of their flow into groundwater and are usually ephemeral (Rossouw *et.al*, 2015). Streams can gain water from groundwater in some reaches and lose water in other reaches. Therefore, some streams have perennial flow in their upstream reaches while the valley further downstream may contain a losing reach and are generally dry or vice versa (Kalbus *et.al.*, 2006).

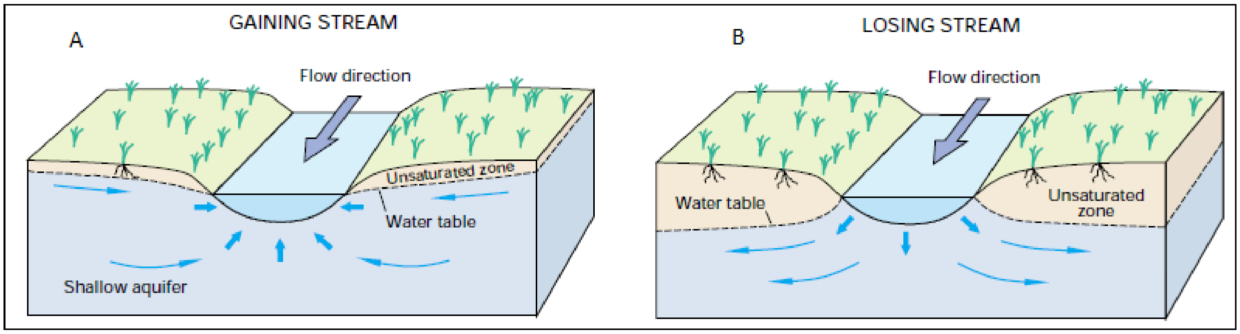


Figure 3-1: Schematic representation of surface water-groundwater interactions. A. Gaining river/stream. B. Losing river/stream. Source: Winter et.al, 1998.

A special case of losing streams are the disconnected/detached streams with no or very little interaction taking place between groundwater and surface water (Rossouw *et.al*, 2015). In disconnected streams, the groundwater table is below the streambed and the stream is disconnected from the groundwater system by an unsaturated zone, figure 3-2A, (Sophocleous 2002; Banks, 2009). In cases where the stream is disconnected from the groundwater system by an unsaturated zone, the water table may form a distinguishable mound below the stream, as in figure 3-2A, if the rate of recharge through the stream bed and unsaturated zone is greater than the rate of lateral groundwater flow away from the water table mound (Winter *et.al.*, 1999). A significant characteristic for identifying disconnected streams is that pumping from the shallow groundwater near the stream does not affect the flow of the stream near the pumping boreholes (Winter *et.al*, 1999; Sophocleous, 2002).

In cases where a stream level rises higher than adjacent groundwater levels due to a flood event, stream water will percolate laterally from the river in flood into the adjacent stream banks, figure 3-2B, some of which may flow back into the river during low flow conditions and this is termed bank storage (Tanner, 2013). Bank storage is usually caused by storm precipitation, rapid snowmelt, or release of water from a dam/reservoir upstream of the river resulting in a rise in stream stage (Winter *et.al*, 1999).

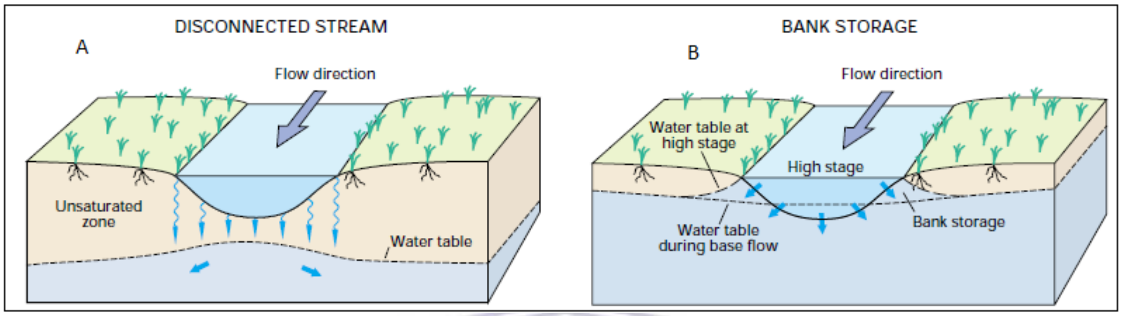


Figure 3-2: A schematic representation of a disconnected stream (A) and (B) Bank storage. Source: Winter et.al, 1998

Groundwater abstractions from shallow aquifers directly connected to a stream can have significant implications on the water movement between the water resources. Withdrawing water from shallow aquifers near surface water bodies diminishes available surface water by capturing some of the water that would have otherwise discharged to surface water or by inducing flow from the surface water into the surrounding aquifer system. Changes in the flow direction between groundwater and surface water can affect the transportation of contaminants associated with the moving water (Winter *et.al*, 1999). Thus, the interaction between the two water resources has implications on the quality and the quantity of water on the gaining and losing water bodies.

The interactions of surface water bodies with groundwater are largely controlled by their relative positions to a groundwater flow system, physiographic setting (topography and geologic characteristics of their beds) and climate or temporal variations in precipitation (Winter *et.al*, 1999; Sophocleous, 2002; Banks, 2010; Levy and Xu 2011). Human influences including land use and the control of water (such as canalisation of water, building dams, and levees) influence the interactions. However, the influence of climate and geology are possibly the most crucial factors affecting the interactions (Levy and Xu, 2011).

In natural environments, groundwater moves along flow pathways of different lengths in transmitting water from areas of recharge to areas of discharge and the flow paths are organised in space and form what is termed a flow system (Sophocleous, 2004). Tóth (1963) proposed three types of flow systems that can occur in a small catchment. These are local, intermediate and regional flow systems (figure 3-3). Tóth (1963) defined a small drainage basin/catchment as an area that is surrounded by topographic highs (e.g. Hills), with its lowest part being occupied by an impounded body of surface water or by the outlet of a relatively low order stream and having similar physiographic conditions over the whole of its surface.

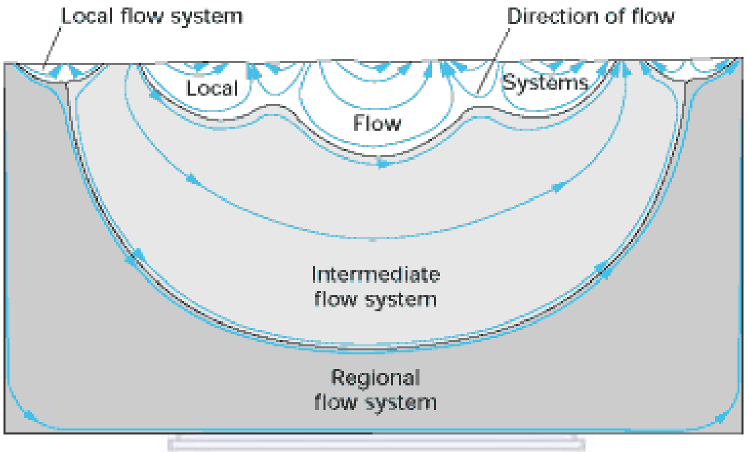


Figure 3-3: Toth's conceptual model of groundwater flow systems. (From: Winter et.al, 1998)

Local flow systems are those in which groundwater flows to a nearby discharge area such as a pond or stream, with the greatest variability in their interaction with surface water, as well as larger recharge rates and shorter residence times (Sophocleous, 2002). The higher the topographic relief of a catchment, the more important the local flow system becomes. On a regional flow system, groundwater flows a greater distance than the local flow system and eventually discharges into major rivers, lakes or to oceans (Sophocleous, 2004). The characteristics of an intermediate flow system are one or more topographic highs and lows located between recharge and discharge areas, however, unlike a regional flow system, it does not occur in both the major topography and the bottom of the drainage basin (Toth, 1963; Sophocleous, 2004). Groundwater recharge is generally considered to occur in topographic highs and discharge in topographic lows in humid regions, whereas in arid alluvial-valley regions groundwater recharge is usually focused in topographic lows, such as channels of ephemeral streams (Wang *et.al*, 2010).

Climate is the main regulator of the water table depth and surface water stage thus it is also a main driving force for interactions that depend on the hydraulic head differences between surface water and groundwater (Levy and Xu, 2011). Recharge into an aquifer from precipitation results in a rise of the water table and an increase of the hydraulic gradient so that the discharge into a stream increase. Hydraulic heads are the sum of elevation and water pressure divided by the weight density of water. They describe the potential energy in groundwater flow systems (Sophocleous, 2004). The differences in hydraulic heads (water levels) and the resistance of the media between surface water and groundwater resources controls the exchange rate of water between the water resources (Rossouw *et.al*, 2015). Climatic factors are particularly important for many alluvial floodplain aquifers, which often rely on flooding for groundwater recharge (King *et.al,* 2014). Therefore, to understand the interaction, it is necessary to have knowledge of the climatic factors and flow systems. However, it is often difficult to identify the interactions, particularly in semi-arid environments which are characterised by intermittent streams that can change from losing to gaining conditions depending on groundwater levels in the adjacent aquifer (Seaman *et al.*, 2013).

3.5 Gaining streams: Aquifers recharging rivers

In water management globally, there is a move towards a conjunctive approach which recognizes that surface water and groundwater are a connected resource (McCallum *et al.*, 2012). The exchange of water between streams and aquifers influences the quality and quantity of water within both domains according to the fluxes and chemistry of the water moving through the streambed and the changes that occur at the groundwater-surface interface (Calderon and Uhlenbrook, 2014). Numerous methods exist for measuring and analysing the relationship between the two interlinked resources. The interaction can be investigated through methods such as direct measurements of flux, heat tracers, methods based on Darcy's law, base flow separation, and tracer-based methods including environmental isotopes (Kalbus *et.al,* 2006).

In the Free State Province of South Africa, Welderufael and Woyessa, (2010) conducted stream flow analysis for the Modder River basin using four different baseflow separation methods which analyse the streamflow hydrograph. The methods used were the Nathan and McMahon (N&M) method, Chapman method, the Smakhtin and Watkins method (S&W) and the frequency duration analysis. The analysis was conducted for the period of 1999 to 2007 for all the seasons of each year. All the methods gave reasonable baseflow values except for the S&W method which underestimated the baseflow component during low flow conditions. In the Upper Modder River basin where the perennial river originates, it was found that the stream flow is primarily recharged by groundwater and this was confirmed by stream flow even during long non-rainy periods. Recommendation for the study was to use a calibrated physically based model that can identify the sources along with quantifying the baseflow amount.

In the Wei River, located in the semi-arid region of the Loess Plateau, the largest tributary of the Yellow River in China, Li *et al.*, (2017) investigated the baseflow contribution to the river. This was done using the Tsinghua hydrological model to simulate runoff generation processes in the upper Wei River and the automatic baseflow separation method or Arnold baseflow separation method to separate baseflow from daily streamflow in the Upper Wei Basin from 2001 to 2004. Based on the hydrological model and the Arnold baseflow separation method, the average baseflow index was estimated to be approximately in the range of 0.30-0.36. Thus, indicating a groundwater-fed system during dry periods. The average-intra-annual monthly baseflow varied during different times of the year representing the seasonality of baseflow due to the seasonality of precipitation and evapotranspiration in the region. The researchers recommended using long-term discharge data and other baseflow separation methods to obtain more reliable baseflow estimates and to compare the current results of the study.

Yang *et al.*, (2012) characterised the interaction between groundwater and surface water in the Jialu River basin in China. Major ion chemistry, the stable isotopes of water, pH, dissolved oxygen (DO), Eh and a comparison of groundwater levels with that of surface water were used as a proxy to establish the nature of the interaction for July and September 2010. The water level of groundwater was higher than that of the river for most of the study period which includes a period of a major flood. Thus, the river was most likely a gaining river for most of the time. The groundwater levels in the region responded rapidly during the flood event because of rainfall. Diffuse recharge by infiltrating rainfall was suggested to be one of the main components of the water table rise. Results of the chemical analyses of groundwater and surface were plotted in a Piper diagram. Surface water samples analyses indicated that human activities negatively influenced the water quality of the river.

The signatures of all the groundwater samples remained the same before and after flooding except for one sample, which indicated that the aquifer is large enough to mask seasonal isotopic variation caused by rainfall, however, the river isotopic signature varied greatly due to precipitation. This illustrated that the groundwater never or rarely received recharge from surface water bodies during the study period. From a conventional hydrogeological survey and a comparison of surface water levels with that of groundwater illustrated that the groundwater feeds the river, most likely because of rainfall. The transitional (closest) well from the river (30 m away) seemed to be connected to the nearest river water because the groundwater had similar trends of stable isotopes signatures and chloride content with the river. This thus suggested that the transitional well was being recharged by river water via bank infiltration.

In South Australia, Banks (2010) characterized the spatial and temporal variations of groundwater-surface and their interconnectivity in three dry temperate climate catchments, Cox Creek, Lenswood Creek, and Kersbrook Creek, western Mount Lofty Ranges. The study was done using hydrochemical methods, including the stable isotopes of water (^{2}H, ^{18}O), major and trace ions, radon and strontium isotopes. Analysis of the results suggested that a connection between the groundwater system and Cox Creek exists throughout the year.

Martinez *et.al.,* (2015) demonstrated how the integration of a large dataset of surface water and groundwater chemistry analysed through multivariate statistical analysis (Hierarchical cluster analysis) can be used with environmental tracers (radioactive ^{222}Rn and stable isotopes ^{2}H; ^{18}O) to determine the connection between the two water resources. The researchers focused their study in the semi-arid south-eastern Queensland, Australia, Condamine River catchment, which is a perennial river where alluvial and basalt aquifers occur. Results from the study showed that the tributaries of the Condamine River are connected to the aquifer types in the area and the connections occur either through consistent baseflow contribution in the upper reaches or by dynamic conditions varying between losing and gaining following flood recharge events.

Bestland *et al.,* (2017) determined the level of groundwater dependency of pools located in seasonal and ephemeral streams over a one-year period in the semi-arid Clare Valley, South Australia. Sampling for paired groundwater and permanent pools was done over the four seasons of the year and these were analysed for environmental isotopes, strontium (^{87}Sr/^{86}Sr), ^{2}H; ^{18}O, and major ions. The hydrochemical relationship between groundwater and surface water was evaluated with scatter plots and the Permutation multivariate analysis of variance (PERMANOVA), in Primer V6, was used to evaluate the difference between groundwater and surface water.

Hydrochemical analysis for the study indicated that a limited number of pools had the mixing of surface water and groundwater. However, most of the evidence showed that the surface water pools were almost wholly dependent on groundwater. Strong evaporation was observed in the pools thus it was noted that there is a disconnection or very low input of groundwater during sometime in the region, especially upstream of the catchment. Therefore, the conclusion was that groundwater inflows into pools in the region cannot be considered as a continuous supply as previously believed for the study area.

In the United States of America (USA), Paces and Wurster, (2014) investigated whether there is mixing between shallow carbonate aquifers and a surface water feature, a wetland, in the arid Pahranagat Valley, Nevada. The study was performed by collecting water samples from 14 sites including springs, irrigation ponds, shallow monitoring wells (3-4m depth) and surface water dams to characterize the sources and evaluate the mixing in relation to the Valley and on the wetland. The collected samples were analysed for their stable isotopes compositions (^{2}H; ^{18}O, ^{87}Sr/^{86}Sr, ^{234}U/^{238}U) and major ions. Piezometers were installed using hand-augers to monitor the potentiometric fluctuations at different times of the year. The springs in the study area had nearly identical stable isotopes compositions that plot close to the Global Meteoric Water Line (GMWL) at relatively light values that are consistent with rainfall at high latitude recharge areas. Shallow wells (3-4 m) and surface water at the wetland indicated the effects of evaporation as they did not plot close to the GMWL. The highest enrichment of the stable isotopes, Na and Cl were observed in the period (August) where the highest evaporation occurred. The water from the regional carbonate aquifers had distinct Strontium and Uranium isotopic signatures and the composition indicated that surface water flow in the Pahranagat Valley is dominated by water from springs originating from the aquifers.

Becker *et al.*, (2004) investigated groundwater-surface water exchange rates along with a 40 km Ischua Creek in the humid, south-western New York State, USA, using a combination of three methods. The study was carried out during the July-October 2001 dry period thus groundwater baseflow contributions were assumed to dominate the flow in the creek. Differential stream flow measurements along the creek were carried out by repeated current meter measurements at specified stations. Streambed temperature surveys were then performed at three depths: just above the streambed, just below the streambed (2-3 cm) and at the maximum depth, the probe could reach numerous locations along the creek. Temperature gradients at the streambed were also determined at three stations along the creek by installing nested piezometers where temperature and heads were recorded using data loggers. The measured temperature gradients were then modelled with a one-dimensional heat transport model to determine the water exchange rates between groundwater and the creek. The estimated groundwater flux to the streambed through the temperature gradient method was found to be significantly smaller than through the current meter measurement. The conclusion was that this might have been the result of local increases in groundwater discharge. Combining the methods was therefore recommended for use in locations where groundwater discharge occurs primarily through local discharge.

In Denmark, Poulsen *et al.*, (2015) assessed the spatial variability of groundwater discharge and quantified the fluxes in a lowland Hotum stream, located in the Temperate Skjern River catchment in Jutland. At point scale, stream discharge at the catchment outlet was measured and groundwater hydraulic gradients monitored several times in piezometers installed in riparian zones at selected sites during three major rainfall events. Reach-scale variability of groundwater discharge was then determined through differential gauging along the Hotum stream between two selected sites. On a catchment scale, the different runoff sources were investigated during the three major rainfall events by sampling for rainwater and the stream water and then further analysing these for electrical conductivity (EC) and stable isotopes ($^{2}H/^{1}H$) to establish the source of recharge. Hydrograph separations were based on the EC and stable isotopes data obtained. The results from point to reach scale confirmed that the Hotum stream is dominated by groundwater. On the 2.5km stream reach investigated, groundwater contributed to about 30% of the stream flow. There was however large spatial variability of groundwater discharge possible due to heterogeneity at streambed hydraulic conductivity.

Hydrograph separations at a catchments scale over three sub-catchments revealed distinct differences in runoff sources due to rainfall variability in these areas and sub-catchment characteristics. The conclusion for the study was that despite a significant groundwater contribution at the lowland catchment, there is still high variability in the groundwater-surface interaction. Therefore, considering the variability of groundwater discharge from point-to-catchment scale, using a combination of methods were recommended for future studies in all environments.

3.6 Losing streams: Rivers recharging aquifers

The connection between surface water and groundwater systems remains poorly understood in many catchments throughout the world and yet they are fundamental to the effective management of water resources. Managing the two water resources as a single resource is not straightforward, particularly if both resources are being utilised, especially in regions that suffer problems of data scarcity (Tanner, 2013). In many cases, rivers and aquifers are hydraulically connected and as such, the interaction between them need to be understood and quantified for the resources to be managed appropriately (Mccallum *et al.*, 2013). In arid and semi-arid regions, natural recharge of aquifers by rivers is a more frequent phenomenon than in humid environments. The sources of the recharge are usually intermittent or ephemeral streams when a river water level is temporary above the groundwater level if any (Simmers, 1987).

In the semi-arid eastern Australia, Mccallum *et al.*, (2014) investigated river-aquifer interaction along a 34 km reach of Namoi River. The interaction was determined using temperature variations over depth at points along the river reach. The principle behind using heat as a natural tracer of water movement is that daily temperature fluctuations within a river due to solar radiation lead to a temperature response in the sediments at the river-aquifer interface because of conduction and convection. The hydrographs recorded upstream and downstream ends of the river reach were used to estimate the loss volume of a flow event and the loss rate during the event. The results of the study revealed slightly gaining to slightly losing conditions during low flows, to strongly losing conditions driven by an increase in the river stage during high flows. The researchers highlighted the need to use field observations to drive conceptual generalisations made in numerical models to have a wider understanding of catchment processes that influence river-aquifer interactions.

In an arid zone of Australia, Costelloe *et al.*, (2009) assessed groundwater recharge from a group of Congie freshwater lakes that are ephemeral to intermittent and the discharge of groundwater into the lakes. The methods used in the study to investigate the interaction between groundwater and surface water included hydrogeological, chemical and environmental isotopes sampling along with numerical modelling of groundwater responses during the flooding of the lakes in dry and wet periods. To sample for groundwater and monitor water levels, piezometers were installed at the three lake sites at depths ranging from 8.5 to 10m in the shallow unconfined sand clay to silty sand with some clay-rich layers. Results from the study indicated that the lakes are zones of net groundwater recharge during periods of flooding (inundation). However, through profiles of soil-water chloride, oxygen-18, and volumetric water content in the unsaturated zone, it was found that drying of the lakes results in drying evaporative groundwater discharge to occur and this, in turn, causes salinization of the soil profile. The study conclusion was that groundwater recharge in the study sites occurs through macro-pore flow during the rising stage of floods.

In the United States of America, Stark *et.al.*, (1994) evaluated the connection between Straight River in north-central Minnesota, underlain by highly transmissive surficial and confined-drift aquifers. The investigation of the connection between the two water resources included the processes first collecting chemical data to define the hydrology and water quality of the drift and the stream. Then measurements of the stream and groundwater temperatures were taken in order to define daily fluctuations and temperature distributions. Following this, an analysis of hydraulic properties of drift aquifers, potentiometric surfaces, and directions of groundwater flow was performed. Then groundwater flow and stream temperature models were constructed to represent the geohydrological system and the interaction between the aquifers and the stream. Finally, an application of model simulation results to test the hydrologic system over long periods of time.

Analysis of the data collected indicated a strong hydraulic connection between the stream and surficial aquifer. The discharge of the Straight River increased in the downstream direction. However, during summer, the rate of gain in discharge during summer decreased downstream, possibly due to groundwater abstractions for irrigation. The water table in the surficial aquifer and potentiometric surface of the uppermost confined-drift aquifer sloped towards the Straight River. There were significant daily fluctuations observed in the river temperature during summer. Groundwater discharge cooled the stream during the summer and warmed it in the winter.

Kebede *et al.*, (2005) traced the source of groundwater recharge in the arid to semi-arid Ethiopian rift valley using environmental isotopes (^{2}H; ^{18}O). The role of lakes and surface waters in recharging groundwater and the role of groundwater in recharging the surface waters was determined from the relation between $\delta^{18}O$ against electrical conductivity or deuterium excess. Lakes in the central sector of the Ethiopian rift were found to play a major role in recharging adjacent aquifers. The researchers, however, noted that limitations exist in fully utilising stable isotopes because of a lack of strong altitude and/ or latitude effect. The conclusion for the study was that the relationship between isotope variability and meteorological processes needs further investigation.

In Switzerland, Vogt *et al.*, (2010) introduced a new approach of measuring the seepage flux from a river into an underlying alluvial aquifer in the Thur River. The researchers used a fibre optic high-resolution vertical temperature profiling technique. Streambed temperature data were analysed with a model based on the assumption that the vertical seepage rate is constant with depth. Temperature profiles for the study had fluctuations diurnal and on a seasonal basis. The method introduced was found to be more advantageous than other temperature profiling methods as it has it is able to approximate the appropriate depth of investigation. The researchers recommended the use of the method in studies of high-resolution temperature profiling in shallow aquifers such as determining aquifer boundaries.

In North-eastern Nigeria, Hassan *et.al*, (2012) performed a hydrophysical investigation of river-aquifer interaction in the semi-arid Dalori, using the Bama-Ridge shallow aquifer and the perennial River Ngada as a case study. Geo-electrical depth soundings were conducted using Vertical Electrical Sounding (VES) devices to collect hydrophysical data and side-by-side curves generated from the data were interpreted over three seasons. The study was initiated at the end of the rainy season (September-October), end of the dry season (June-July), and the wet season (July-October) in 2007. At the end of the rainy season, a low resistivity layer was found at a depth of 14.72 m below the groundwater level, indicating a water-bearing formation. The formation was encountered for 88 m. At the end of the dry season, a low resistivity formation was encountered at a depth of 38.5 m suggesting drying up of the formation from October-June-July before it was recharged by rainfall and the river from July to October.

A comparison of the results of the study with that obtained in 2008 and 2009 indicated a variation in the water table during the different seasons due to drying during the dry season and recharge during the wet season. Observations on shallow wash boreholes located in nearby settlements agreed with the results of the study. It was suggested that hydrophysical investigations of river-aquifer interactions are more complex in the semi-arid environment than other hydrological regimes due to more extreme hydrological conditions in combination with the spatial variability of topography. The method in the study was successfully used to show that the Bama-ridge shallow aquifer is hydraulically connected to the perennial River Ngada.

Calderon and Uhlenbrook, (2014) investigated stream-aquifer interaction mechanisms and flow rates in a system where tidal sand ridges influences control the river discharge to the sea on a coastal catchment located in the south-western Pacific of tropical Nicaragua. An experimental cross-section was set up at the Ostional River for the period from March 2012 to April 2013 in the study area. Ten piezometers were installed at the cross-section at a distance of 25 m from each other. Water table fluctuations and temperature were then monitored continuously every 30 minutes in the piezometers and within the river. Pressure head changes in at the piezometric cross section were then simulated within a numerical model using HYDRUS 2D. The changes in river stage were also simulated for the period with the most volume of rainfall during the study and the effect of the larger river fluctuations determined through modelling.

Results for the study in terms of river stage and hydraulic head fluctuations displayed a synchronous pattern throughout the study period, indicating a strong hydraulic connection between the river and the adjacent aquifer. The presence of sand ridges in the study area prevents surface water discharge to the ocean, resulting in surface water accumulation and aquifer recharge from the river. Average river temperatures were warmer than that of groundwater due to being exposed to the sun. Bank storage occurred during stream stage increases and the stored water is quickly released back into the stream after the peak river stage in very small amounts. The hydraulic gradients across the river banks showed shifts during flood events. During dry conditions, a flood event caused a reversal in the hydraulic gradient. The authors recommended using chemical data to improve process understanding through quantification of fluxes and modelling.

3.7 Groundwater recharge mechanisms

Xu and Beekman (2003) identified four main modes of groundwater recharge that can be distinguished, and they are natural recharge by the downward flow of water through the unsaturated zone reaching the water table, Lateral inflow and or inter-aquifer flow, recharge that is induced from nearby groundwater abstractions and artificial recharge. In the current study, the focus is on natural groundwater recharge. Depending on the type of hydrogeological terrain, natural groundwater recharge may occur uniformly over the subsurface (diffuse/direct recharge) or may be focused (focused recharge). Diffuse/direct recharge is the direct infiltration of precipitation more than soil moisture and subsequently percolating through the unsaturated zone to reach the groundwater body (Xu and Beekman, 2003).

Focused recharge occurs in cases where water has accumulated in depressions or streams and in cases where the streambed is directly above the water table. Focused recharge may also occur through unsaturated flow instabilities, through geological features such as fractures, faults, clastic dykes, and karstic sinkholes; and man-made infrastructure including recharge wells and waste disposal facilities. There are two distinct types of focused recharge: indirect recharge and localized recharge (figure 3-4). Indirect groundwater recharge occurs through preferential flow paths of streambeds, cracks, and fractures whereas localized recharge occurs through depression cracks (de Vries and Simmers 2002; Xu and Beekman, 2003). While one type of groundwater recharge mechanism typically dominates an area, both diffuse and focused recharge are important, especially at a regional scale (Izbicki *et.al,* 2002).

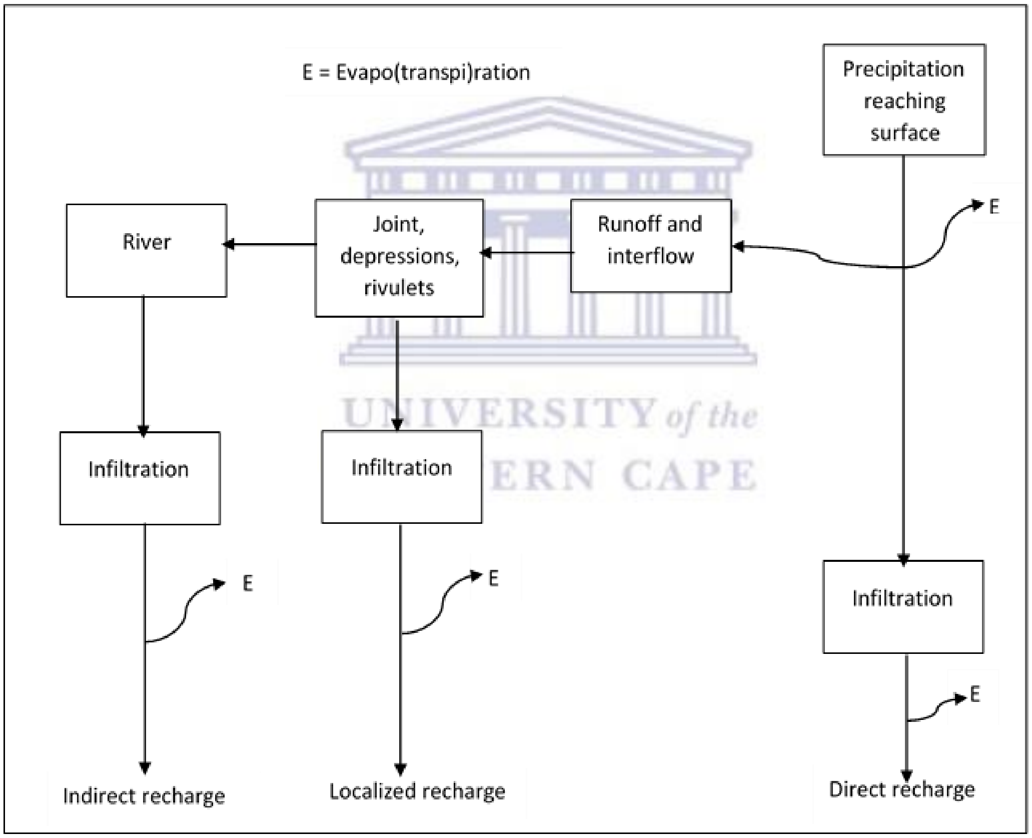


Figure 3-4: Simplified expression of the various groundwater recharge mechanisms in a semi-arid environment. Adapted from: de Vries and Simmers (2002).

Vries and Simmers (2002) suggested that a combination of the various types of recharge mechanisms occur in many environments, with percolation to groundwater by one or more of the following processes. Diffuse percolation, as either an unsaturated flux or saturated front (piston flow), Macro-pore flow through abandoned root channels, burrows, desiccation cracks of soils (particularly clay), and fissures; or preferential flow caused by unstable wetting fronts and differentiated soil physical properties within the soil, particularly between sandy and clayey sediments. Preferential flow occurs via preferred pathways/macro-pores or zones such as streambeds in the unsaturated zone with relatively high infiltration and or percolation capacity.

Generally, diffuse recharge dominates in humid environments whereas, in arid and semi-arid environments, the potential evapotranspiration generally exceeds the rainfall, and groundwater recharge depends on high-intensity rainfall events, the accumulation of rainfall in depressions and streams, and the ability of rainfall to escape evapotranspiration by rapid infiltration through cracks and fissures. Hence, direct recharge in terms of total aquifer replenishment tends to be less important than localized and indirect recharge in semi-arid environments (Vries and Simmers, 2002; Wang *et.al,* 2010).

3.8 Conceptual model of groundwater recharge mechanisms

Groundwater resources represent a relatively complicated system, which is not easy to understand under complex hydrological conditions as it reacts to disturbances from the outside environment. The development of a sound conceptual model is thus imperative for understanding the recharge mechanisms and for the selection of appropriate methods for evaluating and estimating recharge (Healy, 2010). According to Younger (2007), a conceptual model is a set of rigorously justified assumptions, which represent a simplified version of a real-world system. The conceptual model depicts a basic idea or constructed understanding of how systems or processes occur. It is a pictorial representation of the flow systems of groundwater, often in the form of a block diagram or a cross-section.

A conceptual model of recharge mechanisms should consider surface water and groundwater flow systems, and how they are linked (Peterson, 2012). The differences in the chemical and isotopic composition of water are often used to characterise groundwater recharge mechanisms, infiltration into groundwater, recognize leakage between aquifers, define areas of saltwater intrusion, assess baseflow contributions to surface currents and investigate recharge conditions through the unsaturated zone. To produce a sound model, information and knowledge of the physiographic, hydrographic, climatic, soils, and geologic characteristics of the region of interest are required

(Betancur *et.al,* 2012). In the current study, an attempt was made to produce a hydrogeological conceptual model of recharge processes and mechanisms for the TKNP.

3.9 Theoretical framework

This study is guided by the theory of infiltration by Philipp (1969), to investigate groundwater-surface water interactions and to conceptualise the recharge mechanisms in the case study area. The theory was used as a guide to interpreting the results of the study, to understand the assumptions and as a guide in choosing the appropriate data collection and data analysis methods. The hydrologic cycle is composed of two phases. The first of which is the atmospheric phase, which describes water movement as gas (water vapour) and liquid/solid (rain and snow) in the atmosphere.

The second is the terrestrial phase, which describes water movement in, over and through the Earth. Surface water (runoff and streamflow) and groundwater (infiltration, percolation, and aquifer recharge) form two components of the terrestrial phase. Generally, groundwater is recharged from precipitation, surface water bodies, and human activities such as irrigation (Reli *et al.,* 2016). The theory of infiltration describes the movement of water from precipitation or surface water, through the unsaturated soil zone and eventually recharging groundwater. Infiltration is the process by which water on the ground surface soaks into or enters the soil.

A large portion of precipitation reaching the land surface moves through the unsaturated soil zone during the subsequent process of infiltration, drainage, absorption of soil-water by plants, and evaporation. The infiltration process significantly depends on the hydraulic properties and the soil type through which it flows. The major factor affecting soil infiltration is soil texture (percentage of sand, silt, and clay). Groundwater recharge is most likely to occur over in areas that have coarse-grained, high permeability soils as opposed to fine-grained, low permeability soils. The presence of coarse-grained promotes recharge because water can infiltrate rapidly and drain through the root zone before being extracted by plant roots (Petersen, 2012).

Furthermore, depending on the amount and type of clay material present in the soil, some clayey soils develop shrinkage cracks as they dry. The cracks are subsequent direct conduits for water entering the soil causing the clayey soil to have high infiltration rates during dry conditions. On the areas where there are no cracks, clayey soils have slow infiltration rates (USDA, 1994). When water is ponded on the soil surface, the entry of water is very high but drops after a short period to a steady state known as the final infiltrability (Simmers, 1988). Water tends to move more quickly through the large pores of sandy soil than through the small pores of clayey soil, even more, when the clay has been compacted.

In semi-arid or arid environments, ephemeral river flow often features significant in-stream infiltration referred to as transmission losses or indirect recharge. High intensity, short duration rainfall, which is a characteristic of arid and semi-arid environments, generally exceeds the capacity of the soil to infiltrate the water and results in overland flow. This phenomenon is widely known as Hortonian Overland Flow (Reli *et al.*, 2016). Water from surface water input takes various pathways to reach stream channels. The water from precipitation will infiltrate the soil and will either remain in the soil, percolate to groundwater, infiltrate as subsurface flow, flow as overland water or directly enter streams (Reli *et al.*, 2016).

Chapter 4 : Research Design and Research Methods

4.1 Introduction

Chapter 1 of the thesis provided the background, aim, objectives, research question, thesis statement, study conceptualisation, scope and nature of the study and the research framework. Chapter 2 provided a setting where the research study was implemented. The chapter described the physiographic features of the study area and assessed the potential influence of such features on the results. Chapter 3 presented a review of the literature on groundwater recharge in semi-arid environments in the global and local context to understand the current discussions related to the study topic.

The current chapter describes the research design and the research methods followed, chosen data collection and analysis methods, procedures followed for data quality assurance, ethical consideration and the limitations of the study. The following research methods are discussed: Hydrochemical analysis, stable environmental isotopes, and Electrical Resistivity Tomography (ERT) geophysics.

4.2 Research design

The research design is presented objective by objective to provide a description of the sampling sites, sample size, study parameters and unit of analysis.

4.2.1 Research design approach

The type of research design approach used in the current study is a case study design whereby an experimental technique was used to assess at site-specific, groundwater-surface water interactions in terms of recharge. Non-perennial rivers within the TKNP, particularly the Tankwa and Renoster Rivers were used to evaluate the interaction between the rivers and the underlying aquifer. At a regional scale, the TKNP was evaluated to develop a hydrogeological conceptual model of the recharge mechanisms.

4.2.2 Description of sampling sites

To establish the groundwater contribution to the river system in the study area, existing boreholes, a dug well and springs at the Tankwa-Karoo National Park were sampled (Figure 4-1). To investigate the role of the river in recharging the underlying aquifer, surface water samples were obtained from the Oudebaaskraal Dam, located upstream of the Tankwa River, and from the Renoster River. Initially, permanent pools along the rivers were the target, however, these were not available at the times of sampling. In addition to obtaining samples from groundwater and surface water, precipitation was sampled from cumulative rain collectors.

To develop a hydrogeological conceptual model of recharge mechanisms, Tankwa-Karoo National Park was surveyed and the relevant data secondary and primary were collected.

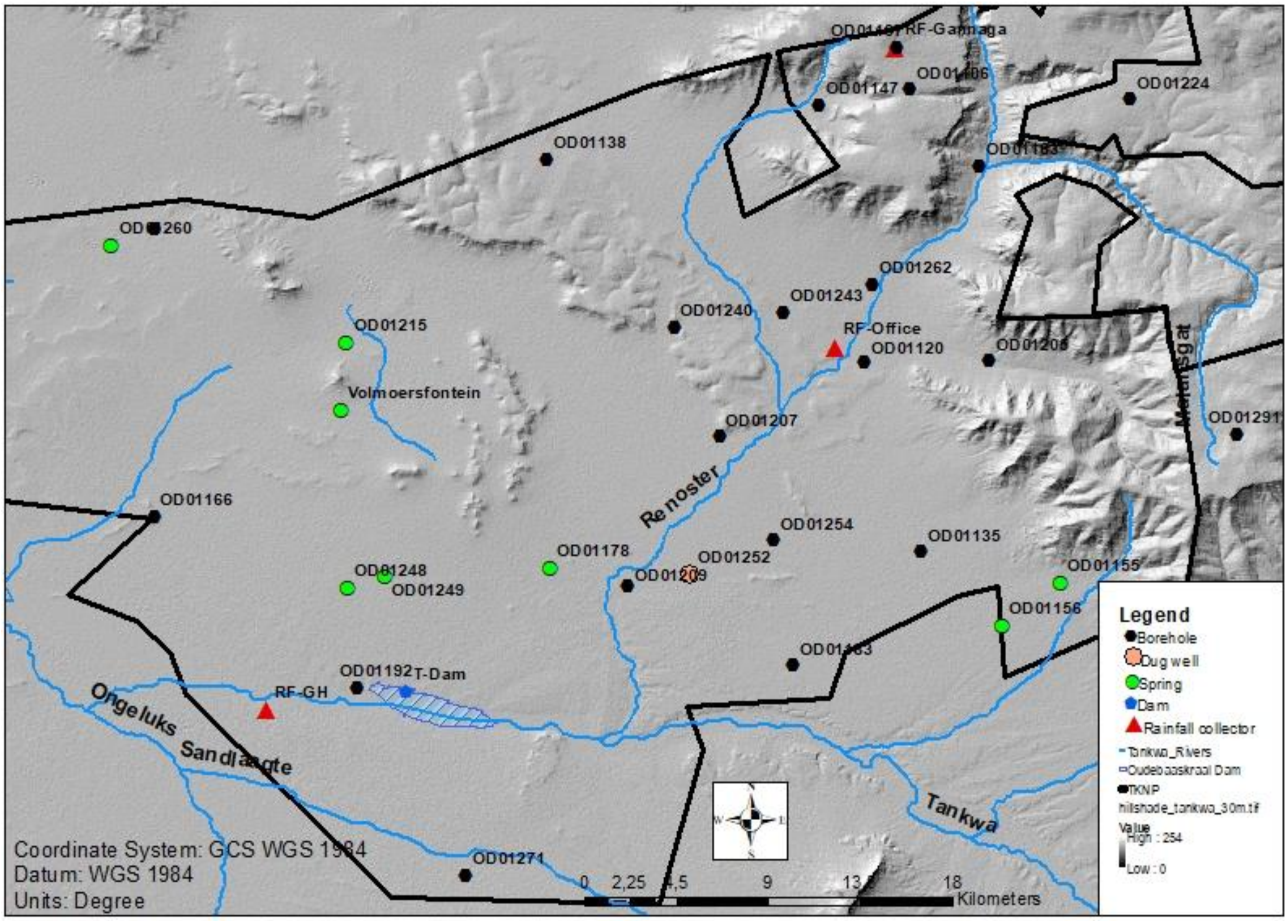


Figure 4-1: Sampling sites within the Tankwa-Karoo National Park.

4.2.3 Study population/parameters and unit of analysis

To establish the groundwater contribution to the river system and the influence of the river in recharging groundwater, the following parameters were analysed in groundwater and surface water: major cations of Sodium (Na^+), Potassium (K^+) Calcium (Ca^{2+}), and Magnesium (Mg^{2+}) and major anions of Bicarbonate (HCO_3^-), Sulfate (SO_4^{2-}) and Chloride (Cl^-). In *situ* measurements of electrical conductivity (EC), pH and water temperature were taken at each sampling point. The stable environmental isotopes of water (δ^{2}H and δ^{18}O) were analysed from groundwater, surface water, and rainfall. This was done with the intention of tracing the source of recharge between the two water resources hence addressing objectives one and two.

To explain the role of recharge in the system through a regional hydrogeological conceptual model, existing climatological, groundwater levels, and land use characteristics data were collected. Groundwater levels were measured on a quarterly-basis to determine groundwater flow directions, climatological data were analysed to determine the recharge patterns in relation to the precipitation patterns and physical characteristics. Electrical Resistivity Tomography (ERT) geophysical surveys were performed at specific sites to characterise the subsurface.

4.2.4 Sampling design approach and samples size

The study followed a purposeful sampling design approach. A site reconnaissance was performed at the commencement of the research in 2017 and possible sites for sampling were chosen. The existing groundwater monitoring sites in the study area were chosen as sampling points. Possible surface water sampling sites were identified during the site reconnaissance. In total, 20 boreholes, a dug well, and eight springs were selected for sampling in the Tankwa-Karoo National Park during the summer (dry) and winter (wet) seasons. Surface water samples were obtained from the Tankwa River Dam (Oudebaaskraal) and rainfall from three cumulative rainfall collectors during each sampling round.

4.3 Data collection methods

The current data collection methods section provides an explanation and description of 1. available data collection methods, 2. chosen data collection methods under each objective, 3. data collection tools used for each objective, and 4. The procedures followed in collecting the data.

4.3.1 Groundwater contributions to the river system

Numerous methods exist for measuring and analysing groundwater contributions to river systems. The methods include the direct measurements of flux, heat tracers, methods based on Darcy’s law, hydrometric methods, baseflow separation, and tracer based methods including environmental isotopes (Kalbus *et.al,* 2006). The methods are further grouped into field based methods and desktop methods. Field measurements methods include hydrochemical analysis, hydrometric methods, seepage meters, environmental tracers, artificial tracers, stable environmental isotope analysis, heat tracer methods, geophysical and remote sensing, water budget and field indicators. The desktop methods include hydrographical analysis, hydrogeological mapping and modelling. The methods differ in terms of their application, procedure, spatial and temporal scale (Gxokwe, 2018). In the current study, the methods that were chosen to determine the groundwater contribution to the river system were tracer based methods and hydrometric methods. The tracer based methods (hydrochemical and stable environmental isotope analysis) were chosen to determine similarities between groundwater and surface water. The hydrometric methods were used to determine the groundwater flow direction. Due to the non-perennial nature of the rivers in the study area, the other available methods were not applicable.

4.3.2 Surface water contributions to groundwater

Accurately determining the interaction between rivers and aquifers from one method alone is difficult and thus an approach combining various methods is required in order to yield reliable results (McCallum *et al.*, 2013). The interaction between a river and aquifer can be measured at points within riverbeds (through piezometers or seepage meters), inferred from hydraulic gradients, estimated from riverbed temperature profiles or using geochemical tracers; calculated from the water balance along a river reach and various other methods (Hatch *et al.*, 2006; Kalbus *et.al.*, 2006). However, rivers in the study area rarely flow or have water (non-perennial) within them hence most of the available methods are not applicable. In the current study, the surface water contribution was inferred from hydraulic gradients and geochemical tracers (hydrochemistry and stable environmental isotopes).

Sampling for hydrochemical and stable environmental isotopes analysis in groundwater and surface water was done during the wet and dry seasons. Wet season samples were collected during the month of May and dry season samples were collected during November. The methods, procedure and tools that were chosen to collect the groundwater and surface water samples for hydrochemical and stable isotopic analysis so as to establish the groundwater contribution to the river system and to investigate the role of the river in recharging the underlying aquifer were as follows:

- **Hydrochemical and stable environmental isotopes**
  - **Data collection methods**

Various methods exist for sampling groundwater resources for hydrochemical and stable isotope analysis. Depending on the length of a borehole screen, the sampling methods that are available include passive groundwater sampling/no purging or fixed volume groundwater purge and sampling. No purge sampling methods use passive sampling devices to collect samples at specific depths in the borehole column with minimal disturbance (Gomo et.al, 2013) and are useful for sampling from short screened (<6m) monitoring wells. Fixed volume groundwater purge and sampling are useful for long screened monitoring boreholes (>6m), where typically three or more times the volume of water in the borehole lining is pumped or drawn with a bailer from the monitoring borehole prior to sampling or using relatively high pumping rates (Sundaram *et.al.*, 2009). Purging a borehole removes stagnant groundwater to obtain samples considered representative of groundwater residing in the aquifer surrounding the borehole screen. The method that was chosen for collecting groundwater samples was the zero-purge method. The method requires the use of a passive sampling device, or a bailer, to collect samples at specific depths in a borehole column with minimal disturbance. The bailer was lowered into a borehole or dug well to a specific depth and this was in turn transferred to sampling bottles.

Available surface water sampling methods include dipping or grab sampling with the use of sample containers, collecting scoops of surface water and transferring it into a sample bottle. Using a peristaltic pump to sample from any depth if the pump is located at or near the surface and using a discrete depth sampler when discrete samples are desired from a specific depth. Other methods include collecting water with a bailer, buckets, submersible pumps and automatic samplers. The use of each of the methods depends on the objectives of the user. Springs were treated the same way as surface water during sampling (EPA, 2007). To obtain surface water samples, the grab sampling method was chosen. The grab sampling method was performed by taking samples directly at the sub-surface from approximately 30 cm depth of a surface water body with a sample bottle, with care to ensure no floating films or organic material were collected unless they are part of the sampling objective (EPA, 2007). The method involves inserting a plastic bottle directly into the surface water vertically with the opening facing down. Once at the required depth, the container is then inverted, allowing the sample to flow into the container. Spring samples were also collected in the same manner as the surface water.

- **Field data collection procedure and tools**

The procedure to sample groundwater for hydrochemical and stable isotopes analysis and measuring water levels was obtained from Weaver *et.al*, 2007. The procedure was as follows: the total depth and the depth to water level or static water level (SWL) within the boreholes were first measured with a water level meter before any sampling took place. These were later used to infer the groundwater hydraulic gradients to determine the groundwater flow direction. The global positioning system (GPS) was then used to determine the coordinates of the sampling points. A bailer attached to a tagline was lowered into the boreholes below the water level to a specific depth, based on the borehole length and screen position, and filled with water. The collected water in the bailer was then discharged into a bucket of known volume and recorded. The electrical conductivity (EC), pH, water temperature and total dissolved solids (TDS) were then measured in *situ* with a YSI Professional handheld multi-parameter meter, which was previously calibrated for the measurements. Samples for hydrochemical analysis in groundwater were first filtered with 0.45 µm syringe membrane filters to preserve the major cations and anions before being transferred into 500 ml polyethylene sample bottles.

In the case of production boreholes in the study area, the pump was turned on and ran until pH, EC and temperature readings stabilised. Samples were taken once the EC, pH and temperature readings stabilised, then filtered with 0.45 µm syringe membrane filters, and transferred into 500 ml polyethylene sample bottles. When collecting groundwater samples for the stable isotopes, deuterium and oxygen-18, no filtration or a preservative was required. The samples for stable isotopes in groundwater were taken with 50 ml polyethylene sample bottles. The samples collected were tightly capped and then labelled with the site information. Care was given to ensure that during sampling, there were no air bubbles within the isotope sample bottles, and no evaporation occurred in the samples to avoid errors in the analysis. The collected water samples were then stored in a cooler box for storage whilst in the field.

To collect samples from surface water for hydrochemical analysis, the parameters of EC, pH, and temperature were first measured in *situ* using a YSI Professional handheld multi-parameter meter. Then surface water samples were collected by hand directly into the water body at approximately

30 cm depth using a glass beaker (grab sampling), which was previously rinsed with the sample water. The beaker was inserted into the water vertically with the opening facing down. Once at the required depth, the container was then inverted, allowing the sample to flow into it. The water collected from the beaker was then filtered through a 0.45 µm membrane filter and transferred into 500 ml polyethylene plastic bottles that were previously rinsed three times with the filtered water. The sample bottles were filled completely to exclude air bubbles. Surface water samples for isotope analysis were also collected in the same manner and transferred into 50 ml polyethylene sample bottles, however, no filtration was required. These were then labelled with the site details and stored in a portable cooler box and transported to the laboratory. The same procedure was followed when collecting samples from springs.

4.3.3 Hydrogeological conceptual model of recharge mechanisms

The methods that are available for developing a conceptual model include records review of literature and field measurements. Records review entails the collection of secondary data from various sources such as geological, climatological, land use characteristics and hydrological data set. Field measurements include geophysical and remote sensing techniques, mapping the hydrogeological environment through cross sections using geological maps, analysing hydrometric potential between groundwater and surface water and conducting water budgets. The methods provide an indication of the direction of flow or recharge fluxes between groundwater and surface water (Madlala, 2015). To collect data to include in the conceptual model, the current study combined hydrometric methods, Electrical Resistivity Tomography (ERT) geophysical surveys and tracer techniques to infer the recharge mechanisms in the study area. Water levels were monitored on a quarterly-basis and ERT geophysical surveys were performed across specific sites in the study area in order to characterise the subsurface.

- **Data collection methods**

The methods that were chosen to collect data to develop a regional conceptual model of groundwater recharge included field measurements, a review of previous hydrogeological studies in the Main Karoo Basin area and desktop collection of existing data from various sources. Fieldwork included the measurement of water levels, discussed in section 4.3.1 and 4.3.2, and ERT geophysical survey along specific sites. The chosen sites for the ERT geophysical survey were rivers and springs in the study area.

- **Field data collection procedure and tools**

The procedure that was followed to perform ERT geophysical surveys across rivers and springs in the study area to develop a hydrogeological conceptual model was as follows: two conducting cables (each 100 m) were rolled across a river channel. The conducting cables were then connected to stainless steel electrodes that were coupled into the ground at 5 m spacing and connected to an ABEM Terrameter SAS 1000 Resistivity and Induced polarisation. The Terrameter was used to induce a current into the subsurface and to record the electric resistivity of the formation to a maximum depth of 30 m. In the case of the springs, two perpendicular line segments were performed. The entire length for each line segment was 40 m with 1 m electrode spacing and the maximum depths of the investigation was 6 m. The apparent resistivity data for the line segments across the river beds and springs were then inverted using RES2DINV software, which is based on a smoothness-constrained least-squares algorithm (Bucker *et.al*, 2017), in order to generate formation resistivity depth cross-sections.

4.4 Data analysis methods

The data analysis for the study is both quantitative and qualitative, meaning it measures the quantity, deals with numbers and a qualitative analysis means that it also deals with the descriptive aspect of the study. The data analysis methods section describes the available data analysis methods for each objective, the chosen data analysis methods, and the data analysis tools that were used.

4.4.1 Assessing surface water-groundwater (river-aquifer) interactions

- **Hydrochemical analysis of surface water and groundwater**

There exist a considerable number of methods and approaches based on the differences in physical and chemical properties, which classify, compare, and summarise large volumes of chemical data. Classification methods characterise the chemical composition of water and these help in identifying the dominant water types. Examples of classification methods include Piper diagrams, Schoeller diagrams, Durov, and Expanded Durov diagrams. Piper diagram, Stiff diagram, Durov plot, Schoeller diagram, bar charts, pie charts and scatter plots form part of graphical methods that provide visible interpretation of water samples. Piper diagrams, after Piper (1944), graphically represent the multiple variables associated with major cations and anions and aid in the determination of similarities and differences in water types.

The grouping of chemical analysis using these methods is useful in identifying hydrochemical facies and understanding the hydrogeological factors that influence groundwater chemistry (Hiscock, 2005). Other methods that can be used to analyse chemical data include correlation and analytical methods. Correlation methods are useful in comparing chemical compositions to find similarities and differences in water compositions such as Stiff diagrams. The Stiff system is a method of showing the differences or similarities in waters and changes in water composition with depth. Analytical methods identify the origin of water, and determine the processes involved in natural water chemistry.

To establish the groundwater contribution to the river system in the case study and to investigate the role of the river in recharging the underlying shallow aquifer, classification methods, correlation, and analytical methods were applied to the surface and groundwater hydrochemical data using Piper diagrams. The hydrochemistry of the samples collected was analysed at the Department of Agriculture's Elsenburg laboratory, following standard laboratory methods and norms. Secondary water quality data, major ions of groundwater for the period 2015 November to 2017 May were analysed by the Department of Water and Sanitation's water quality analysis laboratory using the ICP Spectrometer.

- **Hydrochemical analysis**

The procedure to analyses the hydrochemical data of groundwater and surface water entailed using Piper diagrams, which are hydrochemical models based on AquaChem® software, a groundwater software package that is used to graphically represent groundwater and surface water major cations and anions data. The Piper diagrams were used to differentiate water types from the different resources. The chemical data for sodium (Na^+), potassium (K^+) calcium (Ca^{2+}), and magnesium (Mg^{2+}); anions: bicarbonate (HCO_3^-), sulphate (SO_4^{2-}) and chloride (Cl^-) were plotted into the Piper diagrams in AquaChem® and the diagram classifies water into four water types. The water types presented in the Piper diagram include $Ca\text{-}SO_4$, $Ca\text{-}HCO_3$, Na-Cl, and $Na\text{-}HCO_3$ water types. Microsoft® Excel was used to performed statistical analyses on the hydrochemical data and to generate scatter plots.

- **Stable environmental isotopes analyses**

The stable isotopes (^{2}H, ^{18}O) compositions of the samples collected from surface water and groundwater were analysed at UWC's Earth Sciences Department using Laser spectrophotometer. All samples were normalised to internal laboratory water standards that were previously calibrated relative to the Vienna Standard Mean Ocean Water (VSMOW). The stable isotopes data are presented in "delta notations" where δ (‰) is defined as:

$$\delta = \left(\left(\frac{R_{sample}}{R_{standard}} \right) - 1 \right) * 1000‰$$

Where:

R_{sample} and $R_{standard}$ = $^{18}O/^{16}O$ or $^{2}H/^{1}H$. **Equation 1**

The isotope data were then plotted along the global meteoric water line (GMWL) of Craig (1961), $\delta^{2}H = 8\delta^{18}O + 10$, and a local meteoric water line (LMWL) for the Western Cape as determined by Diamonds and Harris (1997) using Microsoft® Excel. The GMWL represents the linear relationship between $\delta^{2}H$ and $\delta^{18}O$ based on precipitation data around the globe (Craig 1961; Baxter *et.al*, 2013). Samples that plot on or slightly below GMWL indicate recharge origin from local rainfall and rivers (Ahmed *et.al*, 2013). A local meteoric water line for the Western Cape Province was used in the analyses after considering the distance of the study area to the province. Microsoft® Excel was used to performed descriptive statistical analyses on the isotope data by summarising the data and scatter plots were generated from the data.

4.4.2 Hydrogeological conceptual model of recharge mechanisms

Golden Surfer® software, which is an analytical tool, was used to produce a conceptual model diagram of the recharge mechanisms. The developed model was further edited using Microsoft® Powerpoint based on records review of secondary data, field measurements and observations including the review of literature from similar studies in the Main Karoo Basin. The review included regions with similar settings as the study area. The model forms a foundation for conceptualising groundwater recharge mechanisms on NPRS in the semi-arid environment.

4.5 Reliability and validity of results

To ensure the reliability of the data that was used to establish the groundwater contribution to the river system in the study and to investigate the role of the river in recharging the underlying shallow aquifer, certain data quality assurance measures were taken. Data quality assurance was carried throughout the study. This included following the sampling procedure guidelines set out by Weaver *et.al* (2007). Such procedures included calibrating measuring instruments before use according to the manufacturer's requirements. Containers used for collecting the groundwater and surface water samples must not affect the integrity of the samples thus they were rinsed with distilled water. Different bailers were used to sample water from one sampling point to another and these were continuously rinsed with distilled water before being used in another borehole to avoid cross-contamination. The surface water sampler was also rinsed with distilled water before use between the sampling points.

Before the hydrochemical data were used in the analysis, they were checked for errors to determine which samples are eligible to be included in the water quality analysis. The common approach is to calculate the cation-anion balance (CAB) for each sample. This calculation is based on the principle that the total anion equivalents should equal the number of anions if charge neutrality is to be maintained. The calculation is performed on the major ions as the minor ions rarely influence the results. Younger (2007) stated that cation-anion balance values less than 5% are regarded to be accurate for all uses, those with values between 5-15% should be used with caution, and samples that have values above 15% should be investigated (Younger, 2007). The CAB is expressed as (ions expressed in Meq/L):

$$CAB\ (\%) = \frac{(\sum cations - \sum anions)}{(\sum cations + \sum anions)} * 100 \qquad \textbf{Equation 2}$$

This was applied to all the hydrochemical data obtained from the laboratory analyses. Stable isotope (Deuterium and Oxygen-18) analysis were performed at the University of the Western Cape’s isotopes laboratory. All samples were normalised to internal laboratory water standards that were previously calibrated relative to the Vienna Standard Mean Ocean Water (VSMOW).

4.6 Research integrity

The ethical considerations for the study were to improve and maintain well-working relations with the organisations involved in the project. The organisations involved include the South African

National Parks (SANParks) and the Department of Water and Sanitation (DWS). The Singapore statement (2010) was used as a guide. According to the Singapore statement on research integrity, the four principles to be considered in research include the following four ethics: 1. Honesty in all aspects of research, 2. Accountability in the conduct of research, 3. Professional courtesy and fairness in working with others, and 4. Good stewardship of research on behalf of others. Prior to commencement of the project, a permit to conduct research at the Tankwa-Karoo National Park was requested through SANParks and the full permission to access the study sites was granted in writing. The sources of secondary data were acknowledged throughout the thesis. The study did not cause any harm to the environment or certain individuals during the sampling rounds. Implications of the data collected were disclosed to all the organisations involved in the study.

Permission to access existing Department of Water and Sanitation (DWS) monitoring boreholes and secondary data was obtained through a verbal agreement between the Department of Earth Science at the University of the Western Cape and the Department of Water and Sanitation. The permission to use data from the South African Weather Services (SAWS) was obtained through a disclosure agreement between the researcher and SAWS (Appendix C).

4.7 Limitations of the study

The limitations of the study include a lack of previous studies in the study area on a similar topic to that being investigated. However, the Department of Water and Sanitation has established a groundwater monitoring network in the study area thus their secondary data were used as a point reference. Another limitation was that the Rivers in the TKNP are un-gauged and thus historical river flow data are unavailable. Ideally, it was preferred that there are historical river flow data available where inference could be made about the previous periods the rivers were in flow. There were limited surface water sampling sites due to low rainfalls in the study area. To overcome this, The Oudebaaskraal Dam was used as a sampling site along the Tankwa River. Boreholes in the area are sparse and some are in remote areas. To overcome this challenge, accessible boreholes along the Tankwa River and the Renoster River were used in the study. Furthermore, some historical data on the aquifer system such as recharge rates, hydraulic conductivities and detailed geological information were unavailable thus these were generalised from previous studies in the Karoo and additional monitoring boreholes were drilled in the study area.

Chapter 5 : Results and discussion

5.1 Introduction

The current chapter presents and discusses the results obtained for the three objectives of the study. The first objective was to establish the groundwater contribution to the river system, the second to investigate the role of the river in recharging the underlying aquifer, and the third to develop a regional hydrogeological conceptual model of recharge mechanisms. The intention was to identify where and when do river-aquifer interactions occur in the study area to understand river-aquifer interactions in non-perennial river settings. The interaction was assessed using hydrochemical and stable environmental isotope analysis. The chapter argues that unless we assess the interaction between groundwater and surface water in NPRS, we cannot improve our understanding of the role of groundwater on the NPRS. Therefore, the question that was posed is what is the influence of river-aquifer interactions in non-perennial river systems in the semi-arid environment?

5.2 Results on assessing interaction using hydrochemistry

The chemical water types were classified based on their relative positions on the piper diagram (Piper, 1944). The piper diagram graphically illustrates the concentrations of individual samples plotted as percentages of the total cation and anions such that the samples with different ionic concentrations can occupy the same position on the diagram. The variation in groundwater quality in an area generally reflects the sources of the chemical constituents, such as rock-water interactions (geological formations) and/ or anthropogenic influence (Freeze and Cherry 1979). Varieties of chemical reactions occur between groundwater and host rocks during the water's movement along flow paths from the point of recharge to discharge areas. The reactions result in different concentrations of the groundwater constituents, which can be used to infer the intensity of the interaction and the chemical reactions that occurred.

5.2.1 Key results on hydrochemical analysis

The key results that were obtained from the hydrochemical analysis of groundwater and surface water samples in the study area are included in this section. The first set of the groundwater hydrochemical data (2015 November, 2016 May and 2017 May) were obtained from the Department of Water and Sanitation (DWS). Before being used in the analysis, the data were first subjected to cation-anion balance calculations to ensure the reliability of the analysis. Cation-anion balance values less than ±15 % were treated as acceptable for the analysis and samples greater than ±15 % were not included in the analysis as discussed in section 4.5. Table 5-1 presents a summary of the results obtained from the cation-anion balance calculations. Appendix A contains the hydrochemical results used in the study. Most of the samples obtained from DWS were acceptable for the analysis, except for a few samples that were not included in the interpretation. Hydrochemical analysis for the collected 2017 November and 2018 May water samples was performed at the Department of Agriculture's Elsenburg laboratory. Some of the samples that had high CAB values had high bicarbonate values suggesting possible errors in sample titration or laboratory analysis despite following the standard methods of analysis.

Table 5-1: The cation-anion balance error (CBE) results for each of the sampling trips.

	Type	2015 May		2015 November		2016 May		2017 May		2017 November		2018 May	
Site ID		**CBE (%)**	**<±15%**	**CBE (%)**	**<±15%**	**CBE (%)**	**<±15%**	**CBE (%)**	**<±15%**	**CBE (%)**	**<±15%**	**CBE (%)**	**<±15%**
OD01271	Borehole	2.2	Yes	5.3	Yes			3.3	Yes	-18.2	No		
OD01254	Borehole	4.8	Yes	3.1	Yes	4.9	Yes	2.6	Yes	-3.7	Yes		
OD01252	Borehole	-0.5	Yes	2.9	Yes	8.2	Yes	0.3	Yes	-14.8	Yes	-3.4	Yes
OD01209	Borehole	-2.7	Yes	-4.7	Yes	1.0	Yes	-1.5	Yes	-9.0	Yes	-2.3	Yes
OD01207	Borehole	4.5	Yes	0.7	Yes	1.2	Yes	3.2	Yes			2.3	Yes
OD01205	Borehole	4.5	Yes	-0.5	Yes	0.0	Yes	-1.0	Yes	-14.3	Yes		
OD01183	Borehole	6.1	Yes	3.3	Yes	2.6	Yes	-0.4	Yes	-14.3	Yes		
OD01166	Borehole	-0.8	Yes	-3.1	Yes	0.9	Yes	4.4	Yes	-33.4	No		
OD01138	Borehole	-4.5	Yes	-1.3	Yes	5.9	Yes	3.0	Yes	-5.4	Yes	2.2	Yes
OD01120	Borehole	-0.6	Yes	-0.6	Yes	10.4	Yes	4.3	Yes	0.3	Yes	2.0	Yes
OD012140	Borehole	3.1	Yes	0.7	Yes	4.6	Yes	0.1	Yes				
OD01224	Borehole	4.7	Yes	1.2	Yes	1.1	Yes	0.6	Yes				
OD01262	Borehole	-1.5	Yes	2.4	Yes	3.4	Yes					-0.5	Yes
OD01155	Borehole	-1.2	Yes	2.5	Yes	-0.6	Yes			-3.2	Yes		Yes
ODO1147	Borehole	3.2	Yes	-2.9	Yes	2.2	Yes			-9.5	Yes	-1.0	Yes
OD01107	Borehole	-0.5	Yes	-2.0	Yes	5.0	Yes			-36.7	No	-6.3	Yes
OD01106	Borehole	-0.1	Yes	-0.2	Yes	1.2	Yes						
OD01213	Borehole	5.4	Yes	1.2	Yes	3.8	Yes					1.7	Yes
OD01243	Borehole	-1.0	Yes	2.3	Yes	0.3	Yes			-10.6	Yes		
OD01135	Borehole	6.9	Yes			2.5	Yes	2.7	Yes	-9.0	Yes		
OD01276	Borehole	1.0	Yes										
OD01257	Borehole					-3.1	Yes			1.5	Yes		
OD01192	Borehole			-2.9	Yes	5.2	Yes	3.0	Yes	-12.1	Yes	-3.2	Yes
OD01163	Borehole			0.7	Yes	1.5	Yes	-3.6	Yes	-22.9	No		
OD01291	Borehole			0.6	Yes	10.7	Yes	-4.8	Yes				
OD01110	Borehole			3.4	Yes	4.4	Yes						
OD01268	Borehole			1.5	Yes			-0.4	Yes	-8.0	Yes	1.0	Yes
OD01257	Borehole			-3.6	Yes	-3.1	Yes	-0.4	Yes			4.1	Yes
OD01240	Borehole											0.3	Yes
Soek-op BH	Borehole											-3.6	Yes
OD01156	Spring/Eye	-7.6	Yes	3.5	Yes	3.0	Yes	-19.7	No	-23.6	No		
OD01178	Spring/Eye	0.8	Yes					3.9	Yes	-24.3	No	15.2	Yes
OD01249	Spring/Eye	-67.6	No					-2.0	Yes			-14.3	Yes
OD01215	Spring/Eye	10.8	Yes					3.4	Yes	-18.0	No	5.4	Yes
OD01248	Spring/Eye	-0.9	Yes							-7.1	Yes	-27.6	No
OD01260	Spring/Eye							2.9	Yes	16.5	No	31.7	No
Soek-op spring	Spring/Eye											7.3	Yes
Volmoersfontein	Spring/Eye											-4.6	Yes
T-Dam	Dam									-13.4	Yes	-1.6	Yes

Figure 5-1 illustrates Piper diagrams generated using dry summer season hydrochemical results. The piper diagrams were generated using AquaChem® software. A total number of 26 samples were plotted for the November 2015 summer season, except for one sample that had a high cation-anion balance error (CBE) percentage. A total number of 16 samples were plotted for the November 2017 summer season, and 8 samples were excluded from analysis due to high CBE percentages.

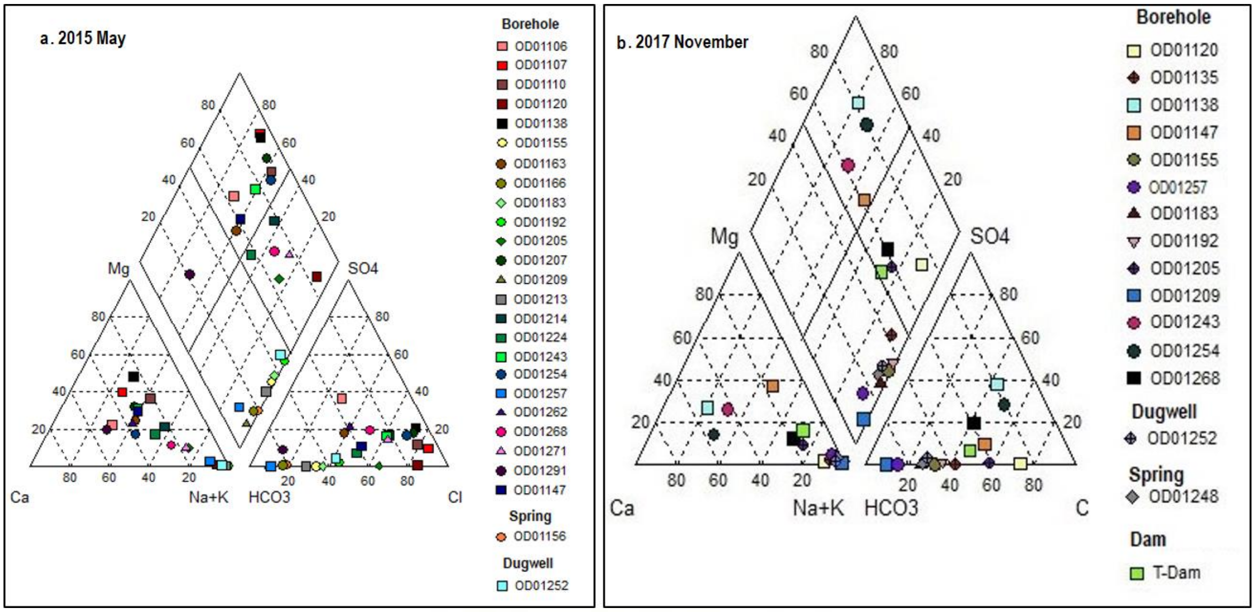


Figure 5-1: Water types in the TKNP during the summer season of November 2015 (a) and November 2017 (b)

Based on the major cations and anions, four water types were identified in the study area during the summer seasons of 2015 and 2017 (Figure 5-1). The samples on the right quadrant of the piper diagrams plot as Na-Cl dominant water type, typical of marine and ancient groundwater (Younger, 2007). The Na-Cl signature of the groundwater was not expected, considering the distance of the study area from the coast, seawater intrusion is not possible. However, considering the geology of the study area, which consists of mainly shale rocks as discussed in section 2.2.5, the Na-Cl water types were possible derived from weathering of the geologic material (rock-water interaction) and/or salinisation processes.

Sample T-Dam, from the Oudebaaskraal Dam, was the only surface water point available during the summer season as expected, figure 5-1 (b), due to low or no rainfall during the period. The sample water type was Na-Cl as expected. This is because evaporation effects concentrate salts in open surface water bodies. Table 5-2 illustrates the samples that were characterised as Na-Cl water type in the study area and their locations. Most of the Na-Cl water types consisted of samples located on the lower lying areas (flats) and some on the foothills of the escarpment, as expected. Na-Cl water types generally occur in discharge and static zones,lower lying areas, (Adams et.al, 2001).A sample obtained from Meintjiesplaas on the escarpment (OD01224) on November 2015 was characterised as Na-Cl and this was unexpected. The salinity in some groundwater samples in the higher lying areas of the TKNP could be attributed to nearby runoff dams and concrete reservoirs, which possess highly evaporated water, which then leaks into the groundwater system (Van Niekerk and Dyason, 2017).

Table 5-2: Samples that were characterised as Na-Cl water type in the study area and their locations (2015 and 2017 November).

Water type	Site	Location	Sample	2015	2017
Na-Cl	De Syfer	Foothill	OD01120	x	x
	Perdekloof	Foothill	OD01205	x	
	Ymasqua	Flats	OD01271	x	
	Waaikop	Flats	OD01268	x	x
	Meintjiesplaas	Escarpment	OD01224	x	
	Potklysberg	Flats	OD01214	x	
	Driefontein	Flats	OD01135		x
	Oudebaaskraal	Flats	T-Dam		x

Some of the borehole samples, including all the springs and dug well tend to yield a similar chemical signature of Na-HCO_3 water type as they plot along a line and cluster on the bottom quadrant of the Piper diagrams (figure 5-1a and b). This provides an indication of a possible interaction and or mixing. The Na-HCO_3 character of the water is typical of deeper groundwater influenced by ion exchange (Younger, 2007). Silicate weathering also contributes considerable amounts of HCO_3 into groundwater systems in the Karoo (Woodford and Chevallier, 2002). Furthermore, springs in the TKNP tend to have high sodium contents due to dissolution processes associated with the springs discharging along dolerite sheets and contacts between the geological formations (Niekerk and Dyason, 2017).

Table 5-3 displays the samples that were characterised as a Na-HCO_3 water type. Most samples with the water type are located on the flats of the TKNP and two samples were located on the foothills of the escarpment.

Table 5-3: Na-HCO_3 water types locations in the study area (2015 and 2017 November).

Water type	Site	Location	Sample	2015	2017
Na-HCO_3	Varsfontein	Flats	OD01257	x	x
	Platfontein	Flats	OD01209	x	x
	Luiperdskop	Flats	OD01166	x	
	Jakkalsfontein	Flats	OD01156	x	
	Potklysberg	Flats	OD01213	x	
	Jakkalsfontein	Foothill	OD01155	x	x
	Muskietkolk	Flats	OD01183	x	x
	Oudebaaskraal	Flats	OD01192	x	x
	Uintjiesbos	Flats	OD01252	x	x
	Springbokvlakte	Flats	OD01248		x
	Perdekloof	Foothill	OD01205		x
	Oudebaaskraal	Flats	T-Dam		x

The groundwater sample OD01291 on the left quadrant of the piper diagram in figure 5-1 (a) plot as Ca-HCO_3 water type that is typical of shallow fresh groundwater with temporary hardness in recharge areas, marked with a higher dominance of Ca and HCO_3. During recharge into a groundwater system, water interacts with carbonate minerals, which results in high Ca^{2+}, Mg^{2+}, and HCO_3^- and this is usually the first process that occurs during the recharge into an aquifer (Gomo *et.al.*, 2013). The sample with the Ca-HCO_3 water type is located on the escarpment, as expected, because Ca-HCO_3 water types generally occur in topographically higher areas, where there is active diffuse recharge (Table 5-4).

Table 5-4: Ca-HCO_3 water type location in the study area (2015 November).

Water type	Site	Location	Sample	2015	2017
Ca-HCO_3	Uitkyk	Escarpment	OD01291	x	

The groundwater samples on the top quadrant of the piper diagrams for the dry seasons (figure 5-1) plot as Ca-SO_4 water type, which is typical of gypsum-bearing sedimentary aquifers (Younger, 2007). The Ca-SO_4 character of the samples was expected, given that gypsum deposits have been reported to occur in the western Karoo region (Adams *et.al.*, 2001; Woodford and Chevallier, 2002).

Table 5-5 illustrates the Ca-SO_4 water types in the study area. All of these are located on the foothills of the escarpments, except samples OD01107 on the escarpment and OD01254 on the lower lying, flat areas of the study area. The Ca-SO_4 water types on the escarpment and foothills of the escarpment were expected, because gypsum dissolution through Ca-HCO_3 water in the recharge zones (escarpment) result in Ca-SO_4 waters (Adams *et.al*, 2001).

Table 5-5: Ca-SO_4 water type location in the study area (2015 and 2017 November).

Water type	**Site**	**Location**	**Sample**	**2015**	**2017**
Ca-SO_4	Langkloof Camp	Foothill	OD01163	x	
	Gannaga (Outspan)	Foothill	OD01147	x	x
	Agterkop	Foothill	OD01106	x	
	Rooiwerf (Kattendoorn)	Foothill	OD01243	x	x
	Uintjiesbos	Flats	OD01254	x	x
	De Syfer	Foothill	OD01120	x	
	Elandsberg	Foothill	OD01138	x	x
	Agterkop (Gannaga Lodge)	Escarpment	OD01107	x	

Figure 5-2 (a) to (d) are Piper diagrams generated using winter season hydrochemical results. A total number of 25 samples were included for the May 2015 winter season, except for one sample due to a high CBE percentage (Table 5-1). All 26 groundwater samples for the 2016 May winter season had low CBE values and were included in the analysis. A total number of 22 samples collected for 2017 May had low CBE values, except one sample that was not included in the analysis. A total number of 21 samples for May 2018 were included in the analysis and two samples were excluded due to high CBE values.

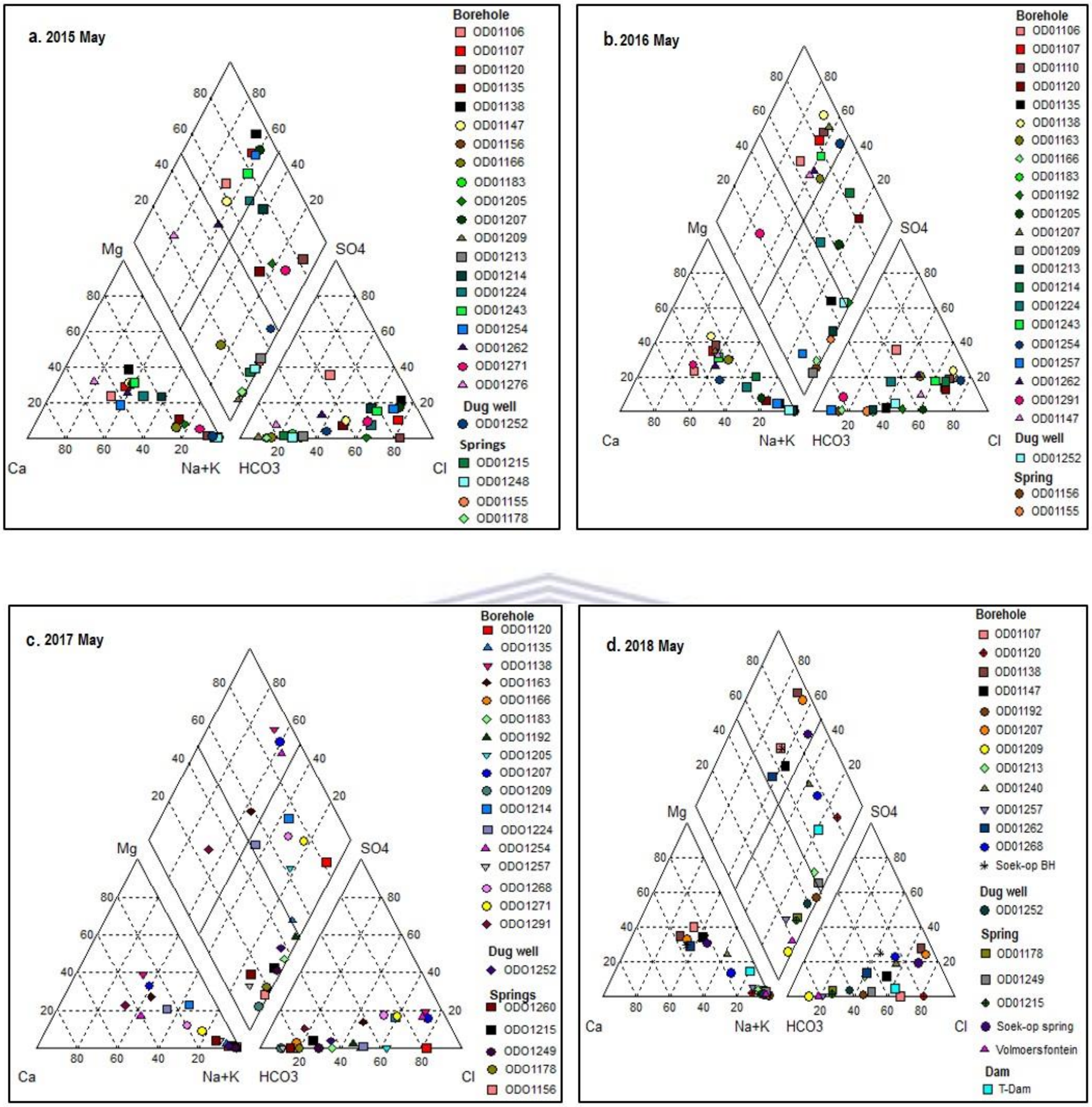


Figure 5-2: Water Types in the TKNP during the winter seasons of 2015 (a), 2016 (b), 2017 (a) and 2018 May (d).

The results obtained from the winter seasons showed similarities with the results obtained in the summer seasons. Based on the major cations and anions, four water types were identified in the study area during the winter seasons of 2015, 2016, 2017 and 2018 May. These were Na-Cl, Na-HCO_3, Ca-HCO_3, and Ca-SO_4 water types. Table 5-6 displays the samples with the Na-Cl water type. Most of the samples are located on the flat, lower lying areas of the TKNP and some on the foothills of the escarpment. The Na-Cl character of the water on the flats and foothills during the period is possible derived from weathering of geologic material and/or salinisation processes. The surface water sample (T-Dam) Na-Cl character is the result of long-term evaporation processes.

Table 5-6: Na-Cl water type locations in the study area (2015, 2016, 2017 and 2018 May).

Water type	**Site**	**Location**	**Sample**	**2015**	**2016**	**2017**	**2018**
Na-Cl	Uintjiesbos	Flats	OD01254	x	x	x	
	Driefontein	Flats	OD01135	x		x	
	Perdekloof	Foothill	OD01205	x	x	x	
	Ymasqua	Flats	OD01271	x		x	
	De Syfer	Foothill	OD01120	x	x	x	x
	Potklysberg	Flats	OD01214	x	x	x	
	Waaikop	Flats	OD01268			x	x
	Rooiwerf	Flats	OD01240				x
	Oudebaaskraal	Flats	T-Dam				x

From figure 5-2, some of the borehole samples, including all the springs and a dug well consistently yield a similar chemical signature of Na-HCO_3 water types as they plot along a line and cluster on the bottom quadrant of the diagrams. Table 5-7 illustrates the Na-HCO_3 water types in the study area. These are mostly located on the flat, lower lying areas of the study area and some on the foothills. The Na-HCO_3 water type is typical of deep groundwater, influenced by ion exchange processes.

Ion exchange is one of the most important processes contributing to groundwater chemistry in semi-arid environments. The favourable conditions for ionic exchange are a recharged source of groundwater with high concentrations of Ca and the presence of minerals with both high cation exchange capacity and Na on their exchange sites (Kumar and James, 2016). The replacement of calcium (Ca) in $Ca(HCO_3)_2$ waters by sodium (Na) through cation exchange result in the formation of $Na(HCO_3)_2$ water types (Adams *et.al*, 2001).

Table 5-7: Na-HCO_3 water type locations in the study area (2015, 2016, 2017 and 2018 May).

Water type	**Site**	**Location**	**Sample**	**2015**	**2016**	**2017**	**2018**
Na-HCO_3	Luiperdskop	Flats	OD01166	x	x		
	Platfontein	Flats	OD01209	x	x	x	
	Mieriesfontein	Flats	OD01178	x		x	x
	Prambergfontein	Flats	OD01215	x		x	x
	Springbokvlakte	Flats	OD01248	x			
	Jakkalsfontein	Foothill	OD01155	x	x		
	Potklysberg	Flats	OD01213	x	x		x
	Uintjiesbos	Flats	OD01252	x	x	x	x
	Jakkalsfontein	Flats	OD01156		x	x	
	Driefontein	Flats	OD01135			x	
	Oudebaaskraal	Flats	OD01192		x	x	x
	Springbokvlakte	Flats	OD01249			x	x
	Varsfontein	Flats	OD01257		x	x	x
	Varsfontein	Flats	OD01260			x	
	Muskietkolk	Flats	OD01183			x	
	Langkloof Camp	Foothill	OD01163			x	
	Volmoersfontein	Flats	Volmoersfontein				x

Sample OD01291 was characterised as a Ca-HCO_3 water type along with OD01276 during the winter seasons of 2015, 2016 and 2017 May (figure 5-2). The Ca-HCO_3 generally indicates shallow recently recharged, fresh groundwater with temporary hardness. Table 5-8 displays the samples with the Ca-HCO_3 water type and their locations. The samples are located on the escarpment, as expected, which is the major recharge zone in the study area.

Table 5-8*:* Ca-HCO_3 water type locations in the study area (2015, 2016, 2017 and 2018 May).

Water type	**Site**	**Location**	**Sample**	**2015**	**2016**	**2017**	**2018**
Ca-HCO_3	Uitkyk	Escarpment	OD01291		x	x	
	Agterplaas	Escarpment	OD01276	x			

Ca-SO_4 water types, which are typical of gypsum-bearing sedimentary aquifers, were observed in some of the groundwater samples, including a spring located on the escarpment (figure 5.2d). This was expected, given that gypsum deposits occur in the western Karoo region (Adams *et al.*, 2001;

Woodford and Chevallier, 2002). Table 5-9 displays the location of these samples. Many of the samples are located on the foothills of the escarpment, and on the escarpment, with one sample (OD01254) located on the flats.

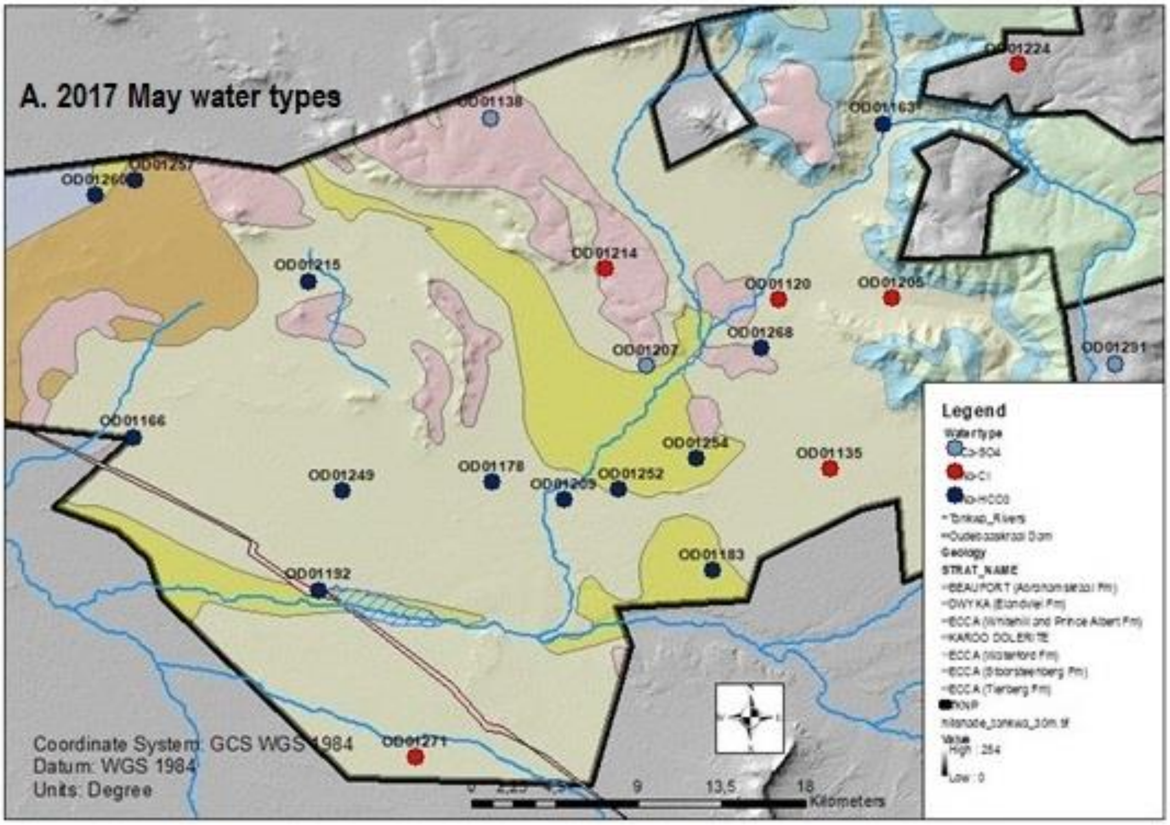
Table 5-9: $Ca-SO_4$ water type location in the study area (2015, 2016, 2017 and 2018 May).

Water type	**Site**	**Location**	**Sample**	**2015**	**2016**	**2017**	**2018**
$Ca-SO_4$	Gannaga (Outspan)	Foothill	OD01147	x	x		x
	Agterkop	Foothill	OD01106	x	x		
	Meintjiesplaas	Escarpment	OD01224	x			
	Voorsorg	Foothill	OD01262	x	x		x
	Rooiwerf (Kattendoorn)	Foothill	OD01243	x	x		
	Agterkop (Gannaga Lodge)	Escarpment	OD01107	x	x		x
	Uintjiesbos	Flats	OD01254	x	x	x	
	Paulshoek (Steenkampshoek)	Foothill	OD01205	x			
	Doringfontein	Foothill	OD01130	x			
	Langkloof (Camp)	Foothill	OD01163		x	x	
	Agterkop (Watervlei/Klipdam)	Escarpment	OD01110		x		
	Elandsberg	Foothill	OD01138		x	x	x
	Perdekraal (Perdekop)	Foothill	OD01207			x	x
	Soek-op	Escarpment	Soek-op BH				x
	Soek-op	Escarpment	Soek-op spring				x

- **Spatial distribution of the water types**

The spatial distribution of the different hydrochemical facies in the study area was generated using ArcMap™ 10.3 software. Figure 5-3 (a) and (b) illustrates the different hydrochemical facies of groundwater for May 2017 and November 2017, respectively. The $Ca-SO_4$ water type comprised of three boreholes (OD01291, OD01138 & OD01207) during the May 2017 winter season. Sample OD01291 was located on the escarpment whereas samples OD01138 and OD01207 were on the foothills of a dolerite outcrop. The locations of the $Ca-SO_4$ were expected given that gypsum dissolution through $Ca-HCO_3$ (in recharge areas) result in $Ca-SO_4$, as discussed in section 5.2.1. The Na-Cl water type was represented by six boreholes, which are situated the eastern side of the TKNP, on the lower lying areas (discharge zones), except for OD0171 on the south-western edge of the TKNP. Most of the samples (14) during the winter season represent Na-HCO_3 water type and these are mostly on the western parts of the TKNP.

During the November 2017 summer season, Ca-SO_4 was characterised in four boreholes on the middle portion of the TKNP and the Na-Cl water type by three boreholes on the eastern side of the park. Most of the summer samples (9) represent the Na-HCO_3 water type. The Ca-HCO_3 was not characterised in the winter and summer season samples obtained during 2017. The higher-lying areas of the TKNP (escarpment and foothills) were dominated by elements such as calcium, chloride, sodium, and sulphate, which correlates with direct or recent recharge mechanisms. Whereas the lower lying areas tend to display dominantly sodium and chloride elements, which correspond with groundwater discharge areas (Van Niekerk and Dyason, 2017). This suggests that the groundwater chemistry evolves as it travels from the recharge areas of the escarpment towards the discharge zones on the lower lying areas, as expected. A variety of chemical reactions occur between groundwater and host rocks during the water's movement along flow paths from the point of recharge to discharge areas (Freeze and Cherry 1979).



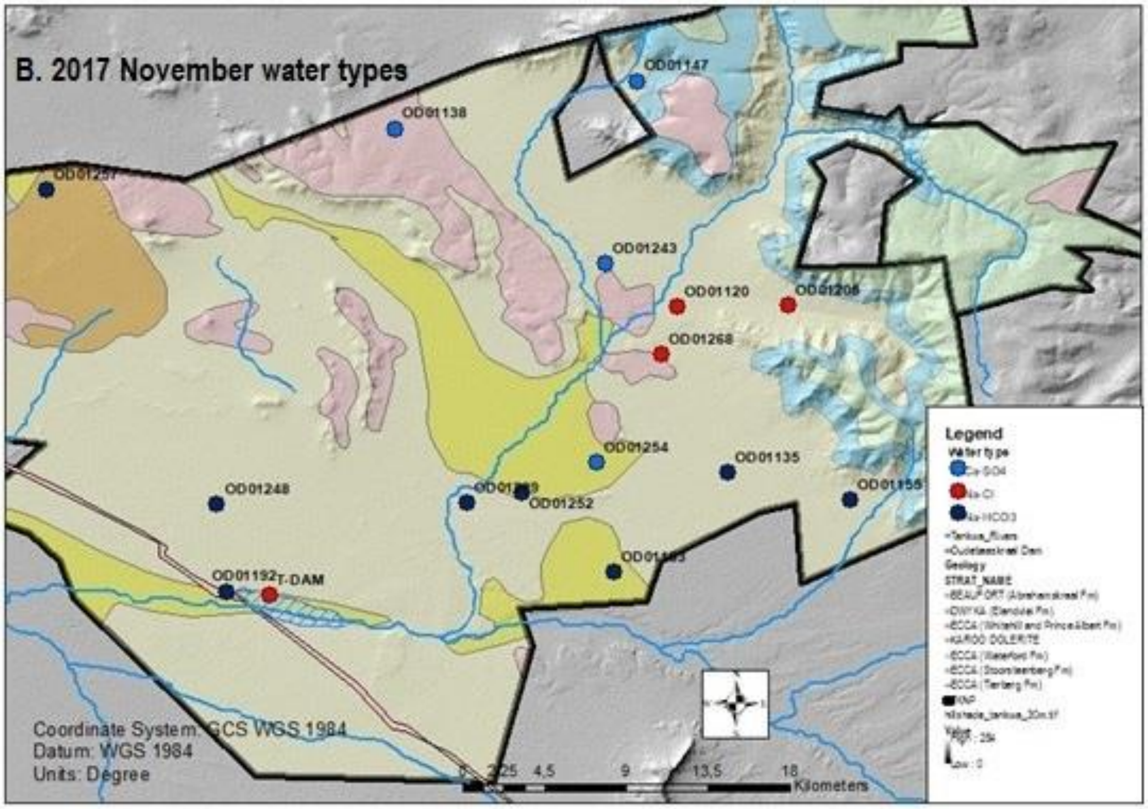


Figure 5-3: Spatial distribution of water types in the TKNP for 2017 May (a) and 2017 November (b).

- **Hydrogeochemical processes influencing the groundwater chemistry**

Younger (2007) explained that given the general low velocities of groundwater flow in the saturated zone, there is normally enough time for even relatively slow geochemical reactions to substantially alter groundwater chemistry through rock-water interactions. In semi-arid environments, the major hydrogeological processes influencing the chemistry of groundwater are usually precipitation, evaporation, and rock-water interactions (Sajil and James, 2016). To understand these complex hydrogeological processes, major ion chemistry and the local geology of the area have to be considered. Bivariate plots were used to identify the major geochemical processes influencing the groundwater chemistry in the study area.

The dissolution of halite is often considered as a source of both Na^+ and Cl^- in groundwater (Narany *et al.*, 2014). Sodium and chloride ions enter solution in equal quantities during the dissolution of halite, thus an approximately linear relationship (1:1 ratio) may be observed between the ions (Solomons, 2013). Therefore, Na-Cl relationships were used to determine the origin of salinity in groundwater. In the current study, most of the samples deviate from the 1:1 ratio line of Na^+ and

Cl^- (figure 5-4A). This indicates that there are some other processes involved in the release of sodium into groundwater. Groundwater salinity may also be related to the formation of salt layers by leaching from the soil surface during evaporation semi-arid environments (Narany *et.al*, 2014).

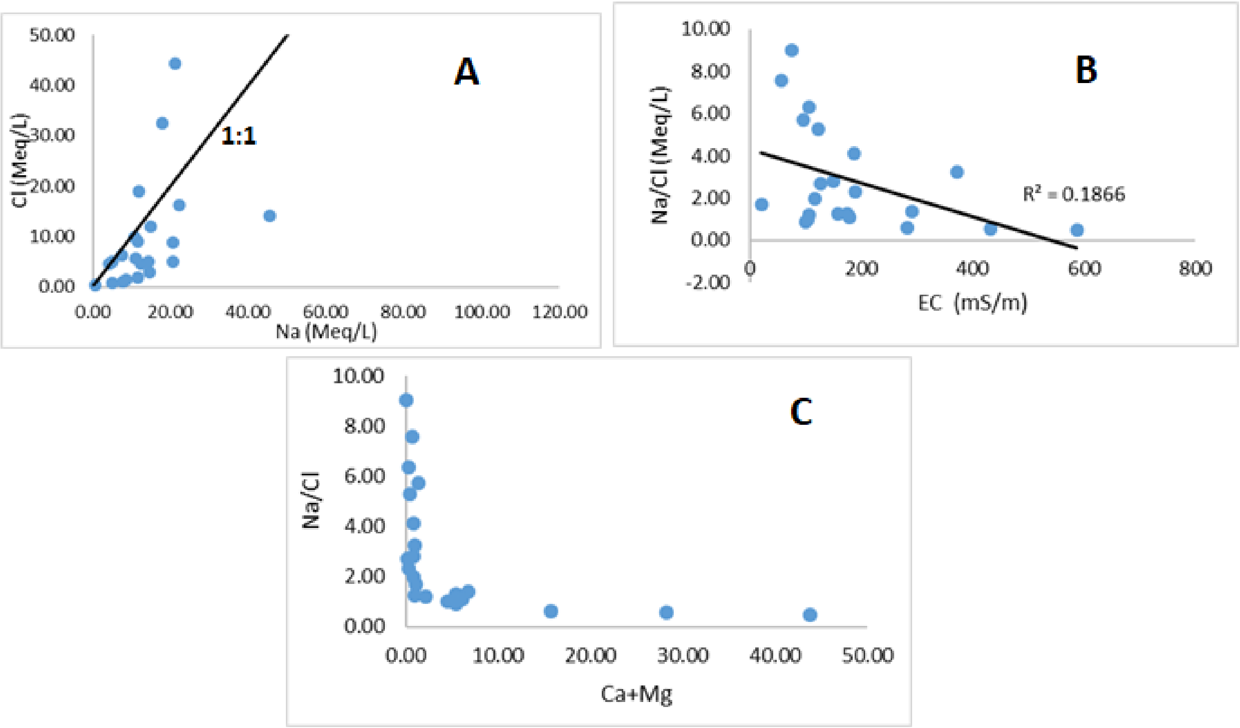


Figure 5-4: The relationship between Na and Cl (A), EC versus Na/Cl (B), and Ca + Mg versus Na/Cl (C)

Because the study area experiences a semi-arid climate, evaporation could be a major process on affecting the chemistry of groundwater and this is typical of semi-arid environment. Na/Cl ratio is one of the good indicators of the evaporation process in groundwater. Evaporation process results in an increase in the concentration of total dissolved salts (TDS) but the Na/Cl ratio remains the same (Sajil and James, 2016). Thus, the correlation between Na and Cl must be constant with an increase in EC. A plot of Na/Cl vs EC in figure 5-4B was used to further determine the origin of salinity in the study area. The Na/Cl vs EC plot shows a decreasing trend with increasing EC (R^2 = 0.186). This indicates that evaporation may not the major process in determining the groundwater chemistry in the study area, suggesting preferential pathways act as conduits for recharge.

The other possible cause of the Na^+ could be ion exchange or the dissolution of calcite (Solomons, 2013; Naranay *et.al*, 2014; Sajil and James, 2016). Furthermore, there exists a negative correlation between Na/Cl and Ca + Mg concentration (figure 5-4C). Therefore, this further indicates possible ion exchange processes (Kumar and James, 2016).

Naranay *et.al*, 2014 illustrated that a plot of Ca^{+} + Mg^{2+} vs HCO_3^{-} + SO_4^{2-} will be near a 1:1 line if Ca^{2+}, Mg^{2+}, $HCO_3^{-}$and SO_4^{2-} are derived from the dissolution of calcite, dolomite, and gypsum. If normal ion exchange is the dominant process, the plotted points must shift towards the HCO_3^{-} + SO_4^{2-} region due to excess HCO_3^{-} + SO_4^{2-}. Whereas if the reverse ion exchange is prominent, the shift is towards the Ca^{+} + Mg^{2+} region. The ion exchange reaction is explained as follows (Sajil and James, 2016):

$$2Na^{+} + Ca^{2+}\,(Mg) - Clay = Na^{+} - Clay + Ca^{2+} + Mg^{2+}$$

In figure 5-5, most of the groundwater points plot on and below the mixing line, towards the HCO_3 + SO_4. Therefore, normal ion exchange is a prominent process influencing the groundwater chemistry in the study area (Sajil and James, 2016).

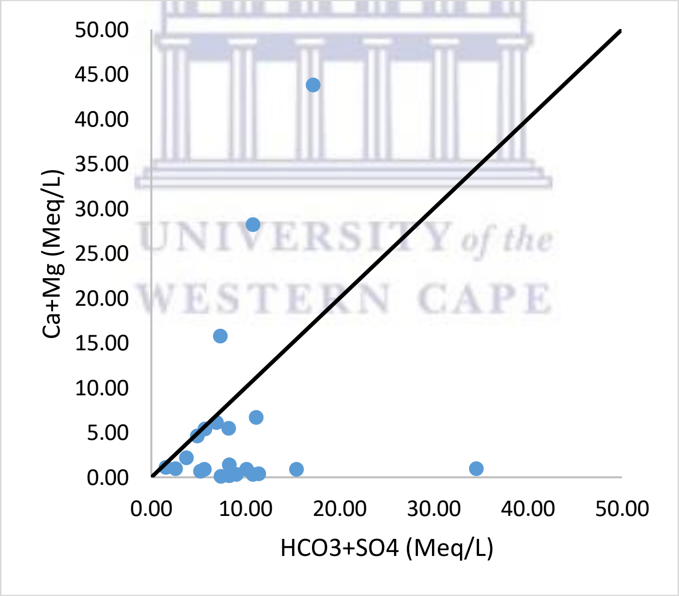


Figure 5-5: Relationship between HCO3 + SO4 versus Ca + Mg

The most important sources of Na and potassium in groundwater is the weathering of silicate minerals (Naranay *et.al*, 2014). Furthermore, the end-product of the weathering process can produce a range of materials consisting of mostly clay. The Na and Cl plot in figure 5-4 (A) show that most of the points shift towards sodium. This shows that Na ion concentrations are higher than Cl concentrations in the study area, which is often an indication of silicate weathering (Sajil and

James, 2016). Silicate weathering was confirmed by plotting Ca + Mg vs total cations. All samples plot towards the cations, which further confirms the prominence of Na and silicate weathering (figure 5-6).

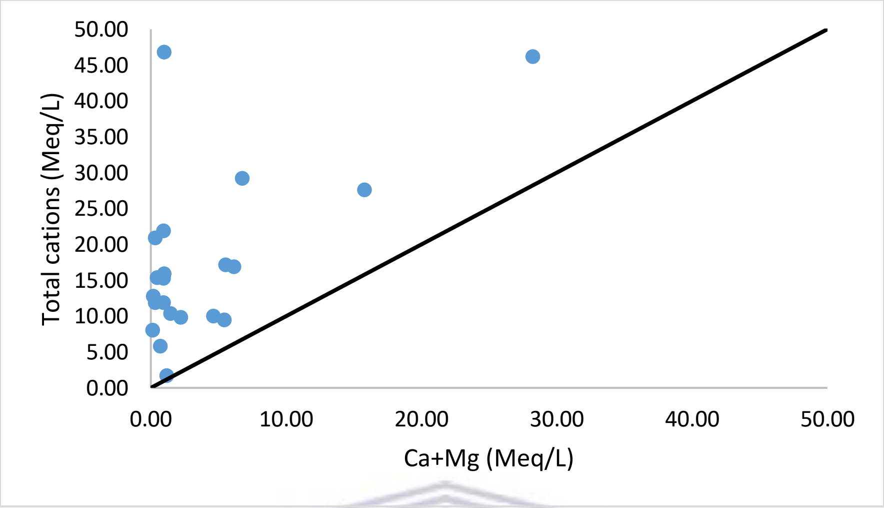


Figure 5-6: Relationship between Ca+Mg versus the sum of total cations

Most semi-arid environments experience the dissolution and deposition of reactive minerals. The common minerals that take part in these processes are calcite, dolomite, gypsum, and halite (Sajil and James, 2016). Among the four dissolution mechanisms, calcite dissolution is often the most common process, with a ratio of 1/2Ca: HCO_3. The calcite dissolution process is explained by the following equation:

$$H_2O + CO_2 + CaCO_3 = Ca^{2+} + 2HCO_3^-$$

The relationship between Ca and Mg with HCO_3 was plotted to study the dissolution of calcite and dolomite. HCO_3 showed a negative correlation with both Ca and Mg (figure 5-7A and B), with $R^2 = 0.067$ and $R^2 = 0.041$, respectively. A plot of Ca with Mg along a 1:1 ratio line showed that Mg dominates over Ca in some areas and Ca dominates in some areas. According to Jacks and Sharma (1995), if Ca/Mg = 1, there is a dissolution of dolomite. If the ratio is between 1 and 2, it represents the dissolution of calcite, whereas if it is greater than 2 it represents silicate weathering. In the current study, the dissolution of calcite and, or dolomite may be processes that occur because the points plot on the 1:1 line and some above the line (figure 5-7C), with $R^2 = 1$. Some samples are below the 1:1 line and this represent the dissolution of calcite in some areas (Bestland *et al.*, 2017).

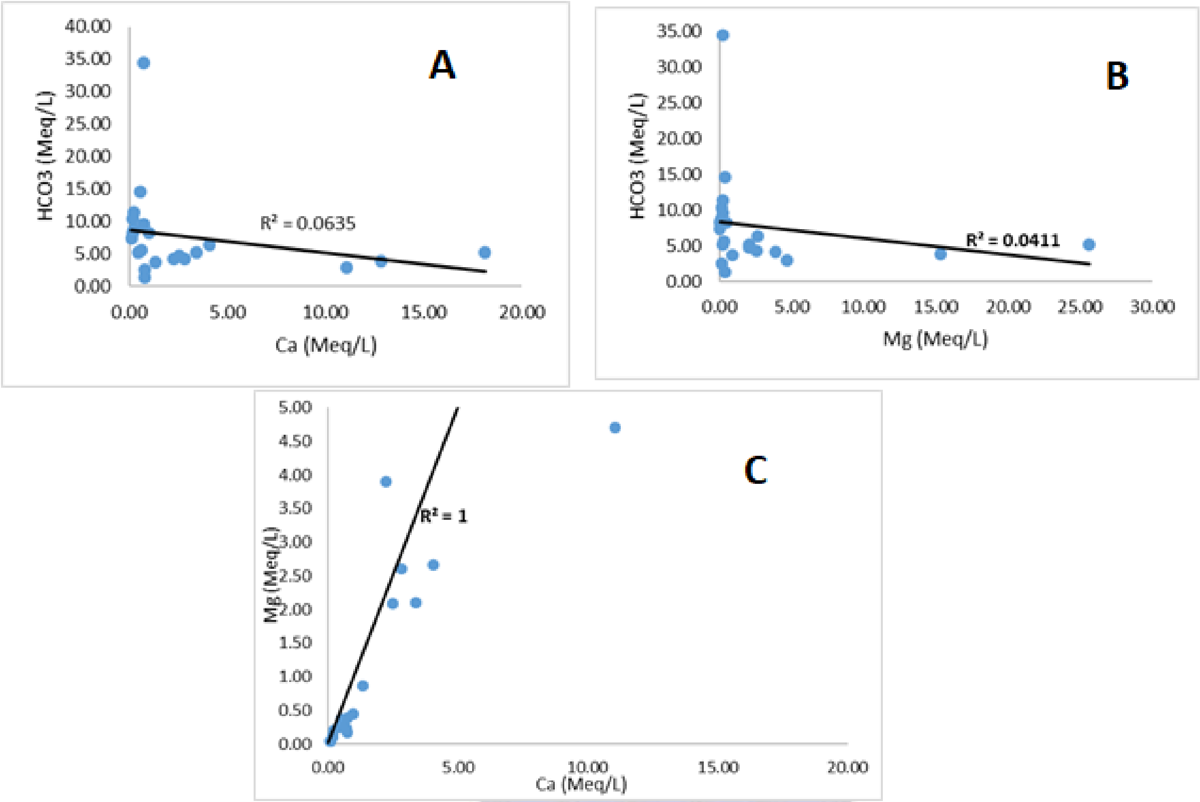


Figure 5-7: Relationship between Ca versus HCO3 (A), Mg versus HCO3 (B), and Ca versus Mg (C).

Solomons (2013) explained that the dissolution of gypsum is an important source for calcium and sulphate in groundwater. During the weathering process, equal amounts of Ca and SO_4 are added to groundwater. Therefore, a correlation diagram between Ca and SO_4 was plotted with a 1:1 ratio line to explain the sources of calcium and sulphate (figure 5-8). The diagram suggests that there is a good correlation between Ca and SO_4 in the study area. Most of the points plot on the equiline of the Ca and SO_4, with $R^2 = 1$. Therefore, this indicates that gypsum is one of the sources of calcium in the study area as expected. A few of the samples fall beneath the equiline due to excess Ca than SO_4, which indicates an additional geochemical process contributing to the excess Ca in solution.

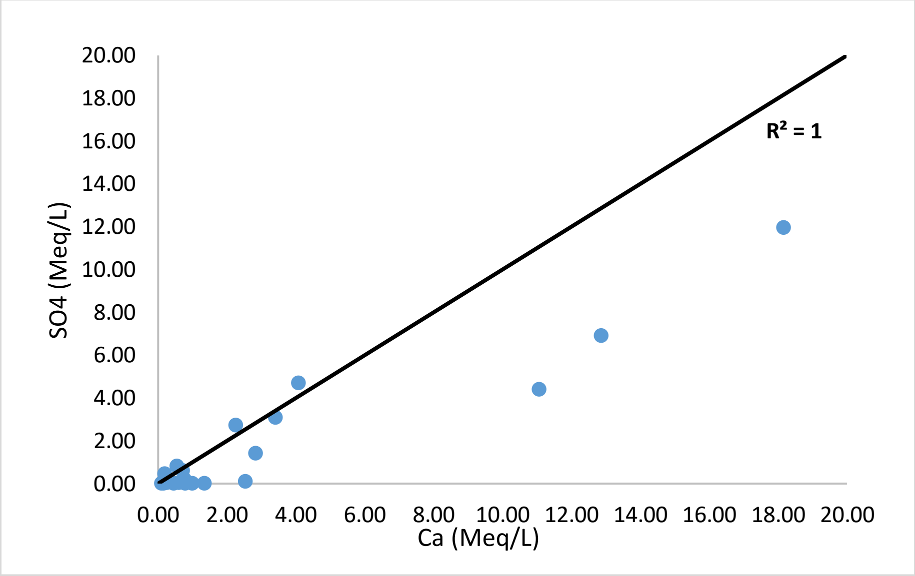


Figure 5-8: Relationship between Ca versus SO4

- **Statistical summary of groundwater physiochemical and hydrochemical parameters**

Table 5-10 presents the physical and chemical properties of the groundwater in the study area. The pH of water is an important parameter in that it contributes to the determination of the species, mobility, accumulation and toxicity of elements present in water (Laar, 2018). The results in Table 5-10 show that the pH of the groundwater samples in the study area is alkaline and ranges between 6.92 and 9.1. The typical range of pH values in most groundwater systems is 6.5 to 8.5 (Younger, 2007. Thus, the pH of the groundwater in the TKNP is slightly above this range. Electrical conductivity (EC), a measure of the total solids and ionised species in water, has a direct correlation with salinity. The variation of EC in groundwater systems is used to identify recharge areas and flow paths as EC increase according to the groundwater flow direction under natural conditions (Laar, 2018). The EC of groundwater in the study area ranges between 66 and 714.5 mS/m, with a mean of 228.77 mS/m.

Groundwater quality maps of the Karoo Basin by Murray *et.al,* (2012) have shown that the EC of the shallow groundwater throughout the Karoo Basin generally ranges between <70-370 mS/m. Figure 5-9 illustrate the spatial distribution of EC in the study area during the 2017 hydrological year. The EC progresses from low values of 70.2-145 mS/m in the higher lying areas of the escarpment to higher values in the range of 198- 647 mS/m. The low EC in the higher lying areas indicates direct recharge whereas the lower lying areas possibly experience much slower processes such as piston or displacement mechanisms (Van Niekerk and Dyason, 2017). The temperature of the groundwater in the study area ranges between 11.4 and 29.7◦C, with a mean of 21.5◦C (Table 5-10). The difference in temperature is a result of the variation in the sampling time of the day and seasonal variations of temperature. Sodium and calcium dominate the observed cations, with mean values of 242.29 and 45.87 mg/l, respectively. These ions represent 69.79% and 15.16% of the total cations, respectively whereas Mg^{2+} represents 13.78% and K^+ represents 1.27% of the total cations (Table 5-11). The dominant anions in the groundwater are chloride and bicarbonate, with mean values of 285.83 and 485.17 mg/L, respectively. These ions represent 46.17% and 45.69% of the total anions, respectively, while SO_4^{2-} represents 8.14% of the total anions (Table 5-12). The high standard deviations of the hydrochemical parameters, particularly HCO_3^-, Cl^- and Na^+ illustrates the heterogeneous nature of water in the TKNP and reveals the influence of different geochemical processes, as discussed in section 5.2.1.3 and 5.2.1.4. The abundance of cations and anions are in the order $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-}$, respectively.

Table 5-10: Statistical summary of the groundwater hydrochemical parameters for 2017.

Parameter	Minimum	Maximum	Mean	Std. deviation
Na^+ (mg/l)	28.65	754.00	242.29	152.26
K^+ (mg/l)	0.75	61.10	7.50	14.15
Ca^{2+} (mg/l)	1.13	312.85	45.87	77.44
Mg^{2+} (mg/l)	0.74	196.80	25.28	48.47
Cl^- (mg/l)	72.10	959.30	284.83	243.88
HCO_3^- (mg/l)	120.48	1760.52	485.17	350.82
SO_4^{2-} (mg/l)	0.80	543.00	68.03	127.79
pH	7.7	9.1	8.4	0.5
EC (mS/m)	66.00	714.50	228.77	168.70
Temp (◦C)	11.4	29.7	21.5	4.6

Table 5-11: Major cation mean concentrations percentages in groundwater (Meq/l) for 2017.

Cations	Na	K	Ca	Mg
% Mean	69.79	1.27	15.16	13.78

Table 5-12: Major anions mean concentrations percentages in groundwater (Meq/l) for 2017.

Anions	Cl^-	HCO_3^-	SO_4^{2-}
% Mean	46.17	45.69	8.14

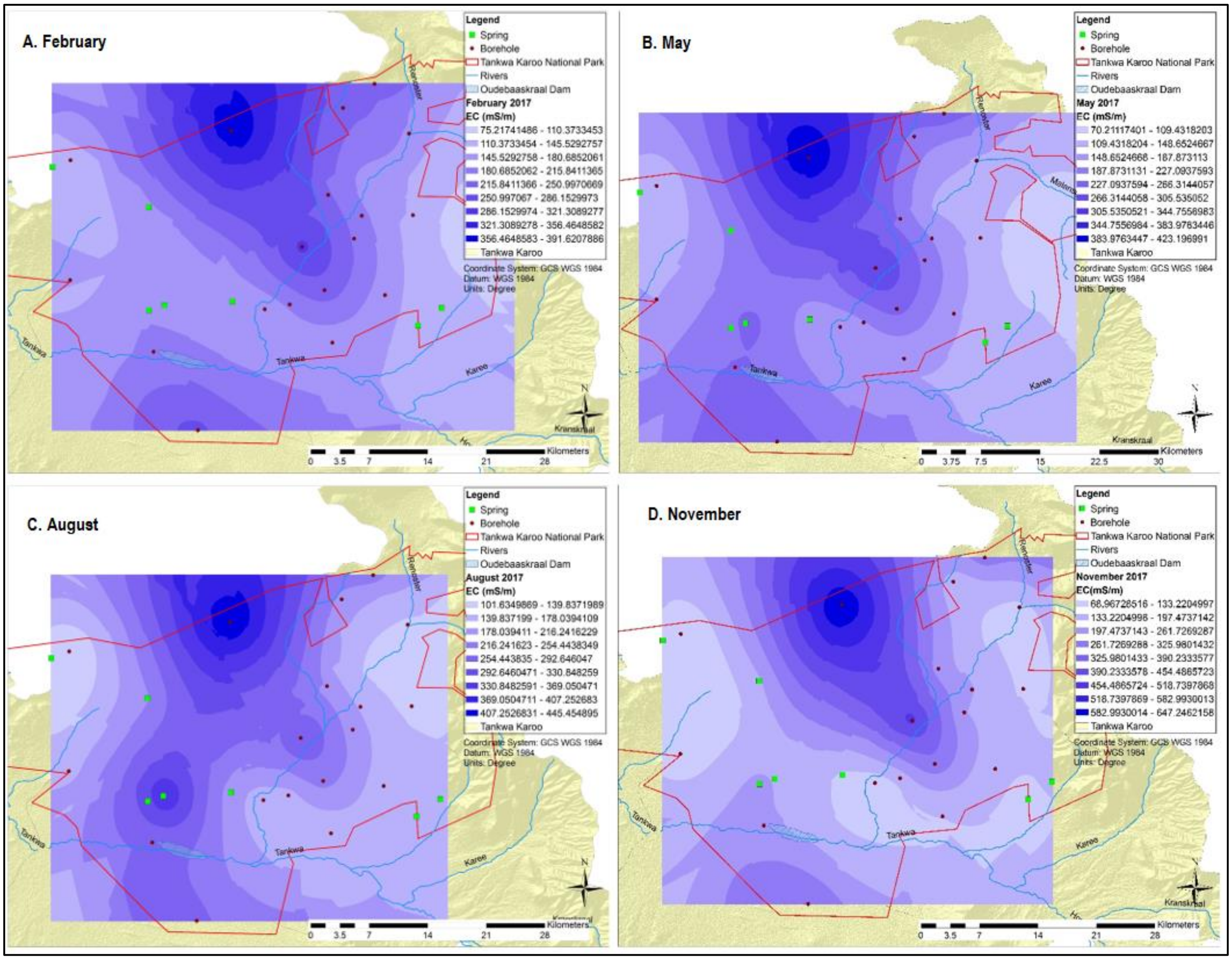


Figure 5-9: Spatial distribution of EC (mS/m) in the study area during 2017, February (A), May (B), August (C), November (D)

5.2.2 Discussion of results on assessing interaction using hydrochemistry

Section 5.2 presented the results on assessing river-aquifer interactions in the study area using hydrochemical analysis of water samples obtained from boreholes, springs, a dug well and surface water samples in dry and wet seasons. The conventional hydro-chemical classification system using Piper trilinear diagrams was used to determine the dominant water types. The intention was to establish similarities between groundwater and surface water resources.

The trilinear diagrams illustrated four groundwater types in the study area for both the dry and wet seasons: Ca-HCO_3, Ca-SO_4, Na-Cl, and Na-HCO_3. The predominant water type in the study area during the dry season was a Na-HCO_3 water type, which is typical if deeper groundwater, influenced by ion exchange (Younger, 2007). Most of the samples that were characterised as Na-HCO_3 water type was located on the lower lying, flat areas of the study area. Two of these were samples located on the foothills of the escarpment. According to Adams *et.al* (2001), Na-HCO_3 water type is water that is generally rich in Ca, Mg, Na, Cl, and SO_4. This water type is associated with the discharge areas of the study area as it was mainly on the lower lying area.

The Na-Cl water type, which is typical of marine and ancient groundwater (Younger, 2007), also dominated the dry season water types. However, considering the location of the study area and its distance from the ocean, seawater intrusions is not possible. As discussed in section 5.2.1, the Na-Cl water were possible derived from weathering of the geologic material (shale rock). Another possible source of salinity in groundwater are salinisation processes as seen in Adams *et.al,* (2001). Recharge events can flush salts into a groundwater system by means of preferential flow. The mechanisms by which salts are introduced into groundwater are: the concentration of dissolved salts by evapotranspiration near the soil surface during slow diffuse recharge, leaching of evaporate salt deposits by water percolating rapidly through preferential pathways, and the chemical dissolution of the aquifer material (Adams *et al.*, 2001; Adams *et.al.*, 2004; Younger 2007). Most samples with the water type were located on the lower lying flat areas of the TKNP as expected.

The results obtained are similar to those reported by Adams *et.al,* 2004, who reported that Na-Cl water types in typically occur in discharging and static regions, which are the lower lying areas in Sutherland (Adams *et.al,* 2004). The only surface water sample obtained in this period was from the Oudebaaskraal Dam (T-Dam), with a Na-Cl character as expected, due to long-term evaporation processes on the surface water.

Some groundwater samples were characterised as Ca-SO_4 water type, which is typical of gypsum-bearing sedimentary aquifers (Younger, 2007). This was expected given that gypsum deposits have been reported to occur on the western Karoo region, in the Tierberg Formation of the Ecca Group (Adams *et al.*, 2001; Woodford and Chevallier, 2002). The oxidation of in-situ pyrite and the reaction of sulphuric acid with carbonate under evaporative conditions were identified to be the processes that operate in the formation of gypsum deposits in the Karoo. Most of the samples with this water type were located on the foothills of the escarpment and some on the escarpment, with one sample located on the flats.

Ca-HCO_3 water type, which represents shallow, recently recharged, fresh groundwater was observed in only one sample during the dry season. The sample was obtained from Uitkyk (OD01291) on the escarpment. Direct recharge occurs on the escarpment, therefore, the Ca-HCO_3 character of the water was expected. Adams *et.al,* (2004), reported that Ca-HCO_3 water types typically occur in areas of recharge (generally topographically higher areas) on the western Karoo region. Adams *et.al,* (2001), reported that the process involved in the formation of the Ca-HCO_3 water type is the dissolution of calcite.

The results obtained from the winter seasons showed similarities with the results obtained in the summer seasons. The same water types, Ca-HCO_3, Ca-SO_4, Na-Cl, and Na-HCO_3 were observed in the TKNP. Some borehole samples, including all the springs on the flats and a dug well were characterised as Na-HCO_3 water type in the wet season. These were mostly located on the flat, lower lying areas on the study area and some on the foothills of the escarpment. Na-Cl water type was observed in samples located on the flat, lower lying areas of the TKNP and some on the foothills of the escarpment. The Na-Cl character of the water on the flats and foothills during the sampling period was possible as a result of rock-water interactions and salinisation processes during slow diffuse recharge as previously discussed. The surface water sample (T-Dam) Na-Cl character was the result of long-term evaporation processes.

The Ca-HCO_3 water type was observed in samples located on the escarpment, therefore further showing evidence that the escarpment is the major recharge area in the study area similar to the report by Mahed (2016) for the western Karoo region. Ca-SO_4 water types were observed in some of the groundwater samples, including a spring located on the escarpment. The majority of the samples with the water type are located on the foothills of the escarpment, and on the escarpment, with one sample located on the flats.

Bivariate plots of the major cations and anions revealed that evaporation is not a major process in determining the groundwater chemistry in the study area. This suggested the presence of preferential pathways that act as conduits for recharge, preventing or minimising evaporation. The major processes influencing the groundwater chemistry in the study area were identified to be ion exchange processes (normal ion exchange), the dissolution of calcite and gypsum, and silicate weathering. The abundance of cations and anions in groundwater were in the order $Na^+> Ca^{2+}> Mg^{2+}> K^+$ and $Cl^-> HCO_3^-> SO_4^{2-}$, respectively.

The hydrochemical results were similar to that reported by Adams *et.al* (2001). The authors undertook a research study to establish, interpret and map the chemical composition of groundwater in the semi-arid western Karoo, in Sutherland. The major processes that were found to influence the groundwater chemistry were salinisation, mineral precipitation: dissolution, cation exchange and human activities. In the current study, the evidence from the wet season in the discharge areas of the lower lying flat areas provided evidence that aquifers recharged rivers. However, there were limited surface water sampling points in the study area to conclusively state that rivers recharged aquifers. The only available surface water sample that could be obtained during the course of the study was from the Oudebaaskraal Dam.

5.3 Results on assessing interaction using stable environmental isotopes

In the current study, the differences in the content of δ^2H and $\delta^{18}O$ in selected boreholes, springs, rainfall, and surface water samples were used to infer river-aquifer interaction and to determine the recharge mechanisms in the study area. Appendix B contains the results of the isotopic analysis used in the study. The stable isotope data are expressed as per mil deviations from VSMOW standard. The data are shown together with the global meteoric water line (GMWL) of Craig (1961), $\delta^2H = 8\delta^{18}O +10$, and a local meteoric water line (LMWL) for the Western Cape as determined by Diamonds and Harris (1997). This provides information on processes that acted on the water as it travelled from precipitation to groundwater.

5.3.1 Key results on stable isotope analysis

This section presents the key results of stable environmental isotopes analysis of rainfall, groundwater and surface water samples in the study area. The samples were analysed for stable isotopic signatures (δ^{2}H and δ^{18}O) at the University of the Western Cape's stable isotopes laboratory. The results presented are for the dry summer and wet winter seasons in the study area. Figure 5-10 shows the results obtained from the isotopic analysis of rainfall, groundwater, and surface water samples collected during the dry summer season of November 2017. The rainfall samples had δ^{2}H ratios of -42.6 to -3.4 ‰ and δ^{18}O ratios of 6.7 to -0.8 ‰, with a mean of -23.0 and -3.7 ‰, respectively (Table 5-13).

Table 5-13: Statistical summary of rainfall samples in the TKNP (November 2017).

	δ^{18}O‰	**δ^{2}H‰**	**d-excess**
Min	-6.7	-42.6	2.7
Max	-0.8	-3.4	10.8
Mean	-3.7	-23.0	6.8

The collected groundwater samples had δ^{2}H ratios of -38.9 to -17.3 ‰ and δ^{18}O ratios of -6.6 to -0.4 ‰, with a mean of -29.7 and -4.6, respectively (Table 5-14). The stable isotopes composition of the groundwater were more negative, indicating that the samples were depleted. This was not expected during the dry season, because high temperature effects and high evaporation rates during summer generally result in enriched stable isotopes in water (Kendall and Coplen, 2001). The unexpected depleted groundwater samples during summer require further investigation. Most of the groundwater samples plot further down along the GMWL and were similar to the rainfall isotopic signature thus indicating recently recharged water of meteoric origin, with or without some evaporation taking place before infiltration.

Table 5-14: Statistical summary of groundwater samples in the TKNP (November 2017).

	δ^{18}O‰	**δ^{2}H‰**	**d-excess**
Min	-6.6	-38.9	-14.0
Max	-0.4	-17.3	14.4
Mean	-4.6	-29.7	7.3

The sampled springs in figure 5-10 had δ^2H ratios of -37.8 to -0.5 ‰ and δ^{18}O ratios of -6.5 to 1.2 ‰, with a mean of -19 and -2.2 ‰, respectively (Table 5-15). Most of the sampled springs had isotopic signatures similar to that of the groundwater in the study area as expected because springs represent groundwater discharge zones. However, springs sampled from three sites in the study area did not retain the isotopic signature of the groundwater. Figure 5-11 shows one of the springs that had not retained the isotopic signature of groundwater and the Oudebaaskraal Dam. Springs in the study area discharge in low volumes and concentrate in shallow ponds. Therefore, the springs are open water bodies subjected to evaporation, resulting in the enrichment of their stable isotopic signatures.

Table 5-15: Statistical summary of spring samples in the TKNP (April 2018).

	δ^2H‰	**δ^{18}O‰**	**d-excess**
Min	-6.5	-37.8	-15.0
Max	1.2	-0.5	15.7
Mean	-2.2	-19.0	-1.6

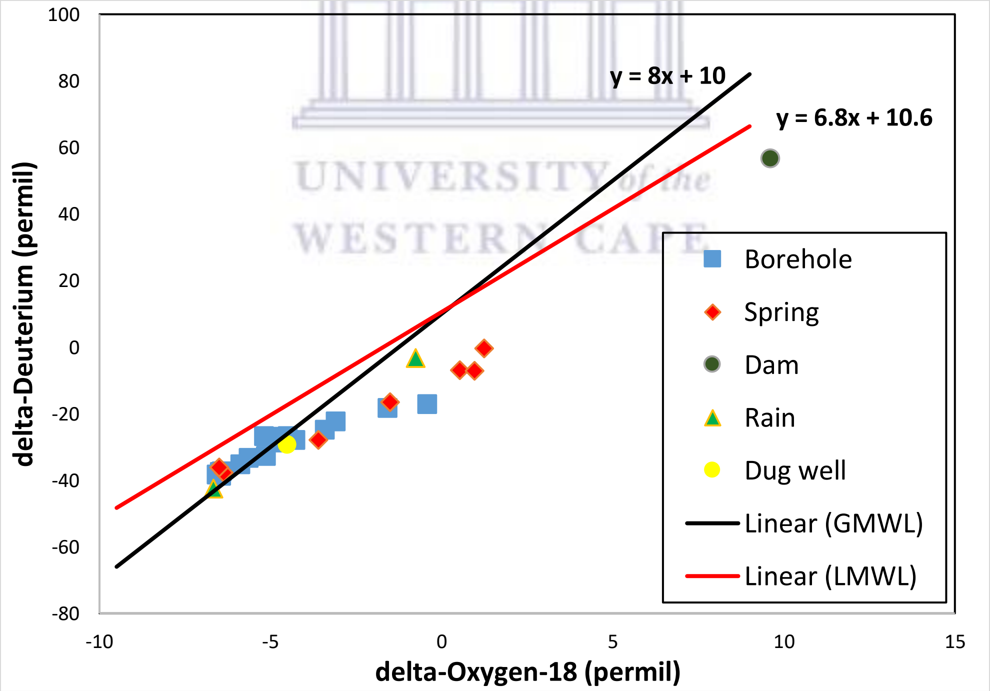


Figure 5-10: Deuterium and oxygen-18 contents of rainfall, groundwater, springs, and surface water in the TKNP, compared to the GMWL and LMWL (November 2017).

Figure 5-11: A spring containing stagnant water (left). The Oudebaaskraal Dam (right). November 2017.

The surface water sample obtained from the Oudebaaskraal Dam plots further away from the GMWL with a δ^{2}H value of 56.4 and δ^{18}O of 9.63 ‰ thus it was enriched as expected, due to the high temperatures that are experienced in the study area during the dry, summer season. Water that has evaporated from open surfaces or mixed with evaporated water generally plots below the meteoric water line (Kendall and Coplen, 2001).

Figure 5-12 shows the stable isotopes results obtained from three cumulative rainfall samplers, a borehole (OD01107) from the escarpment, a spring and surface water (river and dam) in the study area. These were collected in April 2018, immediately after a rainfall event. A section of the Renoster River had flowing water during the period (figure 5-13). Another surface water sample obtained in this period was at the Soek-op Dam, which is located on the Roggeveld escarpment. The rainfall samples had δ^{2}H ratios of -45.4 to -40 ‰ and δ^{18}O ratios of 6.8 to -5.8 ‰, with a mean of -41.8 and -6.4 ‰, respectively (Table 5-16).

Table 5-16: Statistical summary of rainfall samples in the TKNP (April 2018).

	δ^{18}O‰	**δ^{2}H‰**	**d-excess**
Min	-6.8	-45.4	6.4
Max	-5.8	-40.0	14.5
Mean	-6.4	-41.8	9.6

From figure 5-14, it is evident that the stable isotopes composition of the Renoster River and Soek-op Dam had similar stable isotopic signatures to that of nearby rainfall stations. This suggests that streamflow in the Renoster River was generated from surface runoff as rainfall δ^2H and δ^{18}O values are similar to the streamflow. This was expected because of the non-perennial nature of the river as it only flows in response to an input of significant rainfall events. All the samples obtained in the period were more negative and plot further down the GMWL, thus evaporation was not a significant process in this period. This indicated that the source of water in all the samples collected was of meteoric origin.

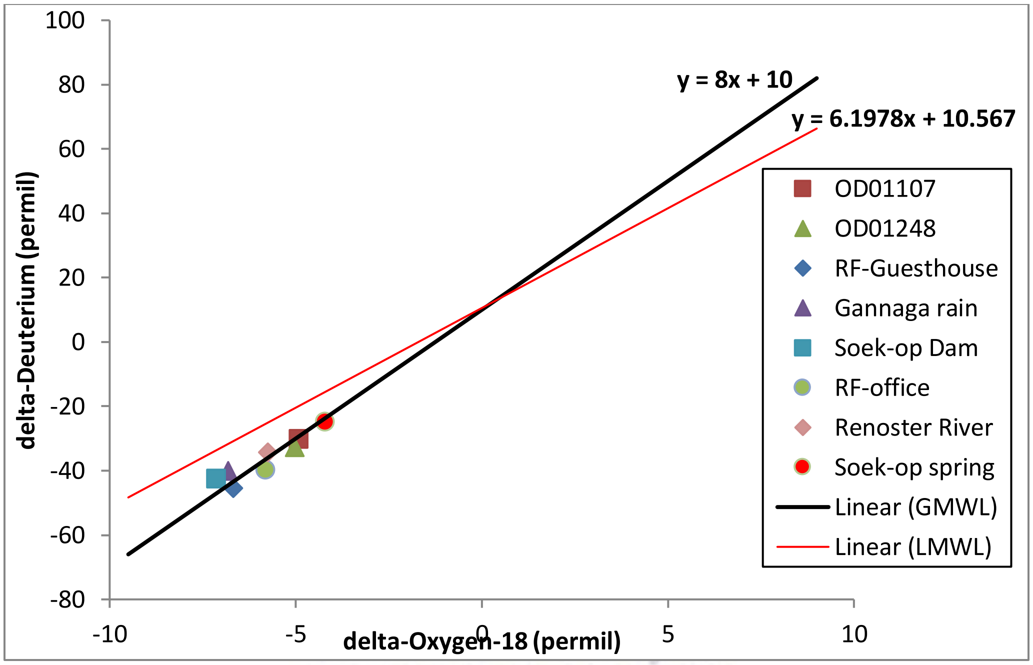


Figure 5-12: Deuterium and oxygen-18 content of rainfall, groundwater, springs, and surface water compared to the GMWL and LMWL (April 2018).

Figure 5-13: The Renoster River in flow (11 April 2018). The River was only flowing along (barely perceptible flow) along an upstream reach of the river stretch.

Figure 5-14 illustrates the stable isotopes results obtained from 12 boreholes, 7 springs, 3 cumulative rainfall samplers and a surface water sample (Oudebaaskraal Dam) during the wet, winter season of May 2018. The majority of samples obtained in the period were more negative and plot further down the GMWL as expected, because the study area experiences lower temperatures during winter thus reduced evaporation effects.

The rainfall samples had δ^{2}H ratios of -23.4 to -11.4 ‰ and δ^{18}O ratios of -5.6 to -2.9 ‰, with a mean of -18.9 and -4.3 ‰, respectively (Table 5-17).

Table 5-17: Statistical summary of rainfall samples in the TKNP (May 2018).

	δ^{18}O‰	**δ^{2}H‰**	**d-excess**
Min	-5.6	-23.4	11.7
Max	-2.9	-11.4	22.7
Mean	-4.3	-18.9	15.5

The sampled groundwater had δ^{2}H ratios of -39.8 to -19.5 ‰ and δ^{18}O ratios of -6.6 to -1.61 ‰, with a mean of -29.8 and, respectively (Table 5-18).

Table 5-18: Statistical summary of groundwater samples in the TKNP (May 2018).

	δ^{18}O‰	**δ^{2}H‰**	**d-excess**
Min	-6.6	-39.8	-6.6
Max	-1.6	-19.5	13.6
Mean	-4.5	-29.8	5.9

The sampled springs have δ^{2}H ratios of -36 to -1.1 ‰ and δ^{18}O ratios of -6.38 to 1.13 ‰, with a mean of -18.6 and -2.7, respectively (Table 5-19). The stable isotopes of the groundwater samples and springs were slightly depleted than the summer samples as expected. This is because δ^{2}H and δ^{18}O values are generally more positive in summer and lower in the winter, and decrease with increasing altitude as a result of seasonal temperature variations (Kendall and Coplen, 2001). The surface water sample from the dam was further enriched during this period, with a δ^{2}H value of 69.6 and δ^{18}O value of 11.87, possible due to long-term evaporation processes that have occurred.

Table 5-19: Statistical summary of spring samples in the TKNP (May 2018).

	$\delta^{18}O$‰	$\delta^{2}H$‰	d-excess
Min	-6.4	-36.0	-10.3
Max	1.1	-1.1	15.0
Mean	-2.7	-18.6	3.2

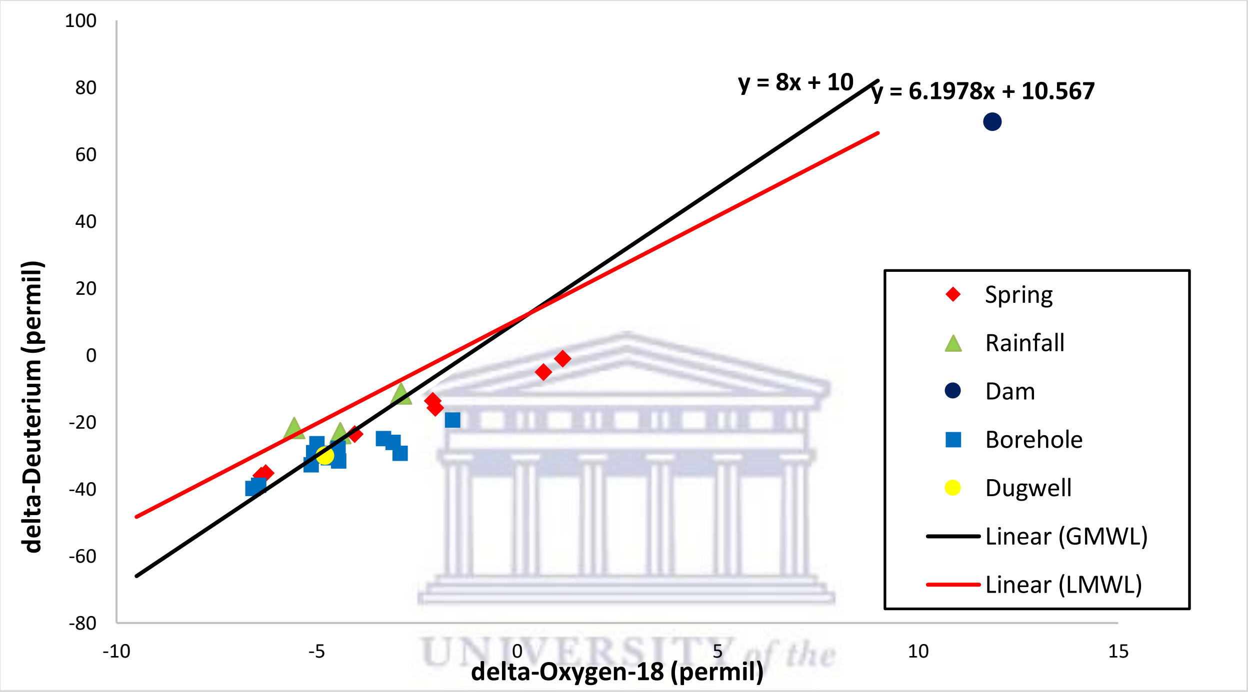


Figure 5-14: Deuterium and oxygen-18 content of rainfall, groundwater, springs, and surface water from the case study area, compared to the GMWL and LMWL (May 2018).

The relationship between EC and the oxygen-18 stable environmental isotope were used to identify the nature of groundwater flow systems, discharge zones and preferential recharge areas (Peterson, 2012; Laar, 2018). According to Laar (2018), EC usually increases along flow paths while the isotopic composition remains constant or changes slightly due to local recharge. Figure 5-15 illustrates the relationship between EC and oxygen-18 in groundwater for the TKNP. No relationship between EC and oxygen-18 stable environmental isotope ($R^2 = 0.19$) was found in the study area.

This indicates that the source of the groundwater had undergone minimal evaporation and that evaporation concentration was not a major process for these samples (Peterson, 2012). This further suggests that there are preferential flow paths that act as conduits for recharge. The high salinity in some of the groundwater samples was largely due to rock-water interactions (shale) as discussed in section 5.2.

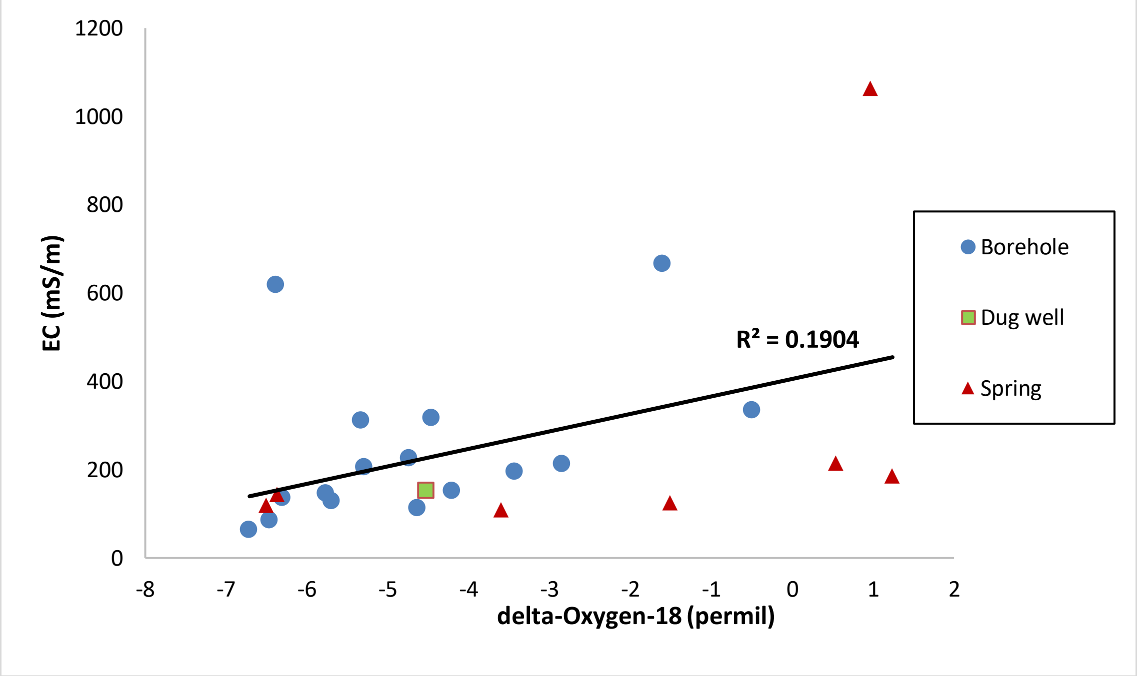


Figure 5-15: Relationship between EC and Oxygen-18 in groundwater.

5.3.2 Discussion of results on assessing interaction using stable isotopes

Section 5.3 presented the results on assessing river-aquifer interactions in the study area using stable environmental isotopes (δ^2H and $\delta^{18}O$) analysis of rainfall, boreholes, springs, a dug well and surface water samples for dry summer and wet winter seasons. The intention was to identify similarities in isotopic signatures between the groundwater and surface water in the study area to determine whether the two water resources interact. This section provides a discussion of the stable isotopic analysis.

The results of the stable isotopes analysis revealed that most groundwater samples were depleted in the TKNP during the dry summer period. This was not expected in the study area because the climate of the Tankwa Karoo is characterized by hot summers and cold winters, as discussed in section 2.2.4. Hot temperatures (38°C) such as those experienced in the study area usually lead to an enrichment of the stable isotopes of water. Furthermore, figure 5-10 illustrated that most of the groundwater samples cluster along the Global Meteoric Water Line (GMWL) of Craig (1961) and some away from the GMWL, indicating the recharge of partially evaporated water taking place in some areas whereas in some areas, recharge seemed to take place rapidly, possible through preferential pathways, preventing any significant evaporation (Adams *et.al*, 2001). Some groundwater samples plot away from the GMWL and LMWL thus the recharge of partially evaporated water took place in some areas of the TKNP (Kendall and Coplen, 2001).

All the samples plot below the Local Meteoric Water of the Western Cape, determined Diamonds and Harris (1997), suggesting that the TKNP has different rainfall patterns to that of the Western Cape. Most of the sampled springs in the summer period had isotopic signatures similar to that of groundwater as expected. However, springs sampled from three sites in the study area did not retain the isotopic signature of the groundwater because of evaporation as discussed in section 5.3.1. The evaporation of water from open water body results in increased sodium and chloride concentrations and the enrichment of δ^2H and δ^{18}O.

The results of the stable isotopes analysis of a surface water sample obtained from the Renoster River and a dam from the escarpment showed that they are similar to the isotopic signature of nearby rainfall collectors. This suggests that streamflow in the Renoster River was generated from surface runoff as rainfall δ^2H and δ^{18}O values were similar to the streamflow. During the winter period, the stable isotopes of the groundwater samples and springs were slightly depleted than the summer samples as expected. As discussed in section 2.2.4, the TKNP experiences cold winters, therefore rainfall of low isotopic ratios influences the isotopic concentration of the groundwater and the process of evaporation during the period is minimal.

The isotopic composition of the groundwater and springs were found to be similar, as expected. Some of the springs had however undergone evaporation, similar to the summer season, thus they did not retained the isotopic signature of the groundwater in the study area. The stable isotopic composition of the surface water sample from the Oudebaaskraal Dam was enriched during both sampling seasons and becomes more enriched during summer as a result of long-term evaporation processes that have occurred. An analysis of the relationship between the EC and the oxygen-18 stable environmental isotope in the study area revealed no relationship between the two variables

($R^2 = 0.19$). This further suggested that evaporation was not a major process in the study as a result of preferential pathways during the process of recharge.

Surface water samples were not available during the sampling periods, thus a conclusion could not be made at this point about the interaction between groundwater and surface water. The results obtained from the stable isotopic analysis did, however, reveal information about the recharge and discharge mechanisms in the study area. Groundwater was recharged mainly along the escarpment through preferential pathways and discharges at the springs on the lower lying areas of the TKNP. Simmers (1987), reported that in semi-arid regions, as in the case study area, intermittent or ephemeral streams are usually a source of recharge, when the river level is temporally above the groundwater level. Because the streambed material of the rivers in TKNP are gravel and cobbles, there are possible significant in-stream transmission losses or indirect recharge during surface runoff. Coarse-grained, high permeability soils, as those observed within the river channels in the study area, have an influence on the recharge process. The presence of coarse-grained soils promotes recharge because water can infiltrate rapidly and drain through the root zone before being extracted by plant roots.

Previous studies in a similar setting to that of the TKNP have shown evidence of transmission losses through streambeds. Costa *et.al.*, (2012); Costa *et.al.*, (2013) noted that channel transmission losses in drylands usually takes place in extensive alluvial channels and streambed underlain by fractured rocks. They play an important role in streamflow rates, groundwater recharge, freshwater contributions, and channel associated ecosystems. Furthermore, Van Tonder and Kirchner (1990); Adams *et.al* (2001); Mahed (2016) reported that groundwater recharge in the Western Karoo primarily occurs through preferential pathways which prevent any significant evaporation.

Groundwater contribution/ discharge to the rivers or the presence of permanent pools during the study period were not encountered, suggesting that the rivers were either detached or remote from the groundwater system in the TKNP. Groundwater discharge in the TKNP occurred in the form of springs, however, these do not feed into the rivers. The springs constantly have some water throughout the year. The non-perennial rivers in the study area only flow in response to an input of significant rainfall events as seen in the similarities in the isotopic signature of water flow in the Renoster River to that of rainfall. There was variability in δ^2H and δ^{18}O values of rainfall from one site to another. The variability was a function of several factors, which include storm-track origin, rainfall amount and intensity, atmospheric temperature, and the number of evaporation and condensation cycles (Kendall *et al.*, 2003).

5.4 Groundwater recharge mechanisms conceptualisation

This section presents the results on the third objective, which was to develop a regional hydrogeological conceptual model of recharge mechanisms. A conceptual model is a set of rigorously justified assumptions, which represent a simplified version of a real system (Younger, 2007), and is developed based on field observations and data interpretation (Adams *et.al,* 2004). The developed model attempts to explain where and how recharge occurs in the Tankwa-Karoo National Park.

5.4.1 Electrical Resistivity Tomography results

The variation in the physical properties of different rocks and fluids within them yield different conductivity or resistivity signatures. Generally, soils with high clay content and/or moisture will have higher conductivity/lower resistivity than others due to the presence of mineral particles that aid electrolytic conduction. Fractured consolidated rocks tend to have lower resistivity than similar rocks with no fractures because fractures are potential paths for groundwater flow and usually contain fluids. Contaminated water and saline water would show higher conductivity/lower resistivity compared to fresh water because they contain dissolved ions that aid electrical conductivity (Airo, 2015). In the current study area, the Electrical Resistivity Tomography (ERT) method of geophysics was applied at specific sites across the TKNP (figure 5-16 to 5-20), to characterise the subsurface.

Figure 5-16 illustrates the two-dimensional (2D) apparent resistivity model across the Tankwa River, 30 m beneath surface. The subsurface directly underneath the Tankwa River had lower resistivity values (10 – 24 ohm.m) than the riparian zone and this was most likely due to higher moisture contents beneath the river. This was expected, given that water-bearing formations are more conductive than dry zones, which are resistive (Loke, 2011). Historical groundwater levels measured at a monitoring site in Wadrif (ODO1187), located near the Tankwa River, ranged between 1.2 to 4.2 m below ground level (m.b.g.l) thus there was a shallow water table at the site as depicted in figure 5-18 with the dotted line. The low resistivity was therefore because of water that had infiltrated through the gravel bed and sand deposits on the floodplains. Gravel bed and sand deposits enable the rapid infiltration of water into the subsurface during runoff events. The higher resistivity range from 146 ohms.m was possible a result of the presence of shale hard rock, as expected. Field observations and geological maps have shown that there are shale outcrops on the sides of the Tankwa River.

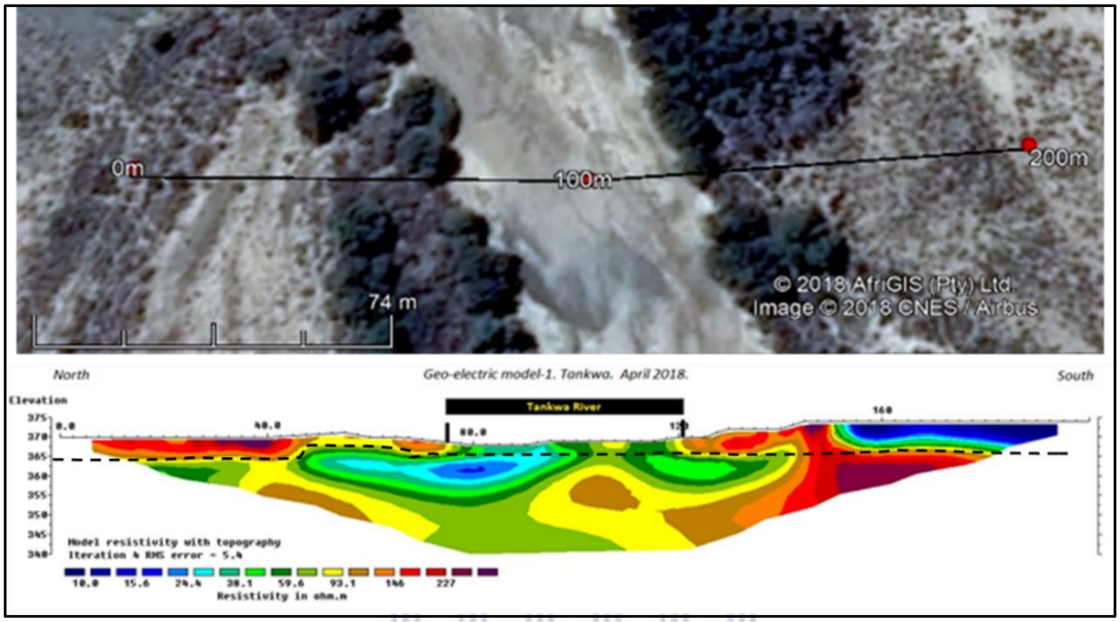


Figure 5-16: 2D apparent resistivity across Tankwa River.

Figure 5-17 illustrates the 2D apparent resistivity model across the Renoster River, 30 m beneath the surface. Similar to the Tankwa River, the Renoster River is a winding river system (figure 5-19). This evidenced by the low resistivity values (10 – 24.4 ohm.m) observed across its floodplain, indicating the presence of water in the subsurface. A water table ranging from 5-10 m, was encountered across the Renoster River. The higher resistivity (93.1 – 227 ohm.m) 10 m below the surface were due to the presence of shale outcrops. There were shale outcrops on the banks of the Renoster River. The River consisted of a sand streambed that possible enables the infiltration of runoff into the subsurface during periods of major rainfall events.

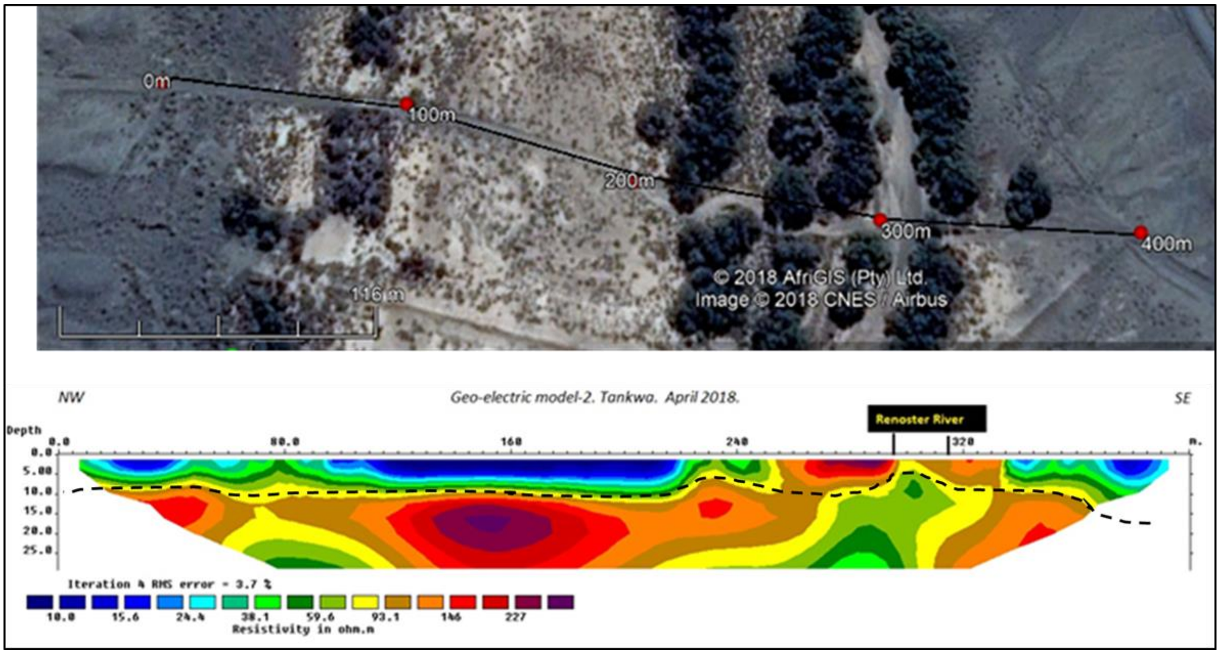


Figure 5-17: 2D apparent resistivity across the Renoster River.

The resistivity traverses in figures 5-18 and 5-19 were performed across springs OD01248 and OD01249, respectively, in the study area. The springs are located on the lower lying, flats of the study area along Springbokfontein. The generated 2D apparent resistivity models were up to 6 m below the surface. The generated ERT models from the two springs displayed similar results. Figure 5-20 and 5-21 show that there is presence of hard rock formation on the surface with high resistivity values (from 44.6 ohm.m).

Field observation confirmed the presence of the hard formation. The hard formation was mainly shale and underneath this, there were possible some fractures that facilitate the movement of water. Water bodies generally have conductive properties thus there is lower resistivity (less than 10 ohms.m) observed at the groundwater table at 2 m below the surface. Underneath the saturated zone, a hard formation possible exists 5 m below the surface. Higher resistivity values were observed 5 m below the surface (from 44.6 ohm.m), which was similar to the shale outcrop on the surface.

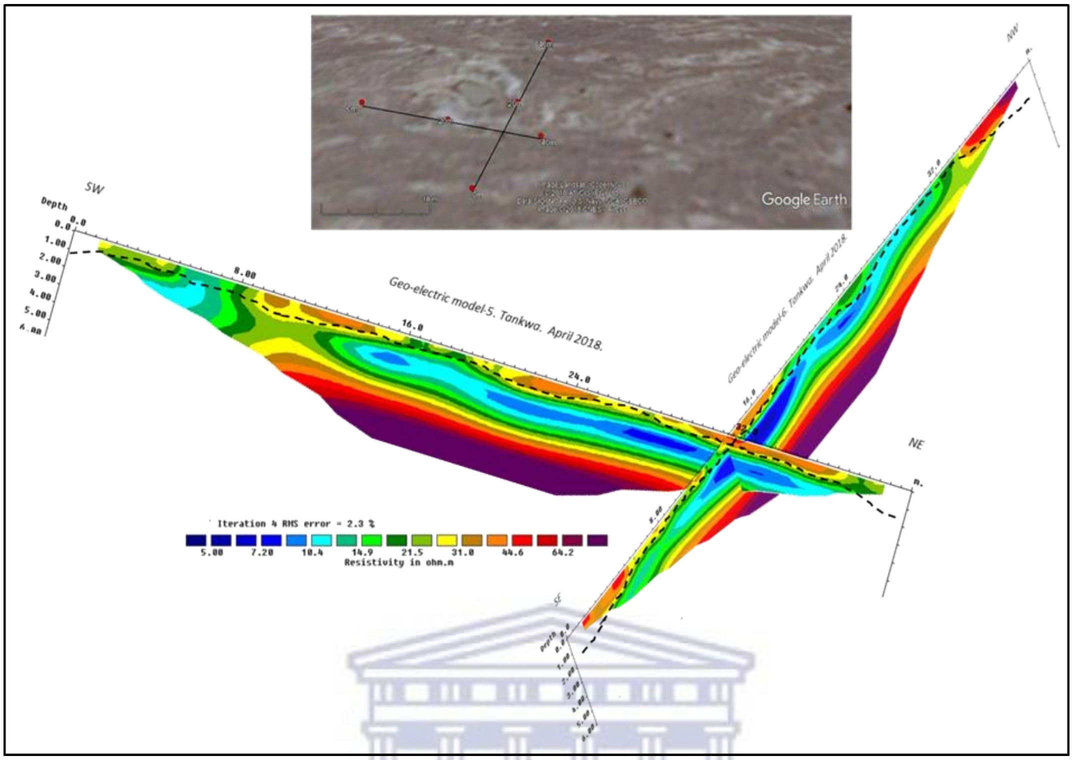


Figure 5-18: *2D apparent resistivity traverse lines across the Springbokfontein (OD01249).*

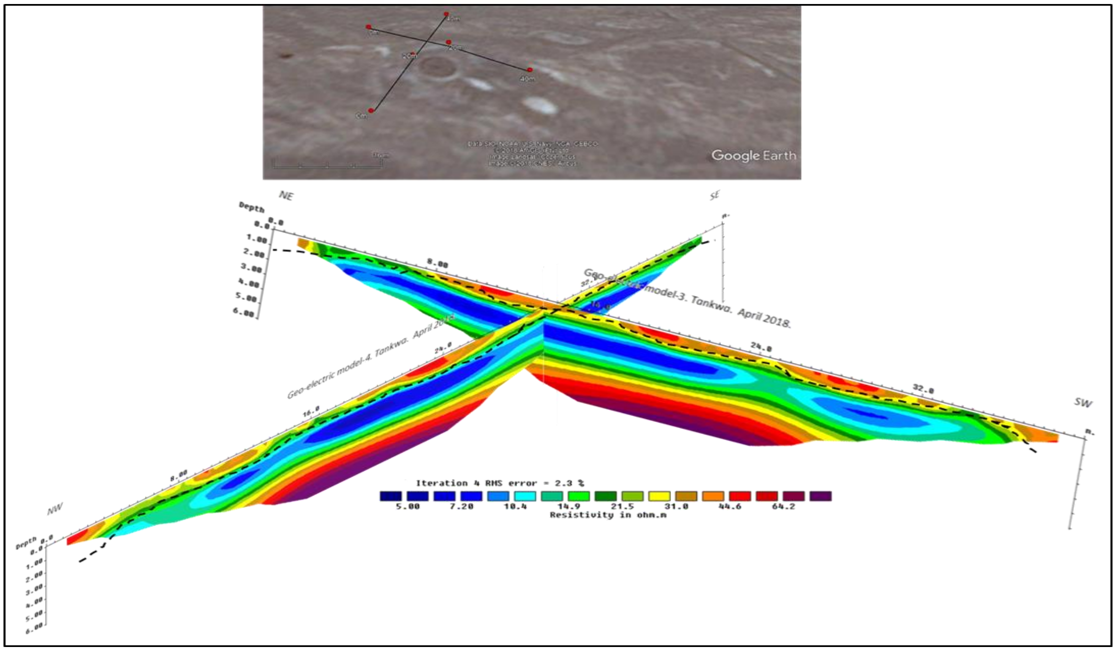


Figure 5-19: 2D apparent resistivity traverse lines across the Springbokfontein (OD01248).

Mieriesfontein spring in figure 5-20 was generally less saline compared to the other two springs as shown in Table 5-20, thus the ERT model generated from the spring shows higher resistivity/lower conductivity at the subsurface. Saline water tends to have higher conductivity/lower resistivity compared to fresh water because they contain dissolved ions that aid electrical conductivity (Airo, 2015). Figure 5-20 indicates high resistivity values in the SW-NE direction of the traverse lines. This is possible as a result of the hard rock, shale, at the site.

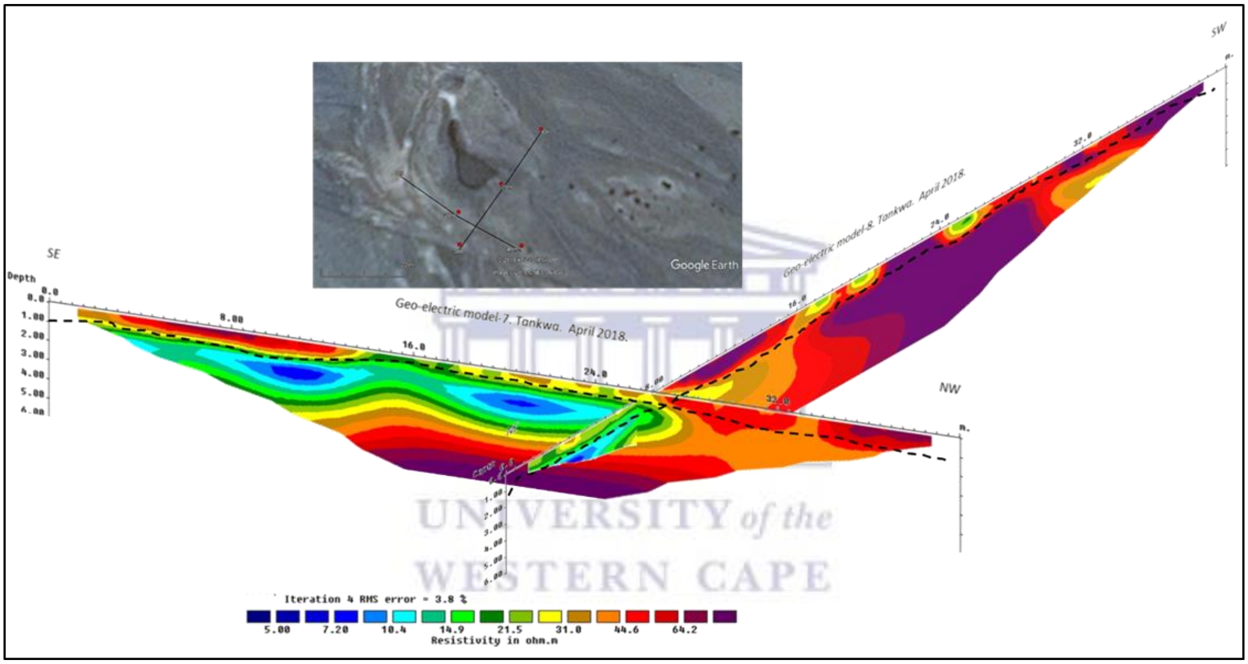


Figure 5-20: 2D apparent resistivity traverse lines across the Mieriesfontein (OD01178).

Table 5-20: The physical parameters of the springs (May 2018).

Spring ID	Location	EC (mS/m)	pH	Temp (◦C)
OD01248	Springbokfontein	171.9	8.95	13.6
OD01249	Springbokfontein	400.3	8.87	13.7
OD01178	Mieriesfontein	101.6	8.80	14.6

In addition to the existing boreholes in the study area, seven additional monitoring boreholes were drilled based on the results obtained from the ERT geophysical surveys. Borehole pairs were drilled next to the riparian zone of the Renoster River and the Tankwa River. Other boreholes were drilled adjacent to the springs that are located along the Springbokfontein and Mieriesfontein. Groundwater levels were measured after borehole constructions (Table 5-21). Figure 5-21 illustrates the geological logs of boreholes constructed using Golden surfer software version 11. Borehole OD01301 close to the Renoster River is 50 m deep and showed a range of lithological units ranging from unconsolidated loose brown soil (1 m), unconsolidated brown soil with gravel (1-5 m), to hard rock grey shale. Borehole OD01302 (5 m) had a similar lithological configuration to the deep borehole.

Measured water levels in the two boreholes were 4.4 and 4.5 metres below ground level (m.b.g.l), respectively, suggesting the presence of water at the depths for plant root uptake. Borehole OD01303 (19 m) at Mieriesfontein displayed artesian conditions, with groundwater being pushed to the surface due to pressure. The lithology ranged from loose brown soil with gravel, hard rock grey shale, to weathered grey shale. Boreholes OD01304 (19m) and OD01305 (19 m) were drilled adjacent to springs at Springbokfontein, with water levels of 1.89 and 0.89 m.b.g.l, respectively. The water levels in the boreholes was similar to that observed in the springs.

The lithology of the borehole logs ranged from loose brown soil at the surface, hard rock grey shale to weathered grey shale. Borehole OD01306 and OD010307 were drilled close to the Tankwa River. The lithology in the deepest borehole ranged from unconsolidated loosed brown soil on the surface, brown dry soil with pebbles, to hard rock grey shale. The measured water levels in the deep borehole was 42.9 m.b.g.l and the shallow borehole was dry. The deep groundwater levels at the Tankwa River site indicates that there is a deep groundwater flow system at the specific site and groundwater is not available for plant use.

Table 5-21: Measured water levels and depths of boreholes drilled in the study area.

Site	**Latitude**	**Longitude**	**Elevation (m)**	**Borehole ID**	**Depth (m)**	**Water level (m.b.g.l)**
Renoster River	32.40488	20.00165	369	OD01301	50	4.4
Renoster River	32.40490	20.00162	366	OD01302	5	4.5
Meriesfontein	32.33601	019.96918	414	OD01303	19	overflowing
Springbokfontein	32.33962	019.89630	415	OD01304	19	1.89
Springbok fontein	32.34496	019.87993	398	OD01305	28	0.8
Tankwa River	32.40484	20.06215	395	OD01306	60	42.9
Tankwa River	32.40484	20.06211	389	OD01307	5	dry

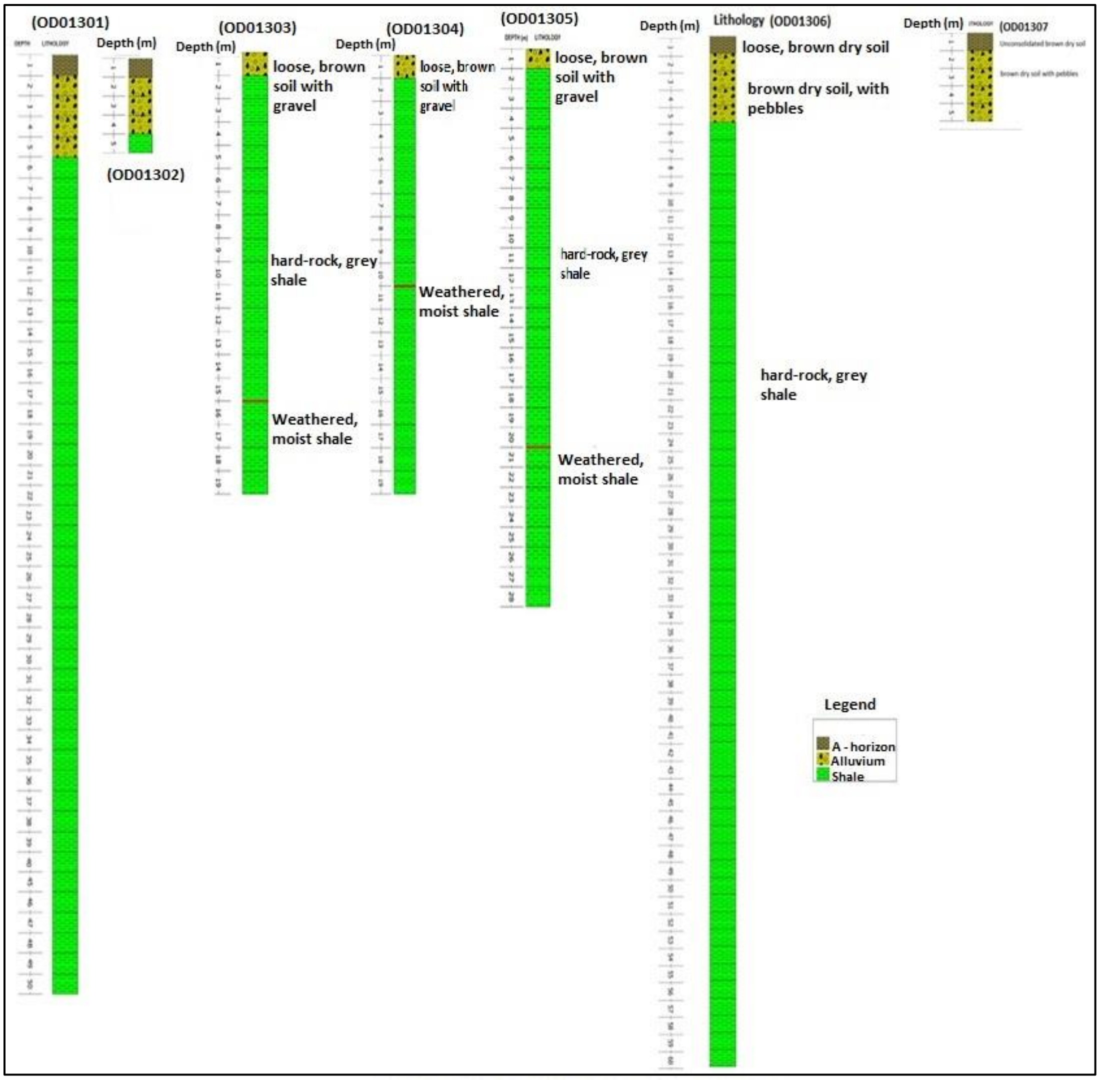


Figure 5-21: Geological logs for boreholes in the study area.

5.4.2 Recharge mechanisms conceptualisation

The potential energy that drives groundwater movement includes both pressure and gravity, and both the effects of topography and geology distribute the effects on groundwater flow (Gleeson *et al.*, 2011). The flow of water in the unsaturated zone is generally vertical because of gravitational pressure. The presence of relatively impermeable soils, rock layers, or geological fracturing or faulting may impede the downward percolation of water into the aquifer. Because of these impeding layers of geological heterogeneity, water movement through the unsaturated zone becomes horizontal until it reaches a surface contact zone where springs and seepages may occur (Madlala, 2015). The discharge of large amounts of groundwater requires a combination of a large recharge area, high recharge rate, and high permeability for large volumes of water to be concentrated at a single point. Furthermore, the presence of a large discrete spring rather than diffuse seepage is evidence of heterogeneity in permeability in the subsurface (Manga, 2001). In some cases, water in confined aquifers may be under sufficient pressure to drive flow upward, against gravity, resulting in artesian wells.

In the study area, the major recharge area consists of the Roggeveld escarpment, and discharge occurs on the lower lying, flats through springs as seen in the hydrochemical and stable isotopes results in section 5.2 and 5.3. The springs are perennial and disconnected from streams. The springs in the study area are driven by a regional groundwater flow system and occur as a result of pressure which drives the flow upwards. Water tables at regional scales can be classified into two distinct types: 1. recharge-controlled water tables that are largely disconnected from the topography and, 2. Topography controlled water tables that are closely related to the topography. Recharge-controlled water tables generally occur in arid regions with mountainous topography and high hydraulic conductivity whereas topography-controlled water tables usually occur in humid regions with low topography and low hydraulic conductivity (Gleeson *et al.*, 2011). Understanding the difference between the two types of water tables is critical to how regional groundwater flow systems are conceptualised.

Regionally, the TKNP displays a topography-controlled groundwater flow system. Deeper depths to groundwater are encountered along the escarpment (20-42 m below the surface), becoming shallower towards the flat lower lying areas (2-6 m below the surface), thus mimicking the topography. Spatially, the groundwater flow direction extends from the north-eastern higher lying areas of the Roggeveld escarpment towards the south-western lower lying areas (figure 5-24), as expected, because groundwater generally flows down-gradient from areas of the high hydraulic head (high water-level elevation) to areas of the low hydraulic head (low-water level elevation) (USGS, 2000). Figure 5-22 illustrates the potential groundwater flow direction in the TKNP, based on measured depths to groundwater and calculated elevations of groundwater. The main water-bearing formations in the TKNP are weathered and fractured sedimentary rocks.

Water levels in the TKNP generally have a delayed response to rainfall events. They tend to have a stabilised trend with no major anomalies, and this was expected given the pristine environment of the park, with limited human impact. The water levels in the higher lying areas on the escarpment do however respond to high rainfall events and or a sequence of rainfall events but this is not the case for lower lying areas. Water levels in abstraction boreholes in the TKNP show a gradual decline and tend to stabilise into a new equilibrium state (Van Niekerk and Dyason, 2017). A similar trend in water levels was observed during quarterly-monitoring at the study site. Generally, the water levels close to rivers in the TKNP are 3-6 m below the ground surface and remain accessible to deeply rooted trees.

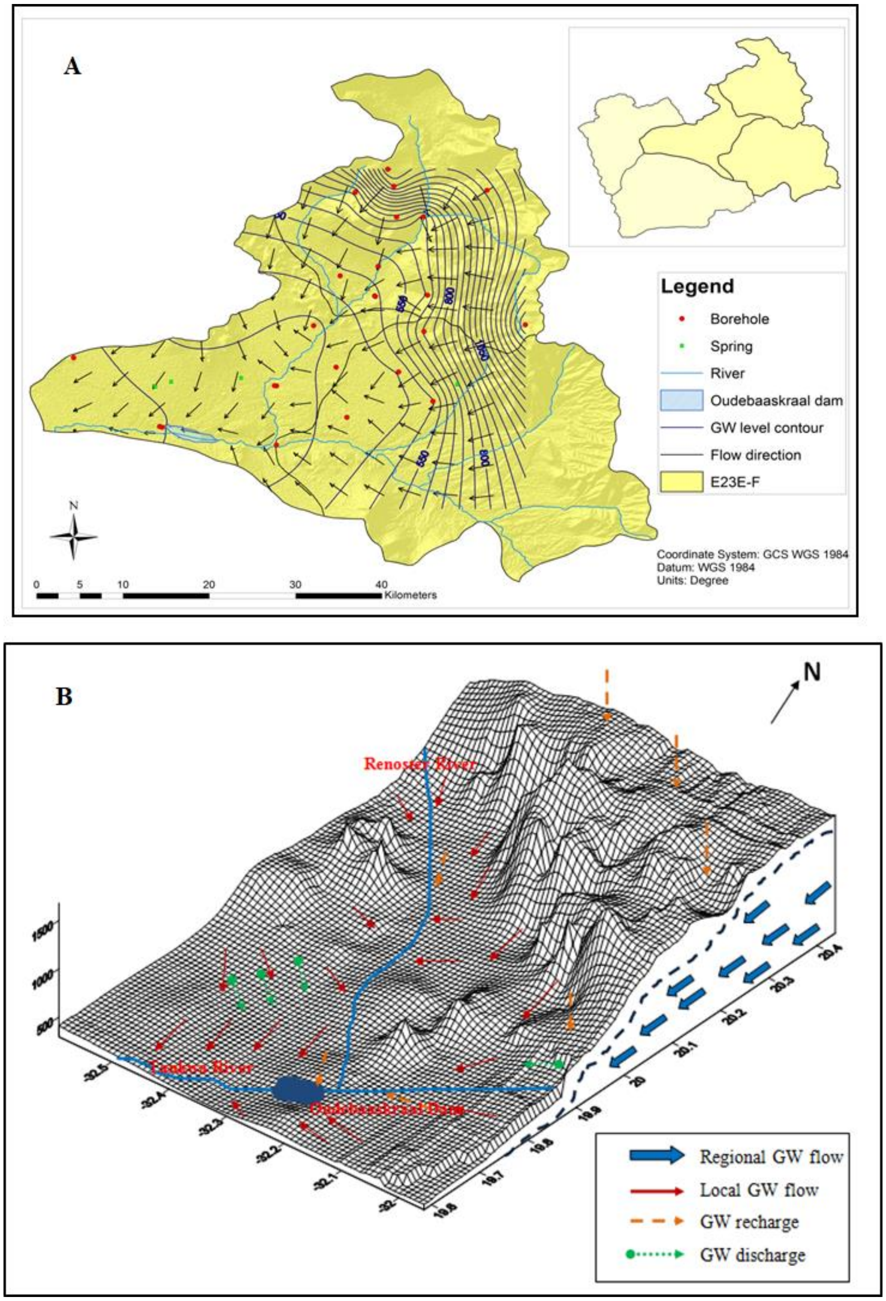


Figure 5-22: Potential groundwater flow direction in the TKNP, based on measured groundwater levels (A), and a 3-dimensional regional schematic diagram of the park (B).

Precipitation amount and intensity varies both spatially and temporally over the study area as discussed in section 2.2.4. Van Wyk (2010) reported that given the climatic variability and hydrogeological environment in semi-arid regions, effective groundwater recharge events are episodic in nature and largely occur once every five years. When the rainfall reaches the ground surface, it infiltrates through the soil, streambeds and through the fractures of rock outcrops. In the study area, runoff generation occurs mainly from the escarpment by high intense rainfall events. The rate and amount of infiltration depend on the amount and intensity of the rainfall, the local topography and the infiltration capacity of the soil (Laar, 2018). In semi-arid/arid environments, such as the Tankwa Karoo, groundwater recharge primarily depends on above normal rainfall events. Insignificant rainfall events evaporate from the surface and produce little to no recharge (Adams *et.al*, 2004).

With significant rainfall events over a few days in the cool winter months in the study area, the water will likely infiltrate deeper and eventually recharge the aquifer. Therefore, groundwater recharge in the TKNP occurs mainly during the rainy season (May to August) and little to none during the dry, hot summer months (September to April). The higher-lying areas (Roggeveld Escarpment) experience higher rainfall events compared to the lower lying areas of the park as discussed in section 2.2.4. Therefore, recharge occurs as primary recharge on the escarpment, where direct infiltration is more likely to occur. The chemistry data illustrated Ca-HCO_3 water types on the escarpment and this was indicative of shallow, recently recharged groundwater as discussed in section 5.2. Indirect recharge occurs through the infiltration of surface runoff and discharges from springs that dominate the Springbok Flats.

The stable isotope data indicated that the recharge of partially evaporated water takes place in some areas of the TKNP, whereas in some areas, recharge seemed to take place rapidly, possible through preferential pathways preventing any significant evaporation. Recharge in Southern African regions is highly variable and is a function of the climate, topography, and drainage (Adams *et.al*, 2004). Van Tonder and Kirchner (1990) determined that groundwater recharge in the Karoo formations varies between 2 and 5 % of mean annual rainfall. In areas underlain by a thick soil cover, 3% of rainfall infiltrated and recharged groundwater while recharge in hilly areas with a thin soil cover was of the order of 5%. Similar recharge rates should be expected for the TKNP as well.

Surface water-groundwater interactions in semi-arid environments typically occur in relatively small and distinct landscape and are typically episodic and variable. One of the most important surfaces water-groundwater connections is through groundwater recharge (Sophocleous, 2002). The TKNP comprises of non-perennial rivers: Tankwa River and its tributaries, the Renoster, Malansgat, Sandlaagte, Karee River, and dams. The rivers only flow in response to peak rainfall events. In the duration of the current study, flow in the rivers was not observed except along a particular reach of the Renoster River, after a major rainfall event in April 2018. The stream material of the rivers in the TKNP is minly gravel, alluvium, and cobbles (figure 5-23). As a result, when significant rainfall events occur during the winter period, groundwater recharge possible occurs indirectly through preferential flow paths of the streambeds.

Recharge through the streambeds of the rivers is largely episodic, only occurs in response to large rainfall events. Analysis of hydrochemical and stable isotopes results for the study area could not identify the contribution of the rivers to recharge because of limited surface water samples. However, in semi-arid or arid environments, ephemeral river flow often features significant in-stream infiltration referred to as transmission losses or indirect recharge (Reli *et.al*, 2016). The runoff generated in rivers during high rainfall events decreases downstream because of transmission losses and evaporation. Costa *et.al.*, (2012); Costa *et.al.*, (2013) reported that channel transmission losses in drylands usually takes place in extensive alluvial channels and streambed underlain by fractured rocks. It is a function of the amount and duration of rainfall received in the higher lying areas as well as the prevailing temperature conditions. Findings by Mahed (2016), suggested that preferential recharge occurs in the Karoo with higher hydraulic infiltration related to the riverbeds and fractures.

The TKNP is part of the Succulent Karoo Biome, which is characterised by low shrubs, with large trees (*Acacia karoo*) dependent on groundwater along the riparian zones. *Acacia* trees have a long tap root system (to a maximum of 12 m) that allows them to reach groundwater. In arid regions, Acacia trees are often used as indicators of underground and surface water (SANBI, 2002). In the study area, the trees were observed along the riparian zones of the rivers suggesting dependency on groundwater, however, their root lengths were not measured in the current study. Evapotranspiration, which is the combined processes of evaporation and transpiration, act to remove water from the shallow aquifer. The presence of vegetation and the associated uptake of water through the plant's roots results in evapotranspiration being active to a greater depth below the root systems of the large trees (figure 5-23). Water also evaporates directly from the aquifer through the various springs in the TKNP.

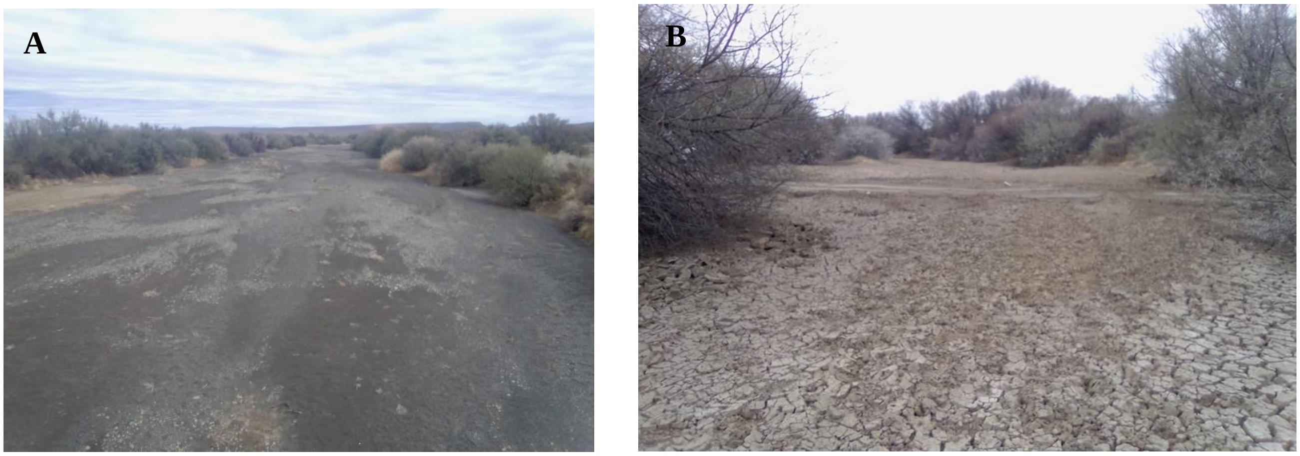


Figure 5-23: Tankwa River (a) looking downstream from bridge on the main road to the TKNP offices. Renoster River (b) looking downstream to its confluence with the Tankwa River.

Figure 5-24 illustrates a hydrogeological conceptual model of recharge mechanism in the TKNP, developed using Golden Surfer™ software version 11. The diagram illustrates that recharge in the system occurs from rainfall and surface water bodies (rivers, dams and overland flow). Spatially, the groundwater flow direction extends from the North Eastern higher lying areas of the Roggeveld escarpment towards the South Western lower lying areas. Groundwater in the TKNP is lost mainly through evapotranspiration and abstraction boreholes. From the stable isotopes data collected from cumulative rainfall collectors, surface water and groundwater, it is evident that evaporation occurs in some areas before infiltration takes place. This mainly occurs in the lower lying areas, through slow diffuse recharge mechanisms.

Whereas in the higher lying areas of the escarpment, evaporation is minimal because of preferential pathways that act as conduits for recharge (direct recharge). The main recharge mechanisms in the Karoo formations of South Africa is flow along preferential pathways (Van Tonder and Kirchner, 1990: Adams *et.al*., 2001; de Vries and Simmers, 2002). Healy (2010) demonstrated the role that topography plays on both diffuse and focused recharge. Steep slopes along mountainous areas tend to have low infiltration rates and high runoff rates. The lower lying, flat areas that have poor surface drainage are more conducive to diffuse recharge and these conditions contribute to floods.

In arid and semi-arid environments, the potential evapotranspiration generally exceeds the rainfall, and groundwater recharge depends on high-intensity rainfall events, the accumulation of rainfall in depressions and streams, and the ability of rainfall to escape evapotranspiration by rapid infiltration through cracks and fissures. Hence, direct recharge in terms of total aquifer replenishment tends to be less important than localized and indirect recharge in semi-arid environments (Vries and Simmers, 2002; Wang *et.al,* 2010). Nearly all the groundwater originates from precipitation that infiltrates through soil into flow systems in the underlying geology.

As groundwater moves along flowlines from recharge to discharge areas, its chemistry is altered by the effects of a variety of geochemical processes (Freeze and Cherry, 1979). In the study area, groundwater chemistry is altered through geochemical processes such dissolution of calcite and gypsum, ion exchange processes and silicate weathering. This gives rise to four water types, namely: Ca-HCO_3 in recharge areas (escarpment), Ca-SO_4 (mainly on the foothills of the escarpment and escarpment), Na-Cl (on the lower lying, flat areas, and foothills), and Na-HCO_3 (on the flats) as discussed in section 5.2.

The presence of dolerite intrusions, as well as dykes and sills within the study area, has a significant influence on the occurrence of groundwater in the TKNP (Levy and Xu, 2011). Dolerite intrusions have the effect of baking, deforming, and fracturing the surrounding geology. This hence allows transmissive zones to develop along the geological contacts (Murray *et al.*, 2012; Maceba *et al.*, 2017). The areas of high permeability for the Karoo formations are therefore those that are associated with dolerite intrusions (Murray *et al.*, 2012). Le Maitre and Colvin 2008; Levy and Xu 2011 reported that in Karoo dykes and sills aquifers, groundwater discharge to rivers usually occurs in limited quantities as springs, seeps or wetlands and is generally associated with Karoo rocks with limited storativity.

In the case of sedimentary aquifers, the discharge may be more extensive and is associated with linear contact zones between sandstones and inter-bedded shale layers or underlying less permeable formations/basement rocks. The groundwater discharge from these aquifers to rivers is generally limited to discrete locations associated with major faults or fractures. In the study area, groundwater discharge occurs through springs that are disconnected from the rivers as previously discussed.

Chavellier *et.al*, (2001) assessed the occurrence of groundwater associated with Karoo dolerite sills and ring structures using morpho-tectonic models. The results of the study indicated that the majority of the more productive boreholes are those that tap the shallow (<30 m) weathered Karoo sediments alongside dolerite dykes. Murray *et al.*, (2012) developed transmissivity maps for the main Karoo Basin. In the study, the areas of high permeability are therefore those that are associated with dolerite intrusions, thick alluvial deposits, folded and faulted formations.

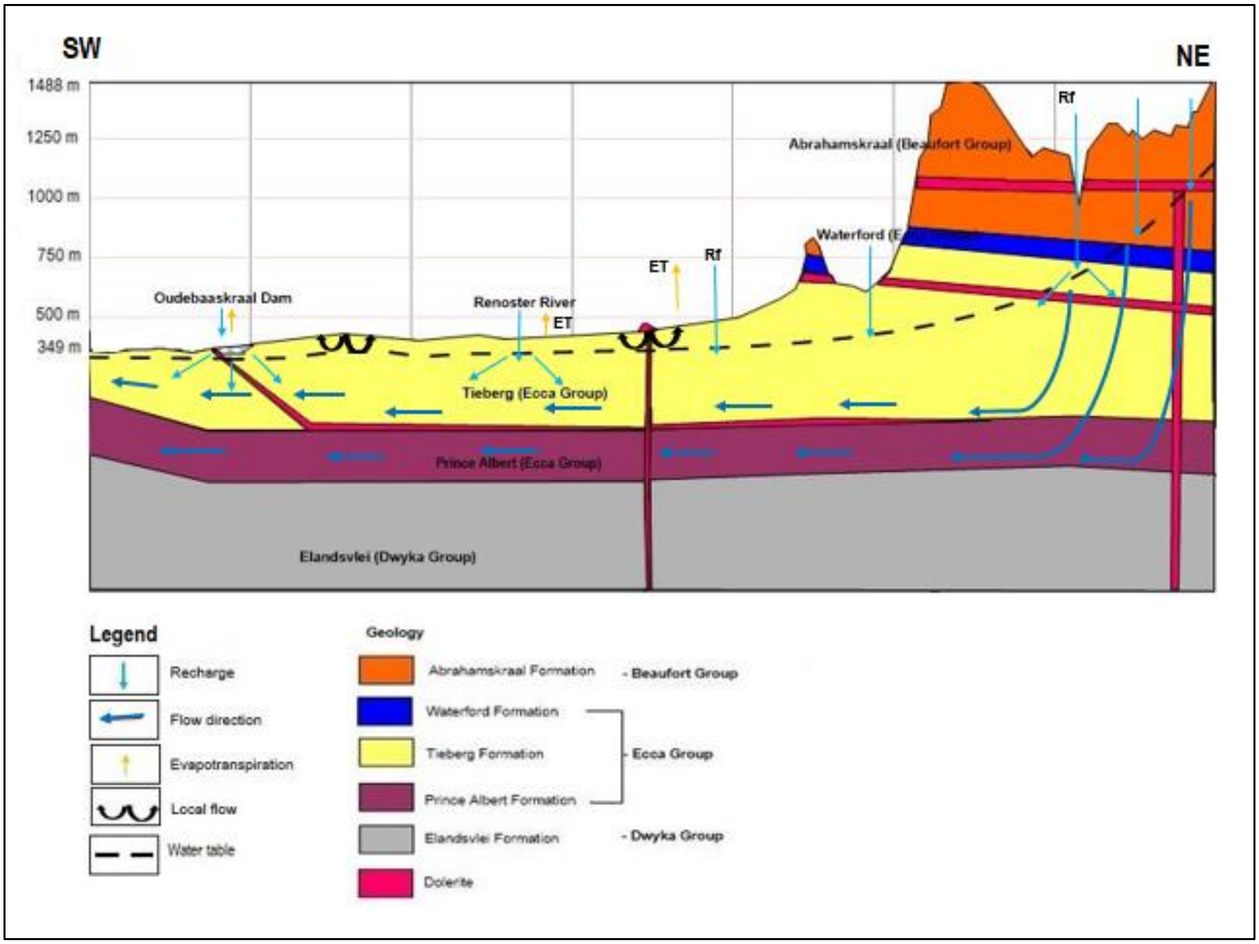


Figure 5-24: A hydrogeological conceptual model of recharge mechanisms in the TKNP

5.5 Chapter summary

Chapter 5 presented results on the assessment of river-aquifer interactions using hydrochemical and stable isotopic analysis. The intention was to identify where and when do river-aquifer interactions occur in the study area thus addressing the objectives of the study. The first objective was to establish the groundwater contribution to the river systems, the second to investigate the role of the river in recharging the underlying aquifer and the third to develop a regional hydrogeological conceptual model of recharge mechanisms. The central argument for the chapter was that unless we assess the interaction between groundwater and surface water, we cannot improve on our understanding of the influence of groundwater on non-perennial rivers. Therefore, the question that was posed is what is the influence of river-aquifer interactions in non-perennial river systems in the semi-arid environment?

Analysis of the dry and wet season hydrochemical results showed that during the dry summer season, four water types occurred in the study area. These were Ca-HCO_3, Ca-SO_4, Na-HCO_3, and Na-Cl water types. Spatially, Ca-HCO_3 water mainly occurred in recharge areas of the escarpment, Ca-SO_4 on the foothills of the escarpment and some of the escarpment, Na-Cl dominated the eastern edge (flats and foothills) of the TKNP and Na-HCO_3 was the predominant water type located on the lower lying flats areas (eastern edge of the park). During the winter season, similar water types as the summer season were observed in the study area. The major processes influencing the groundwater chemistry were ion exchange processes, silicate weathering and the dissolution of calcite and gypsum. The results of the stable isotopes analysis revealed that most groundwater samples were depleted during the summer season and this was not expected, given the warm summer temperatures.

The majority of the groundwater samples were similar to the rainfall isotopic signature thus indicating recently recharged water of meteoric origin, with or without some evaporation taking place before infiltration. This suggested that recharge occurred rapidly, most likely through preferential pathways that prevent any significant evaporation. Some groundwater samples plot away from the GMWL and LMWL thus the recharge of partially evaporated water took place in some areas. The isotopic composition of the groundwater and springs was similar as expected because springs represent groundwater discharge zone. However, some springs did not retain the isotopic signature of groundwater due to the effects of evaporation. A similar trend was observed in the isotopic signatures of the groundwater in the winter season to that of the summer season, however, the groundwater samples were more depleted as expected. This is because δ^2H and δ^{18}O values are generally more positive (enriched) in summer seasons, and lower in the winter and decrease with increasing altitude because of seasonal temperature variations. The surface water sample obtained from the Renoster River showed that an isotopic signature similar to that of rainfall, suggesting that flow in the river is driven by rainfall events. Groundwater-surface interactions could not be identified with the use of the hydrochemistry and stable isotopes due to limited available surface water sampling points in the study area. The methods, however, proved useful in the identification of groundwater recharge mechanisms.

On the third objective of the study, to develop a hydrogeological conceptual model of recharge, primary data from field measurements (ERT geophysical surveys, water levels monitoring, hydrochemical and stable isotopic analysis), secondary data from various sources and the review of literature were used as inputs into the model. The conceptual model revealed that spatially, the groundwater flow direction extends from the North Eastern higher lying areas of the Roggeveld escarpment towards the South Western lower lying areas, thus mimicking the topography, as expected. Deeper groundwater levels were measured on the escarpment, becoming shallower towards the lower lying areas. Therefore, a topography-controlled water table occurs in the TKNP. Groundwater recharge in the higher lying areas occurs mainly as direct recharge through preferential pathways. In the lower lying, flat areas recharge occurs as slow diffuse recharge. Recharge through the streambeds (transmission losses) of rivers TKNP was largely episodic, only occurring in response to large rainfall events. Furthermore, the areas of high permeability were associated with areas of dolerite intrusions.

Chapter 6 : Conclusion and recommendations

6.1 Introduction

The aim of the study was to assess surface water-groundwater (river-aquifer) interactions in non-perennial river systems to provide an insight as to how these water resources interact in semi-arid environments. To achieve the aim, the study set three objectives. The first objective was to establish the groundwater contribution to the river system, the second was to investigate the role of the river in recharging the underlying aquifer, and the third objective was to develop a regional hydrogeological conceptual model that described the recharge mechanisms in the non-perennial river systems within semi-arid environments.

To address objectives one and two, hydrochemistry and stable isotopic analyses were used. To address the third objective, the study combined secondary data from records review and field data from hydrometric methods, ERT geophysical surveys and tracer techniques. The research problem identified in the study was a lack of a broader understanding of river-aquifer interactions in non-perennial river systems in terms of the role of river-aquifer interactions in the non-perennial river systems within semi-arid environments and Tankwa Karoo in South Africa was used as a case study. The research question was: "What is the influence/role of river-aquifer interactions in non-perennial river systems in the semi-arid environment?" Therefore, the central argument for the study was that unless the role of river-aquifer interactions in the non-perennial river systems within semi-arid environments is assessed, improved knowledge or improved understanding about the influence of groundwater on these river systems cannot be established in such environments or settings.

6.2 Conclusions

The first objective was to establish the aquifer contribution to the river system whereas the second objective was to investigate the role of the river in recharging aquifer. In both objectives, hydrochemical and isotope analyses as tracer methods were used to investigate the role of river-aquifer interactions in non-perennial river systems. With the hydrochemical analysis, results showed that during the dry season, four distinct water types in the study area were characterised. These were Ca-HCO_3, Ca-SO_4, Na-Cl, and Na-HCO_3. The dominant water types were Na-HCO_3 and Na-Cl, on the lower lying flat areas of the study area. These water types were associated with discharge zones thereby confirming the role of aquifers in recharging rivers (aquifers losing water to rivers whereby rivers gaining water from aquifers). Therefore, it was concluded that the results showed groundwater contribution to rivers thereby addressing objective one of the study. In addition, the Ca-HCO_3 and Ca-SO_4 were associated with recharge zones on the escarpment and foothills. The groundwater chemistry evolved as it travelled from the recharge areas of the escarpment to the discharge areas of the lower lying flat areas, as expected, through rock-water interactions. The same four water types were characterised during the wet seasons of sampling. The evidence from the wet season in the discharge areas of the lower lying flat areas also provided evidence that aquifers recharged rivers. However, there were limited surface water sampling points in the study area to conclusively state that rivers recharged aquifers. Nevertheless, inference about rivers recharging aquifers was made using the reviewed records from similar settings. Rivers in settings similar to the study area are usually preferential pathways for groundwater recharge and contribute to groundwater recharge via transmission losses during episodic flood events.

The results of the stable isotopes analyses showed that most groundwater samples were depleted during the dry, summer period and were similar to that of rainfall. The depleted groundwater samples during the dry season were not expected, considering that the climate of the study area is characterised by hot summers, which usually lead to an enrichment of the stable isotopes of water. Therefore, the study concluded that recharge in some areas occurred rapidly through preferential pathways, preventing any significant evaporation. Therefore, the conclusion was that the results possible show rivers contributing to groundwater recharge through preferential pathways thus addressing objective two of the study. During the wet period, the groundwater and rainfall samples were more depleted due to lower temperatures, as expected. This further provided evidence of preferential pathways during recharge. However, there were limited surface sampling points during the sampling rounds to conclusively state that the rivers recharged the aquifers. The isotopic signatures of springs were similar to that of some of the springs, as expected, during both dry and wet seasons. Therefore, the conclusion was that groundwater contributes to surface water through spring discharges further confirming the role of aquifers in recharging rivers, hence addressing the first objective of the study.

In addition, surface water samples obtained from the Renoster River and a dam from the escarpment showed similar isotopic signatures to that of nearby rainfall stations, therefore indicating that streamflow in the Renoster River was generated from surface runoff, which originated from a recent rainfall event, as expected. An analysis of the relationship between EC and the oxygen-18 stable environmental isotope in groundwater revealed no relationship between the two variables, further suggesting that evaporation was not a major process in groundwater in the study area, possible as a result of preferential pathways during recharge. The evaporation of available surface water bodies and some springs in the study area altered their isotopic signatures; hence it was not possible to compare their signatures to that of groundwater. The evaporation of the water from open water body resulted in increased sodium and chloride concentrations and led to the enrichment of $\delta^{2}H$ and $\delta^{18}O$.

The third objective was to develop a regional hydrogeological conceptual model that described the recharge mechanisms in the non-perennial river systems within semi-arid environments. The model was developed based on secondary data from records review and field data from hydrometric methods, ERT geophysical surveys and tracer techniques. The model showed that recharge occurred mainly in the higher lying areas, as direct recharge along preferential pathways. In the lower lying flat areas, recharge occurred as slow diffuse recharge. The rivers in the study area contribute to recharge through transmission losses and discharge occurs through springs resulting from a pressure system in the deep groundwater, evidenced by the hydrochemistry results. The steep slopes along the escarpment tend to have low infiltration rates and high runoff rates. The lower lying, flat areas have poor surface drainage and are more conducive to diffuse recharge and these conditions contribute to floods. Recharge in the system was primarily driven by above normal rainfall events. Insignificant rainfall events evaporate from the surface and produce very little to no recharge. With significant rainfall events over a few days in the cool winter months, recharge mostly occurs during winter. Therefore, the third objective of the study focusing on developing a regional hydrogeological model of recharge mechanisms was fulfilled.

6.3 Recommendations

The results of the study form the foundation for understanding how surface water (river) and groundwater (aquifer) resources interact in semi-arid environments. The methods that were chosen to assess the interaction, hydrochemistry and stable environmental isotopes, were effective in the study area, however there were limited surface water sampling points in the study area to conclusively state that rivers recharged aquifers and the effects of evaporation altered the chemistry of the available surface water. Therefore, it is recommended that a combination of different approaches should be implemented for settings similar to the study area. However, using different methods in one study area results into interpretation challenges of the findings because different methods tend to have different principles, assumptions and theories.

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Appendices

Appendix A: Cation-anion balance for the samples collected in the study

Site	Sampling date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Charge balance (%)	Use
OD01178	2015-05-14	5.241	0.75	364.613	6.056	843.34208	79.777	0.6	0.78	Yes
OD01271	2015-05-15	49.047	18.828	590.81	8.522	507.65664	626.143	127.391	2.19	Yes
OD01262	2015-05-12	44.647	19.764	55.908	1.715	203.008	82.626	41.389	-1.47	Yes
OD01254	2015-05-14	247.974	66.58	259.282	2.757	198.3964	671.091	208.238	4.82	Yes
OD01252	2015-05-12	10.607	2.04	330.123	6.642	497.94788	234.806	28.959	-0.52	Yes
OD01209	2015-05-14	1.25	0.75	176.747	3.118	457.4634	27.735	2.164	-2.67	Yes
OD01207	2015-05-12	304.188	189.069	459.955	3.05	250.29642	1213.573	387.586	4.55	Yes
OD01205	2015-05-12	34.229	11.182	210.32	2.145	225.69024	250.95	1.378	4.53	Yes
OD01183	2015-05-14	1.25	0.75	309.576	3.515	526.34948	112.686	14.139	6.13	Yes
OD01156	2015-05-14	1.25	0.75	247.95	2.369	668.85768	63.236	1.458	-7.61	Yes
OD01155	2015-05-14	1.25	0.75	316.999	3.837	-1.420156326	160.712	0.6	-1.16	Yes
OD01166	2015-05-14	4.045	0.75	15.854	2.314	590.59468	65.877	2.212	-0.84	Yes
ODO1147	2015-05-13	95.75	56.496	125.052	3.004	343.43244	248.22	66.051	3.24	Yes
OD01138	2015-05-13	242.895	202.497	322.95	10.533	172.386	1216.876	480.041	-4.48	Yes
OD01135	2015-05-14	56.776	22.641	297.09	1.528	403.1368	272.862	52.223	6.86	Yes
OD01120	2015-05-12	17.291	2.651	310.902	2.453	153.19418	435.769	1.937	-0.59	Yes
OD01107	2015-05-13	305.059	155.324	369.715	6.171	355.23472	1215.33	219.028	-0.47	Yes
OD01106	2015-05-15	118.913	38.259	95.218	1.692	288.17864	136.675	226.268	-0.08	Yes
OD01213	2015-05-14	3.071	0.75	292.375	2.553	473.78578	133.507	5.95	5.45	Yes
OD012140	2015-05-13	73.548	55.004	256.326	2.84	264.17148	385.382	146.262	3.12	Yes
OD01243	2015-05-12	123.233	81.126	195.365	2.977	286.23762	491.518	158.263	-1.04	Yes
OD01224	2015-05-13	94.994	47.946	179.283	13.273	263.9104	349.451	54.742	4.67	Yes
OD01276	2015-05-13	43.507	16.955	18.584	1.085	203.11414	23.478	15.381	1.05	Yes
OD01215	2015-05-14	6.619	0.75	278.215	3.134	470.6699	80.631	6.625	10.78	Yes
OD01248	2015-05-14	6.199	0.75	557.673	9.522	1119.82092	244.221	3.981	-0.90	Yes
OD01249	2015-05-14	4.472	0.75	300.86	11.267	3446.14498	501.342	1.208	-67.59	No

Site	Sampling date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Charge balance (%)	Use
OD01271	2015-11-24	105.542	38.359	530.63	10.069	403.97738	634.736	195.023	5.26	Yes
OD01268	2015-11-24	90.562	27.184	283.045	7.058	339.33324	336.181	174.619	1.50	Yes
OD01262	2015-11-24	77.4	28.7	93.9	2.4	233.508	140.5	100.3	2.43	Yes
OD01257	2015-11-26	9.7	2	117	4.5	341.6	23.9	0.6	-3.56	Yes
OD01254	2015-11-24	217.9	60	283.7	3.1	198.616	665.4	215.7	3.13	Yes
OD01252	2015-11-24	10.753	1.701	342.37	6.694	492.46276	217.147	31.9	2.88	Yes
OD01209	2015-11-25	3.7	0.75	188.8	2.6	514.23	32.3	1.5	-4.72	Yes
OD01207	2015-11-24	319.9	196.5	414.2	3.7	259.372	1292.3	424.7	0.70	Yes
OD01205	2015-11-24	32.3	13	180.2	2	226.188	246.1	1.8	-0.54	Yes
OD01183	2015-11-24	4.064	0.75	307.78	4.461	494.94546	168.789	0.6	3.31	Yes
OD01156	2015-11-26	1.25	0.75	298.2	3.8	607.316	78.7	6.6	3.46	Yes
OD01155	2015-11-26	3.468	0.75	318.485	4.715	545.32048	161.617	0.6	2.53	Yes
OD01166	2015-11-26	3.921	0.75	227.645	3.147	551.60958	63.385	3.527	-3.13	Yes
ODO1147	2015-11-25	84.364	48.536	119.208	3.768	330.95794	258.991	75.539	-2.94	Yes
OD01138	2015-11-24	225.793	276.748	294.195	10.866	176.00086	1255.828	482.534	-1.30	Yes
OD01120	2015-11-24	17.8	2	323.1	3.2	142.618	459.2	4.5	-0.64	Yes
OD01110	2015-11-25	218.9	223.2	479.2	16.1	278.038	1315.2	267.8	3.39	Yes
OD01107	2015-11-25	272.9	195.8	241.1	6.9	132.98	1268.6	197.1	-2.03	Yes
OD01106	2015-11-25	127.674	36.44	89.874	2.555	287.59182	135.273	234.059	-0.22	Yes
OD01213	2015-11-26	3.104	0.75	275.235	2.955	521.83426	120.026	1.5	1.22	Yes
OD012140	2015-11-26	89.1	52.9	265.3	3.1	264.13	440.1	162.3	0.73	Yes
OD01243	2015-11-24	132.4	81.1	190.2	3.9	288.042	444.9	164	2.29	Yes
OD01192	2015-11-24	1.25	0.75	426.87	4.556	656.63084	308.873	21.301	-2.86	Yes
OD01163	2015-11-24	71.109	31.051	93.57	2.857	265.75992	138.575	88.13	0.73	Yes
OD01224	2015-11-25	38.504	14.126	76.246	12.288	169.5007	116.845	23.068	1.21	Yes
OD01291	2015-11-25	11.798	2.74	7.159	0.5	53.92766	4.914	4.948	0.57	Yes
OD01224	2015-11-25	38.504	14.126	76.246	12.288	169.5007	116.845	23.068	1.21	Yes

Site	Sampling date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Charge balance (%)	Use
OD01262	2016-05-25	94.8	46.2	137.6	0.5	247.416	237.5	135.9	3.37	Yes
OD01257	2016-05-26	9.7	3.4	119.2	2.7	348.188	22.4	3.2	-3.12	Yes
OD01254	2016-05-24	197.8	64.9	319.7	2	114.924	703.2	226.1	4.93	Yes
OD01252	2016-05-24	10.1	1.8	362.3	4.6	435.418	221.3	30.4	8.24	Yes
OD01209	2016-05-25	1.25	0.75	190.3	2.2	449.814	30.8	2.4	1.00	Yes
OD01207	2016-05-26	279.2	207.3	413.4	1.9	258.762	1227.5	431.1	1.22	Yes
OD01205	2016-05-25	32.5	10.2	183.5	1.5	236.314	230	5.6	0.02	Yes
OD01183	2016-05-24	3.1	0.75	311.9	2.6	527.528	159.2	0.6	2.60	Yes
OD01156	2016-05-24	1.25	0.75	302.1	2	654.896	63.8	0.6	2.98	Yes
OD01155	2016-05-24	1.25	0.75	330.4	2.7	620.614	160.7	1.5	-0.58	Yes
OD01166	2016-05-26	3.8	1.7	257	1.6	576.816	63.6	4.7	0.89	Yes
ODO1147	2016-05-25	76	53.9	123.7	2.3	269.62	261.8	61.7	2.17	Yes
OD01138	2016-05-25	219.9	223.7	286.9	9.5	191.662	897.5	428.4	5.95	Yes
OD01135	2016-05-26	19.1	7.8	279.7	1.1	460.428	187.6	12.9	2.54	Yes
OD01120	2016-05-25	79	22.9	539.7	5.2	265.716	583.4	147.9	10.40	Yes
OD01110	2016-05-25	229.9	204.6	346.9	16.8	323.666	967.9	363	4.36	Yes
OD01107	2016-05-25	143.5	102.4	191.5	6.9	238.266	527.4	145.8	4.96	Yes
OD01106	2016-05-25	118	36.6	89.1	1.4	265.472	131.3	214.1	1.18	Yes
OD01213	2016-05-26	4.2	0.75	292.5	2	483.364	143.4	6.5	3.75	Yes
OD012140	2016-05-25	55.1	54.7	346.7	2.2	198.372	483.2	170.3	4.58	Yes
OD01243	2016-05-25	118.1	79.1	194	2.5	274.5	446.7	176.6	0.31	Yes
OD01192	2016-05-24	3.2	1.6	442.5	2.5	520.696	313	14.3	5.21	Yes
OD01163	2016-05-26	40.5	32	92.4	1.6	148.962	151.6	83.9	1.46	Yes
OD01224	2016-05-25	27	11.5	89.7	15.9	185.44	81.7	53.8	1.06	Yes
OD01291	2016-05-26	11.7	4.3	8.2	0.5	42.72	4.8	4.3	10.69	Yes

Site	Sampling date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Charge balance (%)	Use
OD01178	2017-05-25	4.7	2.5	335.6	11.8	694.79	98.4	1.6	3.872919	Yes
OD01271	2017-05-23	81.4	32.4	511.6	8.2	391.254	573.6	226.5	3.334422	Yes
OD01268	2017-05-23	68	25.5	263.6	6.5	315.004	319.5	148.2	-0.3963	Yes
OD01257	2017-05-25	8.8	3	116.6	3.9	318.542	23.7	0.6	-0.37492	Yes
OD01254	2017-05-24	221.6	57.1	271.5	2.8	179.34	669.6	211.5	2.614815	Yes
OD01252	2017-05-23	14.1	2.5	325.9	7	582.428	178.2	29	0.290629	Yes
OD01209	2017-05-24	1.7	0.47	180.4	2.8	452.01	30.8	0.6	-1.51421	Yes
OD01207	2017-05-23	257.8	186.8	411.8	2.7	238.876	1152.3	332.7	3.208408	Yes
OD01205	2017-05-23	26.9	10.5	173.8	2	227.652	222.1	0.6	-0.9623	Yes
OD01183	2017-05-23	2.8	0.47	287.7	3.7	504.226	163.6	0.6	-0.40389	Yes
OD01156	2017-05-25	1.25	0.75	171.6	3.2	580.232	67.8	0.6	-19.704	Yes
OD01166	2017-05-25	4.1	1.2	265.2	2.7	533.14	64.6	16.5	4.403476	Yes
OD01138	2017-05-24	363.7	311.6	485.2	13.5	319.64	1570.7	574	2.957048	Yes
OD01135	2017-05-25	12	3.8	251.7	1.7	343.186	198.6	2.1	2.732522	Yes
OD01120	2017-05-23	15.5	2.2	341.6	2.7	157.624	424.4	0.6	4.320771	Yes
OD012140	2017-05-25	45.1	47.3	246	2.5	256.81	351.7	132.1	0.081932	Yes
OD01192	2017-05-23	3.8	1.6	470.7	4.3	632.57	313.7	22.2	3.02483	Yes
OD01163	2017-05-23	56.7	31.6	92.6	2.2	261.08	160.2	68.7	-3.61663	Yes
OD01224	2017-05-24	50.4	25.3	114.8	15.4	291.458	176.6	5.1	0.605375	Yes
OD01215	2017-05-25	10.7	4.5	474.4	12.9	891.088	177	39.5	3.429248	Yes
OD01249	2017-05-25	14.8	2.9	1047	11	2105.842	501.3	1.9	-1.9816	Yes
OD01260	2017-05-25	19.8	5.4	194.7	19.2	506.422	52.7	0.6	2.939943	Yes
OD01291	2017-05-24	15.2	4.7	12.3	0.5	82.35	11.2	9.5	-4.78768	Yes

Site	Sampling date	Cl (mg/L)	SO4 (mg/L	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	HCO3 (mg/L)	Charge balance (%)	Use
1107	13-11-2017	328.47	12.31	75.00	1.70	36.91	110.80	644.16	-36.677	No
1138	13-11-2017	277.33	317.80	123.87	2.71	65.27	223.05	317.2	-5.44	Yes
1147	13-11-2017	293.19	67.40	131.36	1.46	42.67	76.02	317.2	-9.50	Yes
1155	13-11-2017	176.04	2.13	278.86	1.25	0.08	0.30	573.4	-3.24	Yes
1156	13-11-2017	38.18	0.63	278.36	0.35	0.34	0.59	573.4	-23.59	No
1157	13-11-2017	20.36	0.00	157.02	2.06	2.90	5.65	261.08	1.48	Yes
1166	13-11-2017	30.41	2.85	98.39	0.23	0.87	2.35	573.4	-33.43	No
1205	13-11-2017	212.85	2.19	121.31	0.10	5.72	16.10	207.4	-14.26	Yes
1215	13-11-2017	186.36	21.33	331.06	16.37	6.19	6.21	1415.2	-17.95	No
1248	13-11-2017	237.72	0.72	381.34	7.50	2.34	3.48	1122.4	-7.08	Yes
1252	13-11-2017	156.95	21.74	230.24	2.66	1.45	6.99	563.64	-14.82	Yes
1260	13-11-2017	84.39	21.78	181.66	17.53	5.27	7.27	549	16.50	No
T- Dam	13-11-2017	527.02	61.28	471.91	11.92	29.86	30.84	366	-13.44	Yes
1120	13-11-2017	630.14	0.00	409.90	1.27	2.27	15.33	158.6	0.29	Yes
1135	13-11-2017	271.18	0.75	225.08	0.95	3.79	10.29	366	-8.96	Yes
1163	13-11-2017	231.86	96.09	97.00	1.48	32.16	78.51	256.2	-22.86	No
1178	13-11-2017	51.44	5.98	459.23	8.41	3.33	6.33	707.6	-24.33	No
1183	13-11-2017	200.02	0.00	535.72	1.99	0.39	1.25	524.6	-14.30	Yes
1192	13-11-2017	416.22	8.96	373.70	2.18	0.79	1.07	624.64	-12.08	Yes
1209	13-11-2017	29.43	0.52	169.49	1.50	0.07	0.64	463.6	-9.02	Yes
1243	13-11-2017	665.35	139.12	177.86	1.80	65.39	109.49	268.4	-10.56	Yes
1254	13-11-2017	1055.33	213.03	199.55	1.35	42.65	154.36	162.26	-3.70	Yes
1268	13-11-2017	385.20	169.28	218.94	3.76	21.30	53.64	353.8	-8.04	Yes
1271	13-11-2017	1121.70	196.56	620.55	6.01	28.63	77.06	448.96	-18.21	No

Sample ID	Sampling date	HCO3 (mg/L)	Ca (Mg/L)	Cl (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	SO4 (mg/L)	Charge balance (%)	Use
OD01178	21-05-2018	488	9	99.97	19	7	317	21	15.2	Yes
OD01207	21-05-2018	97.6	214	764.53	1	130	246	361	2.3	Yes
OD01268	21-05-2018	183	42	231.6	3	21	201	137	1.0	Yes
OD01215	21-05-2018	263.52	7	54.81	1	1	142	4	5.4	Yes
OD01257	21-05-2018	197.64	7	30.67	2	3	88	1	4.1	Yes
OD01138	21-05-2018	122	239	729.17	6	140	210	421	2.2	Yes
OD01260	21-05-2018	170.8	17	49.56	51	31	87	10	31.7	No
OD01213	21-05-2018	370.88	14	183.32	2	7	273	72	1.7	Yes
OD01249	21-05-2018	1029.68	14	601.8	56	19	1130	47	-14.3	Yes
OD01107	21-05-2018	231.8	53	281.87	3	51	80	2	-6.3	Yes
OD01120	21-05-2018	92.72	17	236.57	1	2	173	2	2.0	Yes
OD01248	21-05-2018	1586	5	169.41	25	8	367	4	-27.6	No
T-DAM	21-05-2018	380.64	17	412.79	10	33	331	44	-1.6	Yes
OD01240	21-05-2018	165.92	29	209.31	1	32	152	98	0.3	Yes
OD01192	21-05-2018	329.4	1	158.33	1	1	212	6	-3.2	Yes
Soek-op BH	21-05-2018	207.4	70	163.87	1	36	80	129	-3.6	Yes
OD01147	21-05-2018	207.4	45	185.31	2	40	92	56	-1.0	Yes
OD01262	21-05-2018	109.8	26	56.94	1	14	33	26	-0.5	Yes
OD01209	21-05-2018	356.24	2	30.96	1	1	143	1	-2.3	Yes
OD01252	21-05-2018	378.2	6	126.52	3	2	206	19	-3.4	Yes
Volmoersfontein	21-05-2018	385.52	3	51.69	2	1	157	1	-4.6	Yes
Soekop spring	21-05-2018	97.6	70	329	3	59	167	128	7.3	Yes

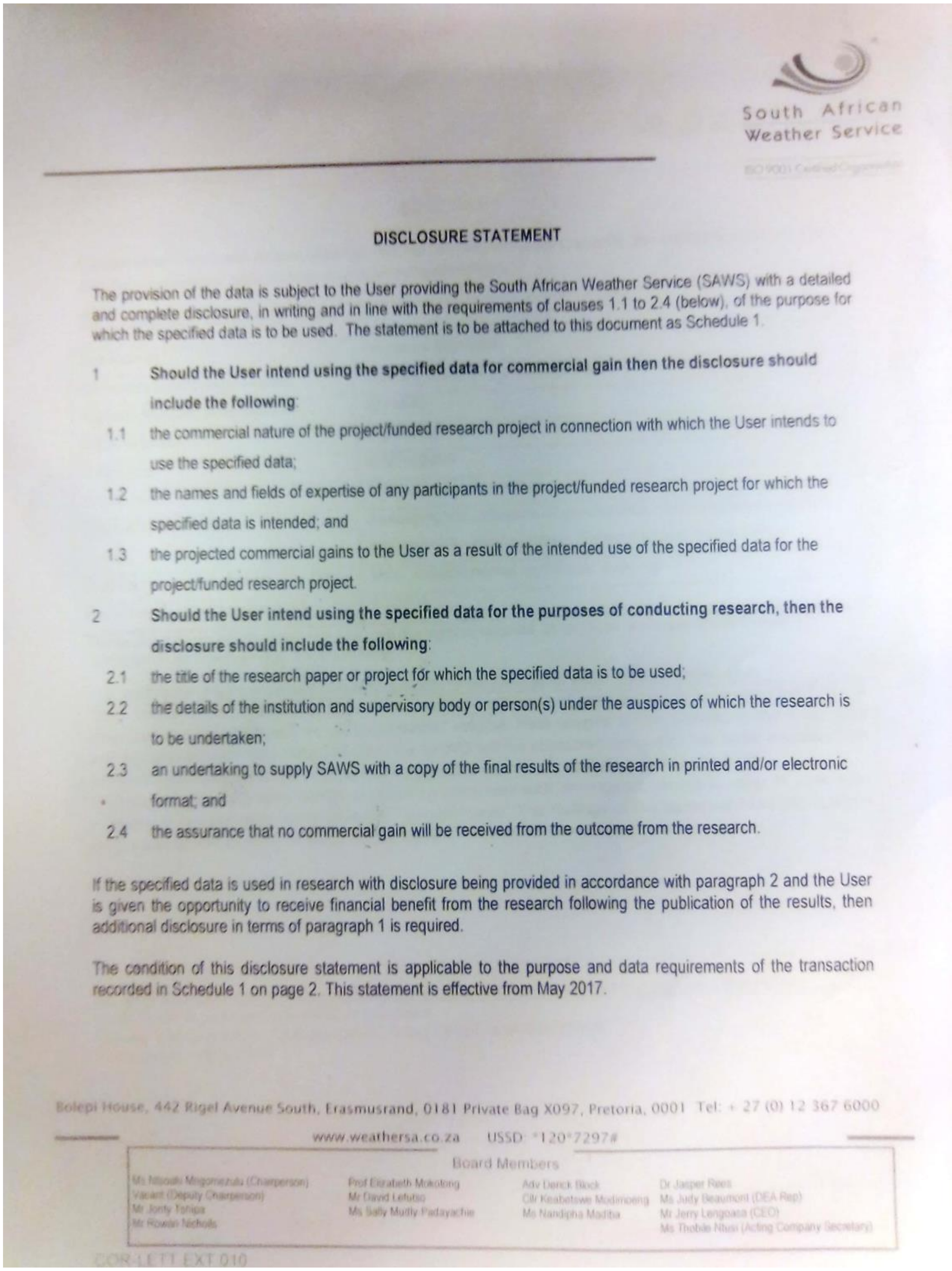
Appendix B: Stable isotope analysis of samples in the study area

Sample ID	Type	Date	δ^{18}O‰	δ^{2}H‰
ODO1209	Borehole	24-Nov-17	-6.46	-37.75
ODO1248	Spring	24-Nov-17	0.54	-6.91
ODO1271	Borehole	24-Nov-17	-0.41	-17.31
ODO1257	Borehole	24-Nov-17	-6.41	-37.56
ODO1252	Dug well	24-Nov-17	-4.51	-29.39
ODO1138	Borehole	24-Nov-17	-1.57	-18.46
ODO1183	Borehole	24-Nov-17	-6.43	-38.86
ODO1147	Borehole	24-Nov-17	-4.25	-28.19
ODO1120	Borehole	24-Nov-17	-5.12	-32.87
ODO1192	Borehole	24-Nov-17	-3.07	-22.65
ODO1166	Borehole	24-Nov-17	-6.56	-38.55
ODO1243	Borehole	24-Nov-17	-4.68	-28.95
ODO1135	Borehole	24-Nov-17	-5.86	-35.38
ODO1178	Spring	24-Nov-17	-1.51	-16.69
ODO1205	Borehole	24-Nov-17	-5.62	-33.53
ODO1155	Spring	24-Nov-17	-6.37	-37.78
ODO1268	Borehole	24-Nov-17	-3.39	-25.13
ODO1249	Spring	24-Nov-17	0.97	-7.21
ODO1163	Borehole	24-Nov-17	-4.71	-27.17
ODO1215	Spring	24-Nov-17	1.24	-0.47
ODO1107	Borehole	24-Nov-17	-5.17	-26.96
ODO1156	Spring	24-Nov-17	-6.5	-36.3
ODO1260	Spring	24-Nov-17	-3.6	-27.93
ODO1254	Borehole	24-Nov-17	-4.48	-26.93
T-DAM	Dam	24-Nov-17	9.63	56.4
RF-PB	Rain	24-Nov-17	-0.76	-3.36
RF-PT	Rain	24-Nov-17	-6.67	-42.56

Sample ID	Type	Date	$\delta^{18}O$‰	$\delta^{2}H$‰
OD01107	Borehole	11-Apr-18	-4.9	-30.4
OD01248	Spring	11-Apr-18	-5.03	-32.7
Soekop dam	Dam	11-Apr-18	-7.12	-42.7
Soekop spring	Spring	11-Apr-18	-1.51	-16.5
Renoster bridge	River	11-Apr-18	-5.75	-34.4
RF-Guesthouse	Rainfall	11-Apr-18	-6.67	-45.4
RF-office	Rainfall	11-Apr-18	-5.8	-40
RF-Gannaga rain	Rainfall	11-Apr-18	-6.82	-40.1

Sample ID	Type	Date	$\delta^{18}O$‰	$\delta^{2}H$‰
OD01262	Borehole	21-May-18	-5	-26.4
OD01252	Dug well	21-May-18	-4.79	-30.1
OD01257	Borehole	21-May-18	-6.45	-38.9
OD01209	Borehole	21-May-18	-6.6	-39.8
OD01268	Borehole	21-May-18	-3.1	-26.1
OD01207	Borehole	21-May-18	-4.47	-27.9
OD01213	Borehole	21-May-18	-2.92	-29.3
OD01240	Borehole	21-May-18	-4.75	-29.3
OD01138	Borehole	21-May-18	-1.61	-19.5
OD01120	Borehole	21-May-18	-5.15	-32.8
OD01147	Borehole	21-May-18	-5.08	-29.1
OD01107	Borehole	21-May-18	-4.71	-30.7
OD01192	Borehole	21-May-18	-3.33	-25
T-Dam	Dam	21-May-18	11.87	69.6
Soekop BH	Borehole	21-May-18	-4.46	-31.7
Soekop spring	Spring	21-May-18	-4.05	-23.6
Volmoersfontein	Spring	21-May-18	-6.38	-36
OD01260	Spring	21-May-18	-2.1	-13.7
OD01249	Spring	21-May-18	1.13	-1.1
OD01178	Spring	21-May-18	-2.05	-15.8
OD01248	Spring	21-May-18	0.66	-5
OD01215	Spring	21-May-18	-6.28	-35.2
RF-Gannaga	Rainfall	21-May-18	-4.42	-23.4
RF-Guest House	Rainfall	21-May-18	-2.89	-11.4
RF-Office	Rainfall	21-May-18	-5.56	-21.8

Appendix C: Ethical clearance letters and forms



South African
Weather Service
ISO 9001 Certified Organisation

DISCLOSURE STATEMENT

The provision of the data is subject to the User providing the South African Weather Service (SAWS) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.4 (below), of the purpose for which the specified data is to be used. The statement is to be attached to this document as Schedule 1.

1 **Should the User intend using the specified data for commercial gain then the disclosure should include the following**:

1.1 the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;

1.2 the names and fields of expertise of any participants in the project/funded research project for which the specified data is intended; and

1.3 the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.

2 **Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following**:

2.1 the title of the research paper or project for which the specified data is to be used;

2.2 the details of the institution and supervisory body or person(s) under the auspices of which the research is to be undertaken;

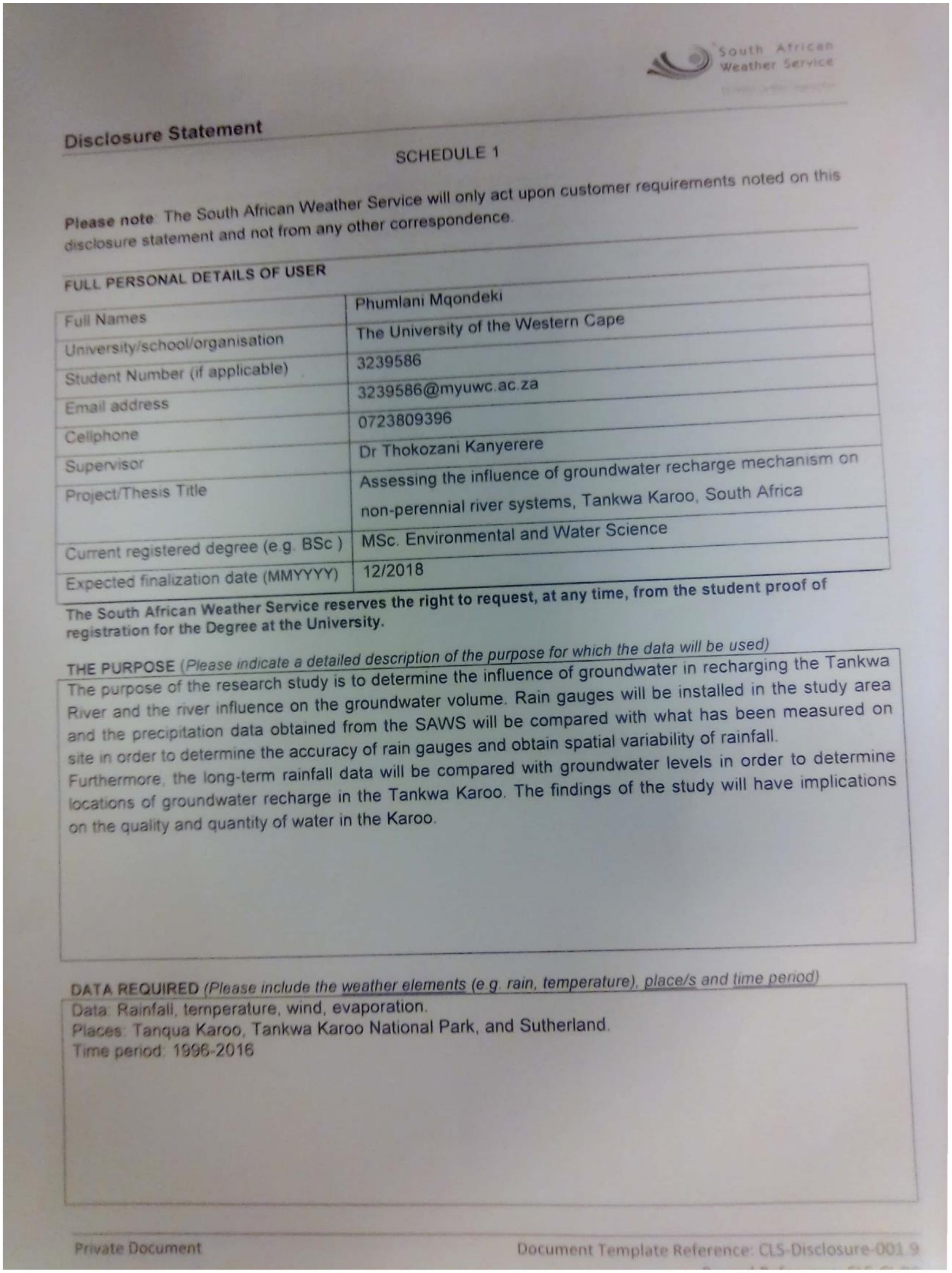
2.3 an undertaking to supply SAWS with a copy of the final results of the research in printed and/or electronic format; and

2.4 the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1 on page 2. This statement is effective from May 2017.

COR-LETT EXT 010



South African
Weather Service

Disclosure Statement

SCHEDULE 1

Please note: The South African Weather Service will only act upon customer requirements noted on this disclosure statement and not from any other correspondence.

FULL PERSONAL DETAILS OF USER	
Full Names	Phumlani Mqondeki
University/school/organisation	The University of the Western Cape
Student Number (if applicable)	3239586
Email address	3239586@myuwc.ac.za
Cellphone	0723809396
Supervisor	Dr Thokozani Kanyerere
Project/Thesis Title	Assessing the influence of groundwater recharge mechanism on non-perennial river systems, Tankwa Karoo, South Africa
Current registered degree (e.g. BSc)	MSc. Environmental and Water Science
Expected finalization date (MMYYYY)	12/2018

The South African Weather Service reserves the right to request, at any time, from the student proof of registration for the Degree at the University.

THE PURPOSE (*Please indicate a detailed description of the purpose for which the data will be used*)

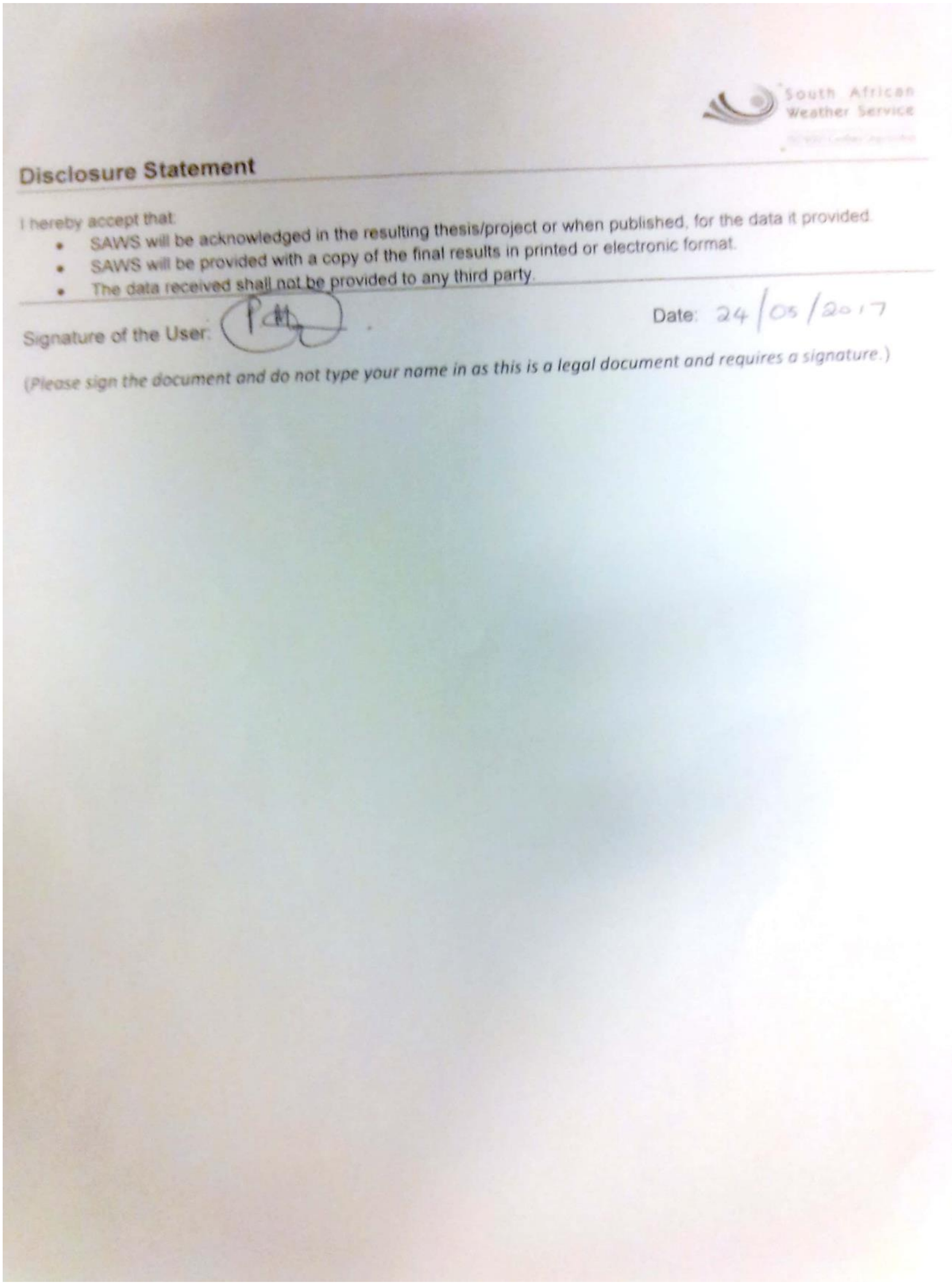
The purpose of the research study is to determine the influence of groundwater in recharging the Tankwa River and the river influence on the groundwater volume. Rain gauges will be installed in the study area and the precipitation data obtained from the SAWS will be compared with what has been measured on site in order to determine the accuracy of rain gauges and obtain spatial variability of rainfall.
Furthermore, the long-term rainfall data will be compared with groundwater levels in order to determine locations of groundwater recharge in the Tankwa Karoo. The findings of the study will have implications on the quality and quantity of water in the Karoo.

DATA REQUIRED (*Please include the weather elements (e.g. rain, temperature), place/s and time period*)

Data: Rainfall, temperature, wind, evaporation.
Places: Tanqua Karoo, Tankwa Karoo National Park, and Sutherland.
Time period: 1996-2016

Private Document

Document Template Reference: CLS-Disclosure-001.9



South African
Weather Service

Disclosure Statement

I hereby accept that:

- SAWS will be acknowledged in the resulting thesis/project or when published, for the data it provided.
- SAWS will be provided with a copy of the final results in printed or electronic format.
- The data received shall not be provided to any third party.

Signature of the User:

Date: 24/05/2017

(Please sign the document and do not type your name in as this is a legal document and requires a signature.)