Investigating the role of groundwater - surface water connectivity in supporting non-perennial river systems, Sandveld, Western Cape, South Africa

Raven Jesse Pietersen 3345873

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

Magister Scientiae (MSc)
In
Environmental and Water Science

Department of Earth Science,
Faculty of Sciences,
University of the Western Cape

Supervisor: Dr Thokozani Kanyerere
Co – Supervisor: Dr Jaco Nel

2021

DECLARATION

I, Raven Jesse Pietersen, declare that *Investigating the role of groundwater - surface water connectivity in supporting non-perennial river systems, Sandveld, Western Cape, 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: Raven Jesse Pietersen

November 2021

Signed…………………………………………………

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the National Research Foundation for providing the personal funding that made attaining this MSc a possibility. I would like to thank the Institute of Water Studies for allowing me to join the research team for The Environmentally Sustainable Management of Non-perennial Rivers Project which provided the research funding to make this study possible.

I would like to express my gratitude to my supervisors, Dr Thokozani Kanyerere and Dr Jaco Nel for their support, sharing of expertise, intellectual debate and guidance which helped develop my thinking around this study topic. Similarly, I would like to thank Prof Jenny Day for her facilitation of the student 'chattys' which formed a significant part of my skill development and the expansion of my knowledge during the course of this project.

I would like to thank Mr Julian Conrad of GEOSS for his sharing of valuable expert knowledge of the Verlorenvlei area. I would like to thank Mr Martin de Klerk for his assistance with the Geophysical Surveys conducted in this study, his expertise and insight into this field were invaluable in this work. A big thank you is also in order to the land owners of the Verlorenvlei and surrounding area for allowing me access to their land for my sampling and data collection needs and providing local insight to the workings of the study area.

I would like to thank the technical staff and my fellow students for their fieldwork assistance and valuable discussions which aided in this research. To Ms Nicolette Vermaak, Ms Nancy Job, my colleagues during my time at SANBI and fellow interns of the 2019-2020 class of the WWF Environmental Leaders Program, thank you for the words of encouragement and positivity that helped sustain my enthusiasm for this endeavour.

Finally, I would like to express my deepest gratitude to my significant other and close friends for their unending support throughout this research. K, thank you for reminding me of all of my capabilities and confidence. You kept me afloat.

ABSTRACT

Non-perennial rivers are characterised by a discontinuous and variable hydrological flow regime which may retreat to form isolated pools along the watercourse during prolonged dry periods. The resulting spatio-temporal variability in hydrological characteristics provides support for a variety of ecological habitats which promote species richness and biodiversity. It is well established that groundwater may offer flow supplementation to perennial river flow throughout the year as baseflow, while fewer authors have unpacked the nuances of the importance of groundwater in dynamics of water persistence and the conditions that determine non-perennial pool reoccurrence. This study explores river-aquifer interaction of the Verlorenvlei catchment within the Western Cape Province of South Africa as a case study in order to create an improved hydrogeological understanding of groundwater's role in non-perennial rivers to improve of water management practices. A multi-method approach was designed to fulfil this aim. In addition to desktop literature review and in-field sampling of water for environmental tracers, a water presence, groundwater level, and geophysical survey was conducted in order to develop a conceptual understanding of the multi-scale interaction occurring within the Verlorenvlei basin. Results of the isotopic and chemical analysis of water sources revealed the water origin and groundwater flow dynamics for the Verlorenvlei. The contribution of groundwater from Table Mountain Group related, fault-driven flow to the groundwater balance of the Verlorenvlei creates regional gaining conditions. Local gaining conditions within the Verlorenvlei river are created through lateral input of upwelling groundwater which moves downgradient with the topography as evidenced by the hydrogeological and geophysical survey. Using the Verlorenvlei as a case study, a contribution is made to the knowledge of the role of groundwater in non-perennial rivers. The results presented in this study indicate that where basin hydrogeology allows, groundwater may play an important role in the supply of water to non-perennial pools, especially during periods of minimal rainfall. The interaction mechanisms of this groundwater contribution within non-perennial rivers are site specific and spatially variable. Basin hydrogeology, subsurface stratigraphy and water availability are key limiting factors to interaction in non-perennial rivers. Future research aimed at generating robust information on discrete zones of water presence along non-perennial rivers may allow for better assessment of the potential vulnerability of these areas to water loss. Where these areas are fed by groundwater, to accommodate for their vulnerability, groundwater capture maps may allow for investigation of the local impact of groundwater use on these areas.

Keywords: Non-perennial rivers, interaction, groundwater, pools, South Africa, gaining, losing

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.1 Study Overview

This study explores the role groundwater may play in a non-perennial river system. Groundwater provides reliable water supply to water scarce countries such as South Africa during periods of less rainfall. To ensure the environmental and human water demand in water scarce areas is balanced, it is important to assess and understand the hydrological components that play a role in the natural functioning of these aquatic ecosystems. As groundwater remains an integral component of the hydrological cycle, there is a need for careful consideration of the role of groundwater in supporting aquatic ecosystems, particularly in non-perennial rivers, common in semi-arid, water scarce areas.

1.2 Background of the study

Within sub-Saharan Africa, water availability is a key challenge due to variable semi-arid to arid climate conditions (UNEP, 2010). Large watercourses which serve the Southern African Development Community (SADC) may flow year-round, while many rivers in these drylands experience infrequent flow occurrences, large transmission losses and, subsequently, flow non-perennially (Rossouw, et al., 2005; Seaman, et al., 2010; Mohamed, 2014).

Rivers that flow non-perennially make up more than 44% of the rivers across Southern Africa (Uys & O'keeffe, 1997; Skoulikidis *et al.* 2017). The South African National Water Act (Republic of South Africa (RSA), 1998) stipulates that flow requirements for aquatic systems, or the ecological reserve, is to be determined for the conjunctive protection of a given system's ecological integrity and water resource sustainability (Levy and Xu, 2011). Despite the abundance of non-perennial rivers in South Africa, methods to assess the environmental water requirements have primarily been developed for perennial rivers and have been determined to be unsuitable for application to non-perennial rivers (Rossouw *et al.*, 2005; Seaman *et al.*, 2010; Seaman *et al.*, 2016).

Non-perennial rivers are characterised by temporary lapses in water flow during indeterminate intervals, resulting in a riverine ecosystem with a characteristic discontinuous and variable flow pattern (Uys & O'keeffe, 1997; Seaman *et al.*, 2016). This temporary flow regime has resulted in these systems being mistakenly undervalued and minimally studied (Skoulikidis *et al.*, 2017).

During prolonged dry periods, non-perennial river flow may retreat such that isolated pools (or waterholes) remain scattered along the drainage line, resulting in differing hydrological characteristics along a single watercourse (Bunn *et al.*, 2006; Datry, *et al.*, 2018). This variability creates a spatio-temporal assortment of hydrological characteristics unique to non-perennial rivers which have been found to support a variety of ecological habitats promoting valuable species richness and biodiversity (Datry, *et al.*, 2018). With increased desiccation, the significance of the role of groundwater in the flow regime and characteristics of non-perennial rivers is believed to strengthen (Rossouw *et al.*, 2005). However, the relationship between groundwater and surface water resources may vary both spatially and temporally along a non-perennial watercourse (Seaman *et al.*, 2010). As such, understanding the characteristics of groundwater - surface water connectivity is crucial in establishing the ecological reserve for non-perennial rivers amid water resource development or abstraction.

Climate change and anthropogenic activities may increase the global distribution of non-perennial rivers as well as the pressure these sensitive ecosystems experience as a result of predicted increased water demand associated flow alteration (Arthington *et al.*, 2014; Skoulikidis *et al.*, 2017). Non-perennial rivers are threatened by multiple stressors. Their unique dynamic flow characteristics allow them to provide ecosystem services to the environment. Anthropogenic activities are noted to potentially affect these ecosystem services through changing the river's natural flow regime (Uys & O'keeffe, 1997). In a study by Seaman *et al.* (2016), which modelled the functioning of a non-perennial river in South Africa, scenarios of increased or decreased flood events resulted in responses in the form of changes to the low flow channel width, low flow channel depth, and geomorphic pool depth and pool length. Seaman *et al.* (2016) recommended further studies be undertaken on future scenario studies that predicted the effect greater water abstraction would have on the river regime.

This current study forms part of a larger multi-disciplinary project. The Environmentally Sustainable Management of Non-perennial Rivers Project conducted by the Institute of Water Studies attempts to facilitate research focused on understanding the hydrology of non-perennial rivers in a way that allows for well-considered development of these river systems such that the value they provide to the environment is protected. The overall project aim is to improve: the understanding of the relationships between river flow, ecosystem characteristics and services provided by non-perennial rivers; and the prediction, decision-making and management related to the ecological and social consequences of flow modifications of non-perennial rivers. This research is multi-faceted and focuses on a variety of interrelated environmental topics relating to non-perennial rivers such as geomorphology, hydrology, hydrogeology and water quality. The research conducted in this current study attempts to provide improved hydrogeological understanding to the questions related to groundwater raised by this project.

The area of interest for this study is the drainage region of the Verlorenvlei, an oligotrophic wetland estuary protected under the RAMSAR convention (Ramsar, 2020). Despite being situated in a low-rainfall, non-perennial drainage area, the Verlorenvlei is one of South Africa's largest wetland estuaries which forms part of the larger Sandveld region (CSIR, 2009). Noted as an ecologically important breeding ground for aquatic bird species, the Verlorenvlei is deemed a wetland of significance under the Convention on Wetlands (Ramsar, 2020). Groundwater abstraction in the Verlorenvlei basin area is of concern for the balance of competing users in the catchment (Conrad *et al.*, 2004). The core economic activity in the Verlorenvlei drainage basin and surrounding area is the commercial production of rooibos and potato. A previous study identified that over 50% of natural Sandveld habitat has already been transformed with an average of 2.7 Ha of the northern Sandveld cleared for agricultural use daily over a 15-year period (Archer *et al.* 2009). Groundwater distribution, recharge mechanisms and groundwater dependency has been a key research interest in this area to ensure sustainable use of the Sandveld groundwater resources (Conrad, 2004; Münch and Conrad, 2007; Münch *et al.*, 2013; Eilers *et al.*, 2017; Sigidi *et al.*, 2017; Miller *et al.*, 2018; Watson *et al.*, 2018). This current study builds on previous work by investigating the interconnected nature of the Verlorenvlei surface water and groundwater and the associated influence groundwater resource development may have on this relationship.

1.3 Research Problem

Many studies assess the hydrological regime of non-perennial rivers however they do not agree on the dynamics of water persistence and the conditions that determine pool reoccurrence. It is well established that groundwater may offer flow supplementation to perennial river flow throughout the year as baseflow, while fewer authors have unpacked the nuances of the importance of groundwater in the flow regime of non-perennial rivers. As a result, the role of groundwater in non-perennial rivers is poorly understood, which may result in inefficient water resource management in groundwater dependent areas.

Development of reference conditions for non-perennial river management, without fully understanding the contributing factors to the establishment of these conditions, would create difficulty in determining measures to protect or remediate non-perennial river ecosystems that deviate from these conditions. To reduce this difficulty, it is pertinent to understand the natural functioning of these systems and the potential impact of increased groundwater resource development.

1.4 Research Question and Thesis Statement

In what way does groundwater contribute to non-perennial rivers?

If the connectivity of groundwater and surface water within a non-perennial river system is explored, then we may better contribute to the knowledge of the role of groundwater in the functioning of non-perennial river systems. Through this understanding we may better assess what impact groundwater use may have on the balance of water resources for a non-perennial river.

1.5 Study Aim and Objectives

1.5.1 Aim

This study aims to characterise river-aquifer interaction for improved hydrogeological understanding of natural functioning of non-perennial river systems in Verlorenvlei.

1.5.2 Objectives

The objectives of this current study are to:

1. Determine applicability of methods to assess groundwater-surface water interaction for use in non-perennial rivers
2. Explore groundwater-surface water interaction processes at regional and local scales
3. Conceptualise the natural functioning of the groundwater-surface water processes

1.6 Study Rationale

Non-perennial rivers create unique environments that support ecosystems reliant on their variable flow regime for their existence. The extremes of the natural flow regime of variable dryland river systems are necessary for the acceleration of aquatic biota production and assist the species that inhabit these areas in survival. The increased water content and water persistence of non-perennial rivers during the wetter period is associated with high aquatic species diversity which has been found to be equally as ecologically important as the dry period, encouraging semi-aquatic and terrestrial biota biodiversity (Datry, *et al.*, 2018). Temporal variability of environmental conditions sustains long-term species richness and unique species composition of intermittent sites. (Katz *et al.,* 2011). Modification of a natural river regime may hinder its ability to maintain key processes that allow for a river to sustain ecosystems (Bunn *et al.*, 2006). By establishing groundwater's role in supporting the unique ecosystems of non-perennial rivers, this study may expand knowledge in preserving the natural regime of these unique environments whilst contributing to better water resource planning for sustainable, multi-use of the water resources. In addition, by conducting this research, this study may also contribute to establishing a method of assessing non-perennial rivers interaction which has been identified as a gap in practise that may be improved.

1.7 Scope and Nature of the Study

1.7.1 Scope

The study is limited spatially to the drainage basin of the Verlorenvlei river and wetland catchment, specifically the Krom Antonies, Krom, Hol river tributaries and the Verlorenvlei river and wetland itself. Groundwater can interact with surface water at varying resolutions. This study specifically focuses on larger scale, namely catchment scale, with reference to local scale exchange between surface water and groundwater at a local case study. The methods chosen are therefore limited to those that may generate information that may be upscaled. Similarly, those methods which investigate interaction over a regional scale allow for greater temporal indication of the variation of interaction. This may result in a generalised representation of interaction and the role of groundwater in non-perennial rivers.

The unit of analysis within this study is the interaction between groundwater and the broader non-perennial river itself which will be understood by investigating the unit of observation: the non-perennial pool and groundwater features (boreholes and springs). This study builds on the knowledge of groundwater's role in non-perennial river systems by investigating the interaction and connectivity of in-stream non-perennial pools with groundwater. Discontinuous flow and pool presence are key defining features of non-perennial rivers and therefore present a distinct feature that may enable exploration of interaction characteristic to the larger topic of non-perennial rivers at a local case study level.

1.7.2 Nature

This study is conceptual in nature with elements of quantitative research to confirm conceptualisation of catchment processes. A desktop review of previous studies informed characterisation of elements of the catchment groundwater budget. A field determination and field sampling campaign of water chemistry and survey of geophysical properties was undertaken to investigate at what scale groundwater – surface water interacts within this catchment. Investigations involving physio-chemical and environmental isotope water analysis and geophysical processes were used to build on the conceptual understanding of the functioning of the Verlorenvlei. As this study is largely exploratory, descriptive statistics were used to analyse the data to identify potential trends that may inform our understanding of how the hydrogeological system works at a catchment scale. The case study informs the research focus and builds on the knowledge of the role of groundwater in supporting non-perennial rivers.

1.8 Study Setting

The Verlorenvlei, located at 32°24'S 018°26'E, is a Ramsar listed wetland (site no. 525), first listed in 1991 for its essential role in supporting indigenous birdlife, more specifically, the essential breeding grounds it provides for the Cape Pelican (CSIR, 2009; Ramsar, 2020). This area is situated along the Atlantic Coast of the Western Cape of South Africa within the former Olifants-Doorn water management area (DWAF, 2013). The Verlorenvlei drainage area forms the southern extent of a predominately sand covered sub-region found along the West Coast, which consists of the Verlorenvlei, Langvlei/Wadrif and Jakkels river catchments; appropriately known as the Sandveld. Water resources of South Africa are managed at predetermined catchment units of which the most basic is the quaternary, upscaled to form tertiary, secondary and primary catchments of similar hydrologic character. The catchments of interest which make up the drainage region for Verlorenvlei are quaternary catchments G30E, G20C, G30D and G30B (Figure 1).

The Verlorenvlei catchment stretches across the coastal low-lying area extending from Elandsbaai from the coast inwards towards an eastern boundary of the elevated Piketberg mountains and includes the Eendekuil basin adjacent to this high lying area. An increase in elevation to the north of the study area forms the boundary to the well-researched Langvlei/Wadrif area. The greater Cederberg Mountain range forms the border to the outer extent of the catchment alongside the Eendekuil basin. The total area covered by this drainage region is 87 km in length and 43 km in width (CSIR, 2009).

Much like the majority of the Sandveld area, the Verlorenvlei floodplain and its surroundings are productive agricultural zones. Approximately 90% of potatoes supplied to the Cape Town urban area are locally sourced from the Sandveld region (Archer *et al.*, 2009). Being a predominantly semi-arid to arid area, water users rely on groundwater to compensate for limited surface water resources within the Verlorenvlei to meet everyday water needs of agricultural use and, to a lesser extent, municipal use (Archer *et al.*, 2009).

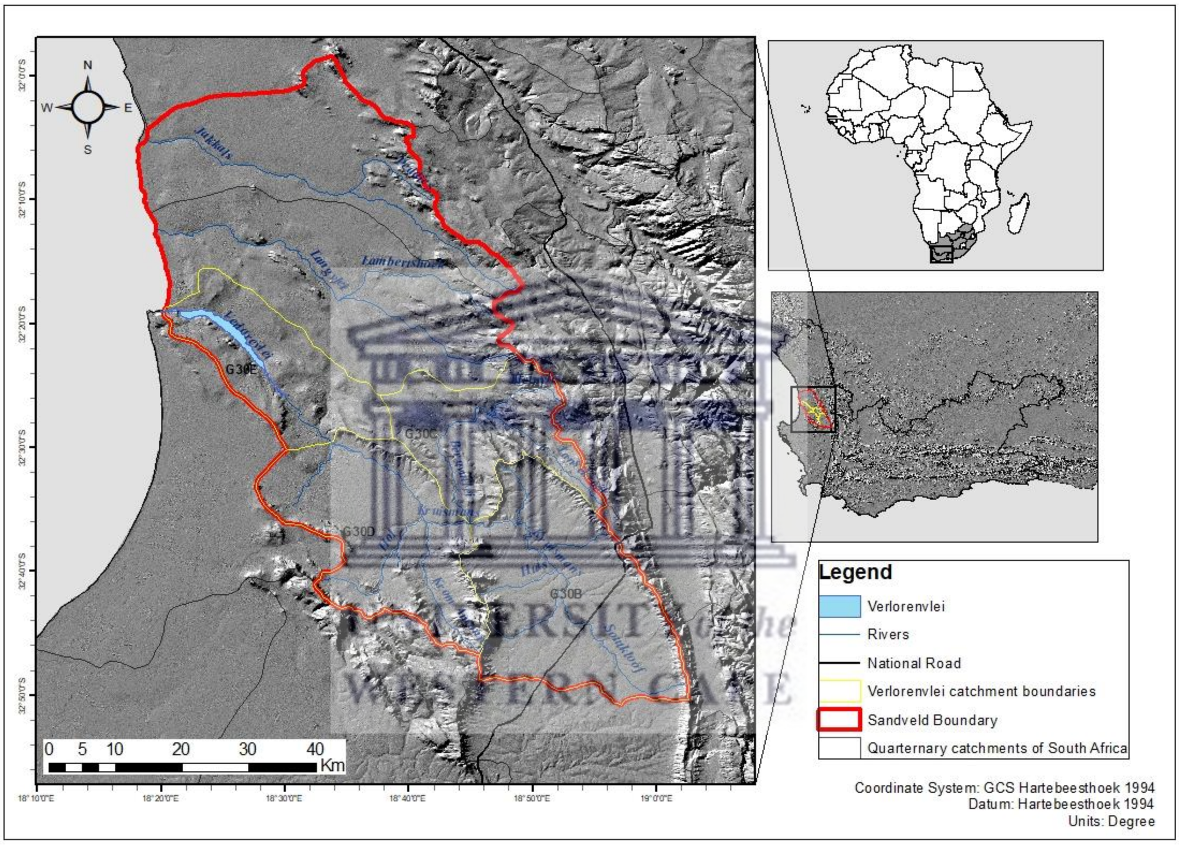


Figure 1: Regional setting of the Study Area, Verlorenvlei within the Western Cape of South Africa.

1.9 Thesis Outline

This thesis is subdivided into seven chapters. The chapters provide information pertaining to the current study in the following order.

Chapter 1 provides the study's synopsis. The research topic is contextualised and the research problem is identified. Here the main aims and objectives which have been chosen to address the identified problem are introduced. The scope and nature of this study is also provided which outline the study's limitations and units of analysis.

Chapter 2 establishes the governing theory and conceptual framework relative to non-perennial rivers which guide this study through review of available literature on groundwater- surface water interaction relevant to the context of non-perennial rivers. The applicability of existing methods for assessing groundwater-surface water connectivity to non-perennial rivers and contextualisation of the study topic within the local hydrogeological framework builds upon the research framework which acts as a guide for the central argument of this study.

Chapter 3 provides a description of the chosen study area for this research. A detailed description of catchment characteristics including the catchment hydrology, geology and climatological conditions relevant to the study focus is presented in this chapter.

Chapter 4 describes the methodological approach to this study. Research approach, selected study sites and sources of data are described here. Data collection and analysis methods are outlined in this chapter to ensure reproducibility of results. The quality assurance principals that apply to this study is also presented here.

Chapter 5 outlines the key results obtained to investigate the groundwater – surface water interaction mechanisms and character of the study area. Spatial and temporal analysis of the results provide insight into the main findings of the study. This chapter provides the conceptualisation of the natural functioning of the chosen study area as informed by in-field observations and literature review. Results are presented in order to establish an understanding of the groundwater – surface water interaction at both the regional and local scale discussed in the following chapter.

Chapter 6 presents a discussion of the case study results with respect to the research question in order to further the research aim and address the research question. Results are discussed in terms of what information they provide on the potential and mechanisms of interaction at various scales of interaction in the chosen study area to further the understanding of groundwater's role in supporting non-perennial rivers. A statement is also made on the success of the chosen methods in assessing interaction in a non-perennial river system in accordance with objective one.

Chapter 7 presents the conclusion in the context of the research question as drawn from the discussed results and key findings. As a reflection on this current study, a few recommendations that may add to further research on the same topic are also presented here in closing.

2.1 Chapter Introduction

The purpose of this section is to study relevant literature on the current knowledge and understanding of the topic of groundwater-surface water interaction within a non-perennial river context. To begin, the theoretical and conceptual framework of groundwater-surface water interaction and connectivity is given which will guide this research. Following an outline of the theory, a brief contextualisation of interaction within non-perennial rivers is given, followed by a review of methodology and approaches that have been used previously to address similar work is presented to showcase the debate upon which the research framework of this current study has been developed. Previous studies on groundwater -interaction within similar local settings are also reviewed to establish an understanding of common practises in similar environments so as to inform the current study.

2.2 Theoretical Framework

Two theories form the foundation of groundwater – surface water interaction in a multitude of environments: the water balance model and Darcy's Law of groundwater flow. These theories dictate two factors in understanding interaction: Darcy's Law explains the movement of freshwater in subsurface porous material whereas the water balance model describes the availability of freshwater in the environment for movement and interaction to occur. These theories provide the framework of theoretical principles that drive this current study and will be outlined in this section.

The hydrological application of the law of conservation of mass is expressed in the long-term dynamic equilibrium of water distribution on Earth. This continuum outlines the basis of the water balance model which specifies that the total inflow and outflow flux for any given water body or natural area of arbitrary volume is balanced by the resultant change in water storage irrespective of time (Sokolov and Chapman, 1974). This can be theoretically expressed as:

$$\pm\text{Change in Storage} = \text{Inflow} - \text{Outflow}$$

Variations of this equation exist for application to the relative inputs and outputs that affect a body of water or resource that may store water. In the case of groundwater, inflow could be precipitation as groundwater recharge or basin inflow from a neighbouring aquifer system, while outflow may be evapotranspiration from vegetation, groundwater discharge to stream flow or springs or outflow to neighbouring basins. An imbalance in these would be reflected in a change in groundwater storage for that specific aquifer.

Below the water table, aquifers store and transmit groundwater according to various parameters which control the flow rate through permeable rock bodies. The rate at which freshwater flows within a porous medium can be explained by Darcy's Law, first theorised by Henry Darcy in 1856 (Younger, 2007). This theory is simply given as:

$$Q = KA\frac{\Delta H}{l} \qquad (1)$$

In the equation above: Q is the flow rate (m/s), K denotes the Hydraulic Conductivity of the medium, A is the area through which flow takes place, ΔH indicates the change in hydraulic head and L is the length of the flow path across the medium. Assuming the occurrence of laminar flow, water moves between two points along a flow path due to differences in pressure and change in elevation according to the water potential or hydraulic head gradient. Darcy identified that in addition to pressure and head, the rate at which the water moves between the two points is directly proportional to a constant of proportionality or the hydraulic conductivity of the medium through which it passes.

The groundwater regime of any given area is limited and affected by the hydrogeologic characteristics of its environment. Topography, climate and geology give rise to the natural phenomena associated with groundwater (Toth, 1963; Toth, 1999). These characteristics govern the major factors constituting the groundwater regime, namely: the water content within rocks, the geometry of the flow system, the specific volume discharging, the chemical composition of the water and its temperature and lastly the variation of these parameters in time (Toth, 1999).

2.3 Groundwater - surface water interaction

The topography of an area creates a drainage basin where precipitation drains to an outlet via a stream channel. Within drainage basins, stream channel permeability, aquifer hydraulic conductivity as well as the correlation between surface topography and the water table play a role in interaction between groundwater and surface water (Winter *et al.*, 1998; Rossouw *et al.*, 2005; Newman *et al.*, 2006; Younger, 2007). The combination of these variables influences the flow regimes between groundwater and surface water: a gaining river will receive groundwater and a losing river will supply water to the subsurface aquifer.

Rivers may receive water laterally from the adjacent riparian zone or through subsurface runoff if the water table elevation is higher than its surface elevation or the river stage height (Winter *et al.* 1998; Newman *et al.* 2006). It is also possible for rivers to receive groundwater inputs via springs present above the river's edge as well as via direct seepage, either upwards from the streambed or lateral flow through the stream channel (Dahl *et al.*, 2007). Inputs of this nature may drive localised gaining river conditions at either a stream or river reach level (Newman *et al.* 2006) as seen in Figure 2 a and b. Alternatively, rivers may recharge associated aquifers through loss of water to underlying aquifers through their streambeds (Younger, 2007) as illustrated in Figure 2 c. Here, the hydraulic gradient would be in favour of river flow towards the aquifer system as the water table is lower in elevation than river stage creating losing river conditions (Winter *et al.*, 1998).

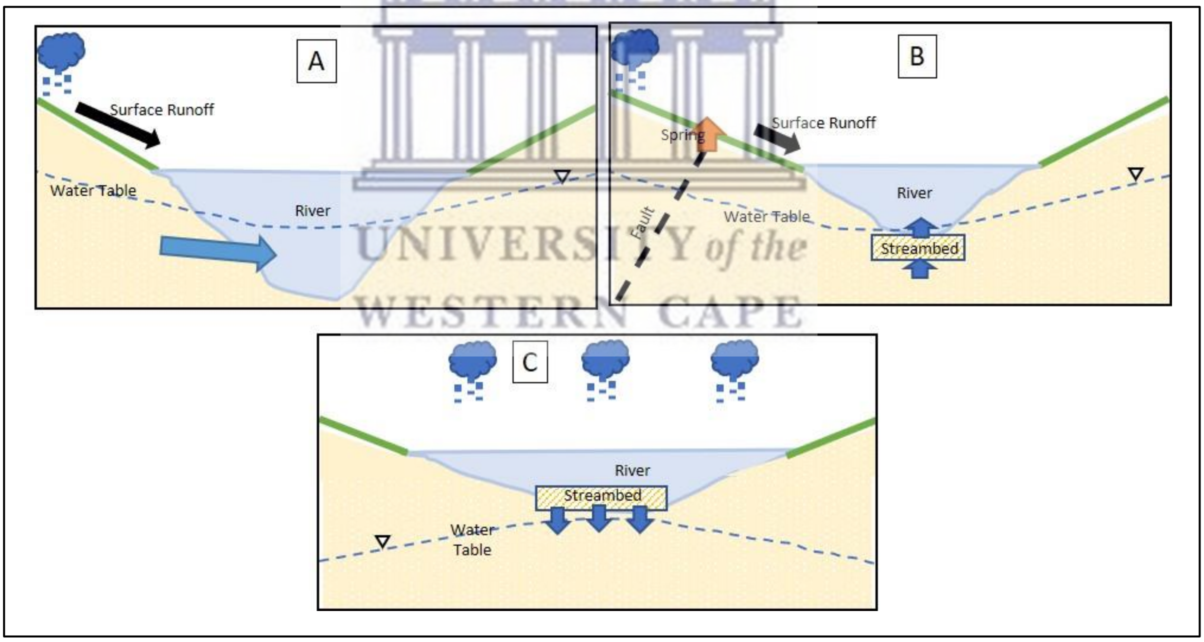


Figure 2: Illustrations of possible interactions between groundwater and rivers based on writings by Winter et al (1998), Newman et al (2006), Dahl et al (2007) and Younger (2007). Figure 2 a) illustrates gaining river conditions via surface runoff and lateral groundwater inputs to the river, b) illustrates gaining river conditions via spring flow surface runoff and upwelling groundwater through the streambed, c) illustrates losing river conditions where the river provides groundwater recharge via the streambed.

A single river channel is not always naturally exclusively gaining or losing. Direction of flow between groundwater and rivers may persist at times but at other times it may vary along a stream with different conditions occurring from reach to reach (Winter *et al.* 1998). Many second order factors contribute to the nonuniformity of interaction along a river channel. This variability is characterised by streambed permeability, aquifer hydraulic conductivity and the channel position in relation to the groundwater elevation, as well as by the geometry and size of the contact area. (Younger, 2007; Dor *et al.*, 2011)

In-stream gaining and losing conditions are influenced by the state of connectivity between the river and underlying aquifer. River - aquifer connectivity is characterised by saturation of the stream bed and aquifer material (Winter *et al.,* 1998). In connected river – aquifer systems complete saturation characterises water flow between the river and aquifer (Brunner *et al.* 2011). When an unsaturated zone is present beneath the surface of a river, it can be expected to be unconnected to the underlying aquifer, and is more likely that the river is either in a transitional or disconnected state (Brunner *et al.*, 2009). When the unsaturated zone (or clogging layer) is notably thicker, it is likely the river will be disconnected from the aquifer below. Disconnected rivers lose water to groundwater with higher infiltration rates than those of connected river – aquifer conditions (Brunner *et al.* 2011). In transitional rivers both connected and disconnected characteristics are present. This state differs from a disconnected river in that changes in the water table will affect the infiltration rate while in disconnected rivers, the infiltration rate would be unaffected due to the thickness of the unsaturated zone.

2.4 Interaction in non-perennial rivers

Whilst perennial rivers are considered to be continually flowing with a chance of flow cessation during periods of drought, non-perennial rivers cease flow periodically and may be sub-divided into semi-permanent, ephemeral and episodic rivers according to their increasing period of no flow (Rossouw *et al.*, 2005). The natural variability of flow regime of a non-perennial river (Bunn *et al.*, 2006; Gallart *et al.*, 2008; D'Ambrosio *et al.*, 2017) provides the framework for variation of groundwater – surface water connection in these systems.

As flow subsides within non-perennial river channels, isolated pools may occur (Rossouw *et al.*, 2005, Larned *et al.*, 2010). Through isotopic analysis, Bunn *et al.* (2006) established that waterholes or pools may persist for up to 23 months to 10% of total bankful volume without contribution from surface water input and primarily evaporative losses. Deeper, larger waterholes were found to remain after 2 years without input. While some authors have suggested that, in addition to rainfall or inundation, these pools are sustained by groundwater inputs from springs or seeps resulting in gaining conditions (Rossouw *et al.*, 2005; Boulton and Hancock, 2006; Newman *et al.*, 2006; Larned *et al.* 2010; Seaman *et al.*, 2010), Bunn *et al.* argued that there is little evidence of groundwater contribution to these pools and rather that permanence of these refugia was a result of channel morphology and the channel evaporative loss, causing the pools to persist for lengthy periods of time with no surface flow connection.

Permanent availability of water may however result in persistent gaining conditions. Rossouw *et al.* suggests that springs, an above ground expression of groundwater, may discharge at the surface and contribute to river flow and unique ecosystems in non-perennial rivers as a result of the permanent water input. Where water availability results in spatial intermittence (naturally or in the case of perennial streams undergoing drought) Boulton and Hancock (2006) suggest input from groundwater and hyporheic flow may sustain pools along a river course and affect the flow duration or water permanence that govern ecosystem processes. Permanence of pool storage along the non-perennial Seekoei River in South Africa (Seaman *et al.*, 2010) was found to be dependent on seasonal balances between spring discharge and evaporation. Where there was no evidence of spring flow, it was suggested that minor groundwater inputs were possible at small volumes as the hydraulic gradient was low (Seaman *et al.*, 2010). In a review of semi-arid drainages, prevailing effluent (losing) or influent (gaining) conditions were found to be as a result of the mode of lateral water inputs to the stream and aquifer (Newman *et al.*, 2006). It is assumed that overland flow is a major lateral contributor of water to the stream channel in many semi-arid drainages, in addition to subsurface runoff or through flow. Where extended recession limbs are found on the hydrograph of semi-arid drainages, it has been proposed that subsurface runoff contribution could be the explanation (Newman *et al.* 2006). Unlike the situation in non-perennial rivers where flow cessation occurs, perennial rivers may continue to flow into the dry period, sustained by groundwater fed baseflow, which is distinct from the flow events associated with precipitation (Sophocleous, 2002).

In a Brazilian study by Costa *et al.* (2013) on channel transmission losses in an alluvial dryland river it was found that at different intervals of the hydrological cycle from dry to wet season, the relationship of the connection of the river and the groundwater body underwent variation. During the dry and beginning of the rainy season no river flow occurred, however, rainfall events had vertical infiltration into the alluvium of the river channel. Towards the end of the rainy season the river was sustained by baseflow and lateral infiltration into the alluvium was observed. In this way the river exhibited two types of connection through its hydrological cycle – a losing connection type during the dry season and a combination of losing/gaining conditions through the wet season. An Australian study by Rau *et al.* (2017) conceptualised four regimes by means of streambed temperature studies of interaction in a semi-arid river. In this conceptualisation of transitory interaction flow regimes, a dry channel is characterised followed by a period of rapid surface run off, the pool-riffle sequence and the period of riffle flow cessation and drying of isolated pools (Rau *et al.*, 2017). These flow regimes support findings of Costa *et al.* in that post dry channel surface runoff resulted in high infiltration in locations depicting ephemeral river flow conditions as a delay in streambed saturation occurred. Further to that, Rau *et al.* conceptualised that, if infiltrated event water did not distribute itself, groundwater mounding would occur, and the water table might rise above the surface intersecting the channel topology creating local pools. As the groundwater mound re-distributes itself in the subsurface, the channel sediments will dry out and decrease the hydraulic head, resulting in isolated pools drying out. This may potentially cause surface water in areas upstream to disappear.

In addition to the temporal variation of interaction following the hydrological regime of these rivers, non-perennial rivers may also be characterised by spatial variability in their connection with groundwater. A study conducted by Lamontagne, *et al.*, (2014) aimed to characterise the various types of connection within the semi-arid to arid Murray-Darling River basin in Australia through experimental comparison of the water table connectivity classification and riverbed fluid pressure classification methods. This study aimed to clarify connection types within the study site and found variable connection types of losing – disconnected, losing – connected and gaining conditions across the selected sites. Losing – disconnected reaches were characterised by the presence of a low conductivity silt-clay or clay unit (clogging layer) and a low water table at times 6 to 25m below the riverbed. This contrasted with connected sites where the water table was never lower than 1m below the riverbed (Lamontagne *et al.*, 2014). The stability of the connection conditions at these reaches remained subject to changes in the hydrological regime of the river basin; during a wetter period, transitions from disconnected to connected were more likely due to resulting decrease in depth to water table and increased infiltration capacity following flood events. A previous study by Fleckenstein *et al.* (2006) found that variation in the water table is higher when the river stage was high with lower variation occurring when the river is mostly dry and mainly influenced by antecedent water table moisture from the previous wet season. Variable seepage during wet seasons were attributed to this variation as it may cause local reconnections between aquifer and river channel upstream. These reconnections could explain seasonal measurements of local gaining conditions in select reaches of rivers (Fleckenstein *et al.*, 2006).

Banks *et al.* (2011) proposes that connectivity states can indeed vary along stream reaches according to seasonal water availability but also take place concurrently at a singular location. In a regional assessment of the connectivity of the semi-permanent Rocky River in Australia by Banks *et al.* (2011), different parts of the catchment showed longitudinal variation in the connection with groundwater flow zones (a localised shallow regolith, a deeper fractured rock aquifer and a shallow perched Quaternary sand aquifer). A change in groundwater discharge, streambed leakage, contribution from surface runoff or evaporative water loss reflected a change in river flow from gaining to losing conditions and where pools were found in this river system, both gaining and losing conditions were established. Banks *et al.* (2011) showed that in addition to geomorphic, hydrologic property and ecological controls (Newman *et al.,* 2006), consideration of the hydrogeologic and climatic controls is needed in developing the conceptual model of interaction in non-perennial rivers. A study by Konrad (2006) established patterns of the spatio-temporal variability of river – aquifer interaction, several geologic and geomorphic controls, and reach-scale gains and losses of streamflow. Investigations of basin hydrogeology and gains and losses of streamflow were reviewed to characterize general patterns in the timing and location of river exchanges. The largest exchanges were associated with relative thickness of unconsolidated aquifers, contact of lithologic units with contrasting permeability, and the hydraulic gradient or cross-sectional area of flow paths between a river and shallow groundwater (Konrad, 2006).

Not only do groundwater inputs to river flow have a water quantity influence but groundwater inputs may have chemical and thermal influences that play a role in instream processes (Boulton and Hancock, 2006). A salt balance that follows the hydrological regime of non-perennial rivers has begun to form conceptually through review of several studies. During the dry period, increases in river salinity due to evaporative concentration and/or input from a saline, high dissolved-ion input baseflow or groundwater source can be expected (Banks *et al.*, 2011; Skoulikidis *et al.,* 2017). In an intermittent river reach in southern Greece containing a spring-fed pool, Skoulikidis *et al.* (2017) observed that the dissolution of soluble salts during initial flood events at the beginning of the wet season resulted in an increase of salinity as salts accumulated during the dry period in soils and groundwater aquifers flushed through to the river. Mobilisation of salt accumulation in the vadose zone through lateral water inputs to semi-arid drainages can potentially drive location-specific accelerated biochemical cycling through impacts on water chemistry (Newman *et al.,* 2006). Findings by Skoulikidis *et al.* (2017) show that salt accumulation processes in soil pores and aquifers of the riparian and groundwater aquifer areas during the dry season progress to dilution with increasing discharge resulting in a decrease in salinity. As the stream hydrograph begins to recede and desiccation increases a minor rise in daily values of physicochemical parameters can be expected as discharge decreases. As desiccation progresses, a return to high salinity levels is observed as concentration processes intensify.

Non-perennial rivers are not only at risk to adverse effects identified by Falke *et al (2011),* such as loss of ecological habitat due to drying of pools or pool isolation, but there is also a potential water quality change that may occur through improper management. Rapid drying of non-perennial river systems and infrequent flooding increases the river's vulnerability to anthropogenic impacts which may degrade the water quality (Skoulikidis *et al.*, 2017). During periods of extreme low flow, nutrient and turbidity concentrations may decrease while river sites experience rises in salinity due to decreased catchment inputs and increased influence of saline water inputs (Mosley *et al.*, 2012). Models of an area's functioning can be used to project conditions into the future under different realistic scenarios, allowing managers to strategically assess the quantity and quality of remaining aquatic refuge.

The concepts discussed above form the foundation of understanding which will inform the method of enquiry of results obtained from the assessment of groundwater – surface water in this current study. These studies were reviewed to create the conceptual framework for this study as they were conducted in areas of similar climatic, geologic and river flow regimes to that of the proposed research area of the current study. Literature reviewed here outlines what can be expected in the temporal and spatial variation in connectivity and interaction between groundwater and surface water sources within non-perennial river environments. These studies show that it is important to focus on the various factors that may contribute to the variation in order to understand the mechanisms and processes that may be behind the variation. Identified important factors include geological characteristics of the area in terms of the lithology and geological features such as contacts, the area geomorphology and stratigraphy, and climatic controls which may influence water availability, river functioning and groundwater – river connectivity. By reviewing the changes to the water quality in these environments we can also understand how the studied system may react in terms of the established units of analysis for us to better understand our results related to the investigative aim and objectives of this current study.

2.5 Methods for assessing connectivity in non-perennial rivers

Multiple methods have been demonstrated to provide an assessment of groundwater - surface water interaction across a spectrum of spatial scales and degrees of complexity, presented in several review papers (Kalbus *et al.*, 2006; Brodie *et al.*, 2007; Fleckenstein *et al.*, 2010), however currently no formal method has been formulated for the collection of data in the context of non-perennial rivers (Seaman *et al.*, 2016). Each method used to investigate interactions between groundwater and surface water is attributed to certain caveats and applicable situations. As previously highlighted, groundwater may interact with surface waters in highly variable settings, so careful consideration of the methods, and context of the study in terms of its spatial and temporal resolution (Shanafield and Cook, 2014) is important in choosing methods to assess groundwater – surface water interaction.

Using the important characteristics for consideration of interaction in non-perennial rivers identified in the previous section, methods are reviewed according to their applicability in a non-perennial river setting. This section provides a review of literature which highlights the methods used to investigate groundwater – surface water interaction and their applicability to non-perennial river environments in accordance with the first objective of this study. The characteristics that are deemed important for consideration in choosing applicable methods are the scale of interaction the method is identifying, the methods ability to still be used during periods of no flow or when dry riverbeds occur, and how they fair according to the standard methods of interaction shown to be successful in previous interaction studies. Methods chosen are then applied in the study's second objective to assess groundwater – surface water interaction within the study area.

- Scale applicability

Newman *et al.* (2006) expresses the difficulty in characterising groundwater-surface water interactions within a system due to high variability across multiple scales of time and space. Groundwater – surface water interaction is typically researched at local river reach scale as discrete individual systems with classified connection types, which does not represent the function of these reaches within the context of regional river systems (Banks *et al.*, 2011). These studies alone cannot be inflated to represent regional information due to areas of high variability. However, a series of local studies or data collected at a local scale may be applied to a larger investigation of regional interaction. Alternatively, information gathered from these studies may be upscaled through applying an understanding of the processes at the local scale to the context of the larger area.

Hydrochemical comparison of groundwater and surface water through the investigation of their relative chemical and isotopic composition has been demonstrated to be an applicable method to water bodies and has been used to infer interaction across a multitude of settings and scales (Négrel and Lachassagne, 2000; Kumar *et al.*, 2008; Menció *et al.*, 2014; Wang *et al.*, 2015; Oyarzún *et al.*, 2016). In a study on the semi-permanent Rocky River catchment in Australia, Banks *et al.* (2011) were able to determine the regional connection type between the groundwater and surface water sources in the area through a combined approach of geochemical tracer-based approaches and shallow (45,5m) hydrogeological surveying. Hydrochemical parameters investigated in this study included: physicochemical parameters, major element analysis and environmental isotopes. This investigation was able to discern that the river system was not connected to the regional saline groundwater aquifer system and can generally be classified as either transitional or disconnected type system overall. A strong understanding of the groundwater flow and geological environment in combination with these parameters informed the development of the conceptual model for the Rocky River presented by Banks *et al.* (2011). Through application of this approach, Banks *et al.* (2011) established the dominant groundwater source to the headwater river system as the shallow sedimentary aquifer system rather than the regional fractured aquifer system as previously hypothesised. Establishing the chemical character of the various inputs lead to the finding that groundwater discharge from the fractured rock aquifer system was unlikely due to its high salinity in comparison to the Rocky River (Banks *et al.*, 2011). Hydrochemical analysis has been suggested as a potential technique for establishing the source of water of non-perennial river pools (Rossouw *et al.*, 2005) and will be used in this study to assess the groundwater – surface water interaction within the study area.

Geophysical and remote sensing advances can be useful tools in mapping characteristics that may be secondary indicators of groundwater-surface water connectivity. To explore underlying lithology and geology, geophysical methods of groundwater exploration can be employed to assist in the assessment of groundwater - surface water interaction. Geophysics allows hydrogeologists to map important characteristics such as soil or sediment texture, groundwater chemistry and moisture content unobtrusively (Brodie, *et al.*, 2007; Samouelian, *et al.*, 2005). Crosbie *et al.* (2014) demonstrated the applicability of resistivity surveys to a regional scale investigation of groundwater – surface water interaction in a 2km losing-disconnected stretch of the Billabong Creek, Australia. By applying a threshold approach to river geophysical profiling, they were able to apply the basic concept of a disconnected river reach to test infiltration at a regional scale through identifying the clogging layer in the river stretch. In this study, contrasting resistivity between sediment layers were used to indicate the clogging clay layer and distinguish it from neighbouring variably unsaturated sand layers. Results of resistivity surveying was then interpreted to calibrate a conceptual cross section infiltration model applicable to the losing-disconnected river. The potential for upscaling geophysical approaches is realised in this study, however it was suggested parallel assessments using multiple geophysical techniques would have improved the interpretation of the results (Crosbie *et al.*, 2014).

- Applicability to no flow & dry channels

Spatial variability of interaction has been accounted for through the application of various methods. Delineation of sites of groundwater – surface water exchange in streams has been accomplished through in-stream profiling of rivers (Haria *et al.*, 2012) or incremental measurements of streamflow (Kalbus *et al.*, 2006; Konrad, 2006; Menció *et al.*, 2014). Consecutive (every 40m) physico-chemical in-stream profiling down the length of the Hafren catchment in Wales by Haria *et al.* (2012) identified discrete inputs of water with a hydrogeochemical signature to streamflow indicating potential groundwater discharge. An incremental stream flow measurement approach was utilised by Menció *et al.* (2014) in conjunction with piezometer hydraulic head surveys and hydrochemistry to give an indication of river- aquifer connection. In establishing the discrete exchange potential between groundwater and surface water in perennial or continually flowing rivers, the unit of measurement is often river flow (in the case of water balance approaches) or stage height (in the case of Darcy's Law approaches) or longitudinal river chemistry survey. However, in non-perennial rivers during extended periods of no flow and dry channels, these units of measurements fail to provide information on occurrence and origin of disconnected pools when surface flow is zero (Gallart *et al.* ,2016).

- Multi-method approach

In several studies a combination of multiple methods is used to overcome limitations to ensure that the correct methods are used for the correct scenario under investigation. Weitz and Demlie (2014) assessed the groundwater contribution to a freshwater lake through a combined water balance approach with an analysis of groundwater head, geological properties and tracer-based studies of hydrochemistry and environmental isotopes. This multi-method approach has been applied often to similar studies with confidence in the conceptualisation of interrelated flow within the studied environment. A combination of geophysical resistivity imaging, a water balance approach and stable isotope analysis was used in a study by Dor *et al.* (2011), which aimed to determine the hydraulic setting of an irrigation system and establish the hydraulic interconnection between aquifer systems. Through 2D electrical imaging techniques, the conductance and relative resistivity of the below strata were observed and an aquifer layer at a specified depth below the surface was identified. Through isotopic analysis, Dor *et al.* (2011) were able to discern a hydraulic link between groundwater and surface water in the catchment as the groundwater isotopic character were revealed to come from evaporated samples. A net loss of water in the water balance of the irrigation canal was connected to the findings of the resistivity imaging survey which found shallow high conductive layers in sections along the canal which could be responsible for water loss to shallow aquifers in the area through groundwater recharge. By analysing the results from a combination of these methods, correlations in findings improved understanding of the interaction processes in this area.

Although the water balance approach is applied incrementally to the inflow and outflow of the irrigation canal (Dor *et al.*, 2011), the reach level application of the water balance methodology is an approach that can be utilised to create more robust information on interaction for the drainage area as a whole. Ivkovic (2009) developed an up-scalable approach to characterise aquifer – river interactions by collating existing data first and then applying a multi method analysis of the interaction processes at the reach scale to identify the hydraulic connection across the regional catchment. River reaches were characterised through hydrograph analysis to gain insight into the presence of hydraulic connection, the dominant direction of flux, and the potential for groundwater extraction to impact rivers. A resulting map of the river – aquifer connectivity and dominant direction of flux across the rivers within the region was developed. Much like in this study, an initial collation of existing data can provide a preliminary understanding of an area's interaction upon which more detailed investigations can be based to improve the understanding of the driving processes of the area. Tanner and Hughes (2015) highlight the importance of establishing a conceptual understanding of the site-specific functioning before a more detailed model of an area's groundwater-surface water interaction can be created. This current study will implement multiple methods at reach level to account for variable interaction processes and gain understanding of the regional scale interaction mechanisms within the selected case study.

2.6 Interaction research in South Africa

The third objective of this current study is to conceptualise the natural functioning of the Verlorenvlei within the context of groundwater - surface water interaction as a non-perennial river system. Groundwater - surface water interaction has been studied in the context of the quantity and quality contribution of groundwater to rivers, in order to establish the role of groundwater in the ecological water requirement of South African rivers. Previous studies on groundwater dependency of ecosystems create the hydrogeological framework for river – aquifer interaction within a South African context. Recent local interaction studies has developed applicable approaches to the growing groundwater - surface water interaction research in South Africa.

2.6.1 Local hydrogeological framework of interaction

Historic monitoring of groundwater and surface water resources has been approached discretely, rather than as a single resource, creating difficulty in the study of interaction in South Africa (Levy and Xu, 2011). However, growing interest in the role of groundwater in environmental requirements has generated more information on interaction between these resources in the context of South Africa. Roets *et al.* (2008) aimed to characterise the connection between the fractured aquifer of the Cape Fold mountains of South Africa and associated aquatic ecosystems of the mountain and lowland reaches of rivers and streams. Roets *et al* (2008) conceptualised that the interface between groundwater and surface resources is associated with geological contact areas. This study identified two major zones of groundwater contribution to rivers and streams which are associated with the recharge zone and the discharge boundary of the aquifer. In the recharge zone, preferential flow creates opportunity for groundwater contribution to headwater stream reaches in the form of interflow, while geological contacts (and/or fractures or faults) in discharge zones create groundwater springs responsible for discreet Table Mountain Group (TMG) discharge and bank storage discharge in the foothill and lowland reaches.

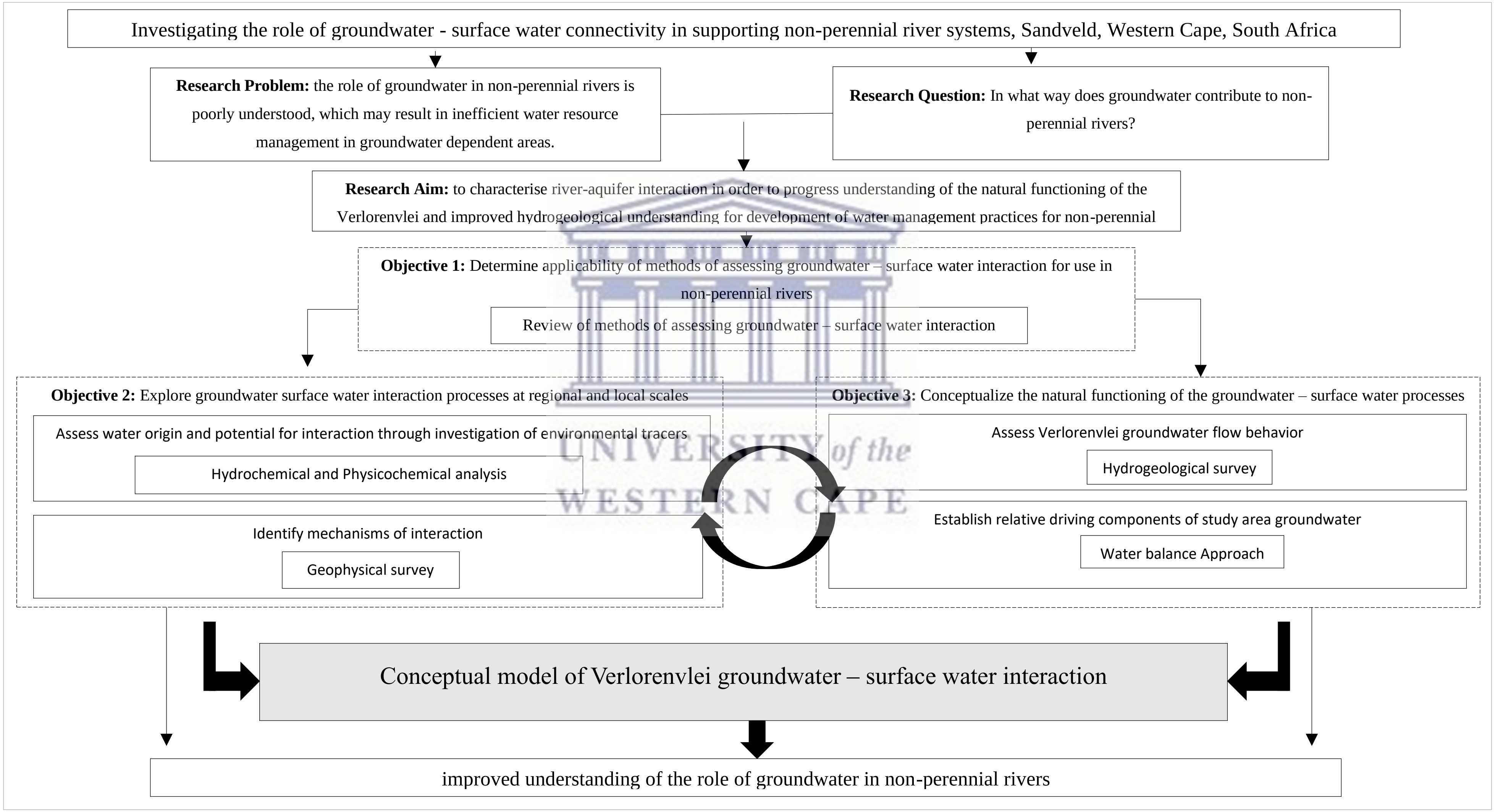
This builds on earlier work by Colvin *et al.* (2007) which aimed to categorise South African aquifer types and their association with various groundwater dependent ecosystem types. Secondary aquifer types such as the TMG are known supporters of spring, in-aquifer, riverine aquatic, riparian, wetland/seep and estuarine/coastal environments within the Western Cape of South Africa. Coastal primary aquifers similarly have known relationships with these groundwater dependent habitats, apart from springs and in-aquifer habitats, which were noted as probable but not known. This research provides the hydrogeological framework of interaction and characteristic groundwater contributions that may be present in South African basins. Studies on ecosystems that rely on groundwater associated with the TMG aquifer by Roets, et al. (2008) and Colvin, et al. (2007) provide insight into the expected environments where groundwater surface water interaction may occur and the role groundwater may play in the water requirements of surface water ecosystems of the Western Cape. By comparing the conceptual models of these two studies to the geology and environmental characteristics of the chosen study area, the expected interaction between groundwater and surface water can be conceptualised.

2.6.2 Previous local studies on interaction

Establishing the driving components of a drainage basin from readily available hydrological information has been a successful approach for developing a conceptualisation of interaction processes within South African river systems. Bugan *et al.* (2012) assessed the hydrological drivers of a saline seasonal tributary of the Berg River in the Western Cape of South Africa by means of a water balance approach. Through establishing a catchment water balance, Bugan *et al.* (2012) found that streamflow here was largely a product of quickflow (soil horizon interflow and overland flow) with minimal contribution from groundwater as is characteristic of the hydrogeological setting. Due to the seasonal nature of this stream, the dominant driver of the area's water balance was derived to be evapotranspiration under the assumption of no further streamflow loss to groundwater. A flow model for the catchment was formulated from the water balance and an assessment of environmental tracers, which is envisioned to inform salinity management strategies for this area in future. A similar approach was utilised by Weitz and Demlie (2014) who were able to identify a link between groundwater sources and Lake Sibayi, a freshwater lake in KwaZulu-Natal, and develop a conceptual hydrogeological model for this area through establishment of the lake's water balance.

The water balance approach is identified as a suitable tool for studies of groundwater surface water interaction in South Africa. Tanner and Hughes (2015) detail the main processes involved in surface water and groundwater interactions within an area by means of a simple water balance before evaluating the applicability of models to local groundwater surface water processes. Tanner and Hughes (2015) presented the Pitman rainfall-runoff model, which conceptualises the main water balance components and their linkages, as a scientific and practical tool for catchment scale hydrological simulation for improved integrated water resources decision-support. A study by Parsons and Vermeulen (2017) refined the understanding of the hydrological drivers of the Groenvlei wetland estuary, a site of highly debated understanding of groundwater surface water interaction processes (Roets *et al.*, 2008; Parsons, 2009), through a water balance approach. As run-off was not a component of this environment, the Pitman model identified by Tanner and Hughes (2015) was unable to be applied as an appropriate tool for conceptualisation of groundwater -surface water interaction in this system. The ambiguous interaction processes and importance of the role of groundwater in the functioning of Groenvlei highlight the need for conceptualisation of these site-specific hydrological processes to be corroborated with all available information (Parsons and Vermeulen, 2017). In this current study, the water balance approach along with conceptualisation of the system be used to develop a hydrogeological conceptual model of the study area to illustrate the natural functioning of the area.

2.7 Research Framework



2.8 Chapter Summary

The aim of this chapter has been to provide a thematic review of recent, relevant literature pertaining to the research topic, question and aim. The theoretical framework which guides the study's argument, the conceptual framework in which it is investigated and the previous work that will support the findings of this study is presented and reviewed in order to develop the research framework that this study will follow to meet its aim. Literature reviewed in this section have been chosen due to their similarity in environmental context to the chosen study area in addition to their topical overlap with the current study focus. Literature from arid environments where rivers are temporary and cease flow for certain months of the year are given greater prominence in serving as a guide for this research.

The key theory of the water balance and Darcy's law is stated to provide an understanding of the theoretical basis upon which the concept of groundwater -surface water interaction is applied. Further conceptual context is given by reviewing previous studies on groundwater – surface water interaction within non-perennial rivers and drawing a comparison of these studies to how they may differ from interaction in perennial river system flow regimes. Literature is reviewed in accordance with each objective that has been put forward to elaborate and add to the research related to how groundwater may contribute to non-perennial river systems through interaction. To determine the appropriate method and expected results to assist in better interpretation of the results in accordance with the research aim, the applicability of common methods of investigating groundwater – surface water interaction to non-perennial river characteristics is discussed.

Local studies that have been previously undertaken are also reviewed to establish a reference point for how interaction may be expected in this environment. Specifically previous studies of groundwater- surface water interaction in a non-perennial river setting and context are reviewed so that a picture of the expected findings of how interaction may occur in this study is developed.

The research framework for this current study is provided which indicates visually the logical structure of the research, which has been informed by previous studies and guiding literature.

3.1 Chapter Introduction

This chapter describes the chosen case study area in terms of its general geographical, hydrological and hydrogeological characteristics relevant to the focus of this study.

3.2. Climate Conditions

The Verlorenvlei is characterised by a Mediterranean climate typical of a coastal area along the Western Cape of Southern Africa. This area is a winter rainfall area which receives a mean annual precipitation (MAP) of ~295mm with very little wetness occurring during the summer months. Seasonal high evaporative rates are characteristic of the Sandveld sub-region; the potential annual evaporation has been estimated at between 1800 to 2482 mm rate per annum (CSIR, 2009). The Verlorenvlei catchment has an annual average evapotranspiration that is estimated at 1460.10 - 1151.60 mm/ a (Schulze, et al., 2009). A precipitation gradient exists from the coast inland where the amount of precipitation increases with increasing altitude further from the coast. Annual precipitation during the duration of this study fluctuated according to the drought conditions with the lowest annual precipitation occurring during the drought of 2017.

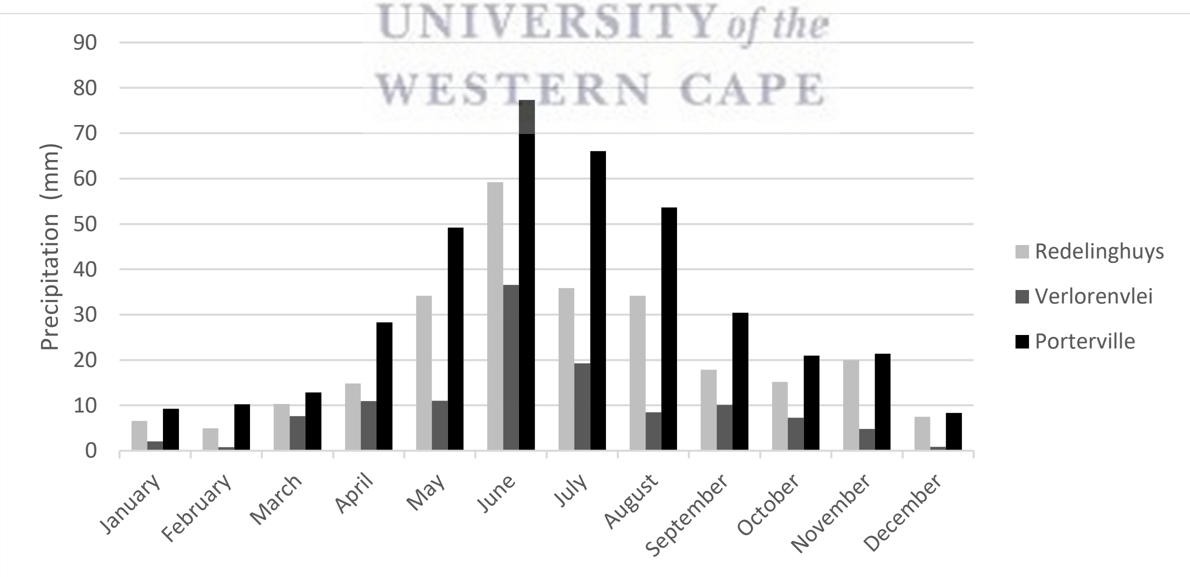


Figure 3: Average monthly rainfall within Verlorenvlei and surrounding area at varying elevations and distances from the coast. Redelinghuys (2008-2018), Porterville (2000-2018) & Verlorenvlei (2015-2008). Source: SASSCAL and Weather SA

3.3 Land Use

The land use classification of the Verlorenvlei area is presented in Figure 4. From the classification conducted in 2013/14 for the Department of Forestry, Fisheries and the Environment, it is clear that a large portion of the Verlorenvlei is demarcated for agricultural purposes. As indicated in Figure 4, cultivated commercial crops are found across the majority of the Verlorenvlei area in both centre pivot and non-pivot forms with some orchards and vineyards found in parts of the north eastern and south western sub-catchments. A small area of settlements makes up the Elandsbaai provincial town found towards the outlet of Verlorenvlei with its neighbouring town, Redelinghuys, further upstream of the Verlorenvlei wetland. Apart from these areas and that land which has been disturbed (i.e., degraded land cover in Figure 4), the natural vegetation of the area is still evident. Natural vegetation of this area is characterised by Fynbos typical of the Cape Floristic Region (Low & Rebelo, 1996).

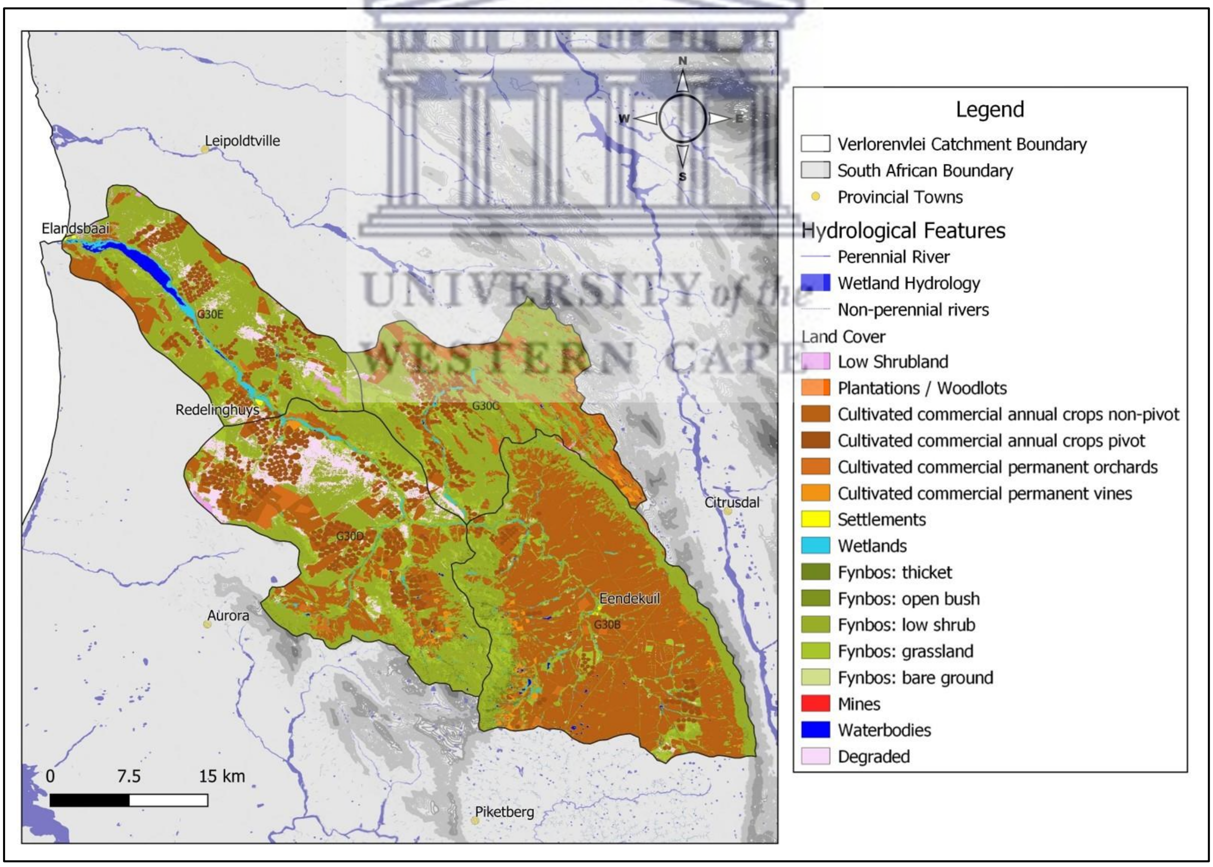


Figure 4: Land Use Classification of the Verlorenvlei area. (DFFE – National Land Cover, 2013-14)

3.4 Hydrology and Topography

The Verlorenvlei is predominantly a low relief area, which rises in elevation the Moutonshoek Valley which drains the moderate relief area of the Piketberg mountains. Across the drainage region, wetland conditions are prevalent for most of the year. Three major tributaries, namely: the Krom Antonies, the Hol, and the Kruismans River drain into the Verlorenvlei River and ultimately the Verlorenvlei wetland. This river system follows the geology creating a dendritic river network with many non-perennial streams feeding into the main river along various points of its profile. These tributaries drain into the Verlorenvlei wetland, which alone is approximately 15 km^2. The paleo-topography of this coastal plain may be as a result of previous floodplain development of the Orange River basin resulting in the deposition of sediment, which characterises the Western Coast of Southern Africa (Dollar, 1998). Two major paleochannels are suggested to remain in the lithostratigraphy of this area. The Berg and Olifants river are suggested by Dollar (1998) to have remained as river basins that cut into the pre-existing paleochannels in this area.

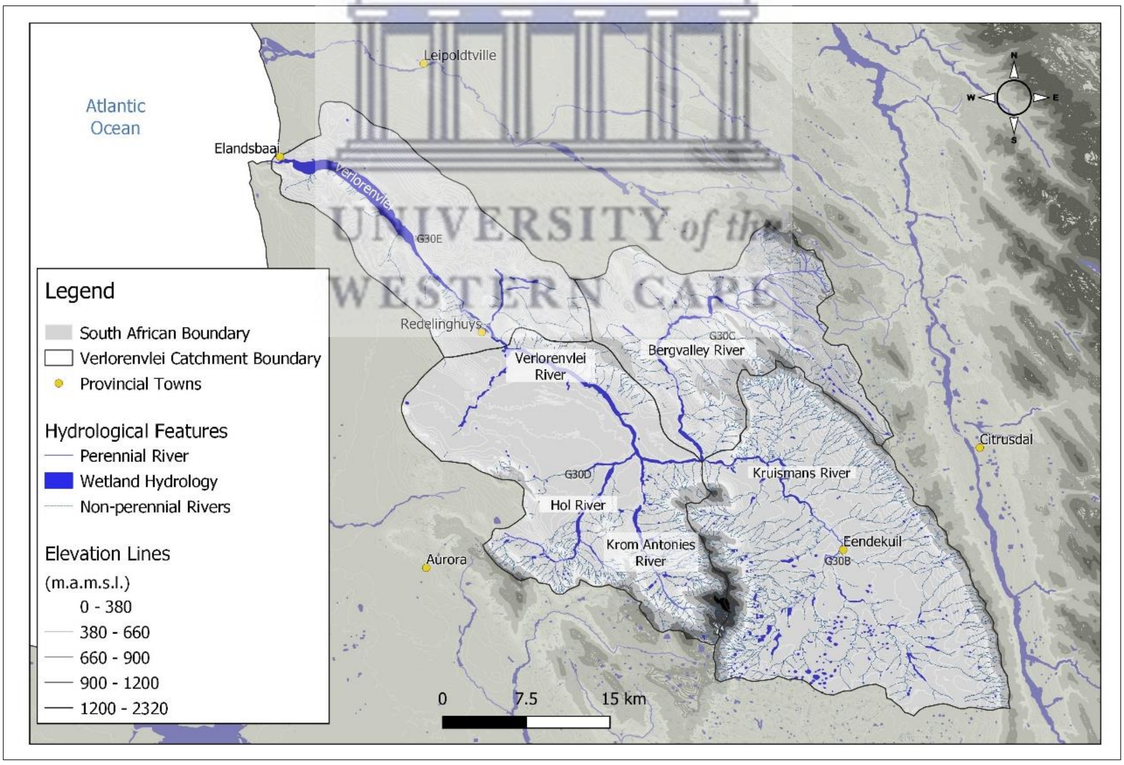


Figure 5: Hydrology of West Coast of the Western Cape, South Africa. (DR:DSLR – NGI, 2014)

At the outlet of the Eendekuil basin (quaternary catchment G30B) the Kruismans river is the last remaining gauge in the Verlorenvlei catchment providing an accurate hydrological record for the Kruismans from 2000 to 2007. The non-perenniality of this river is clear from the hydrological record (Figure 6) where this river flows intermittently with runoff occurring during wet periods. No indication of baseflow can be seen in this hydrograph during summer months as no-flow periods exist.

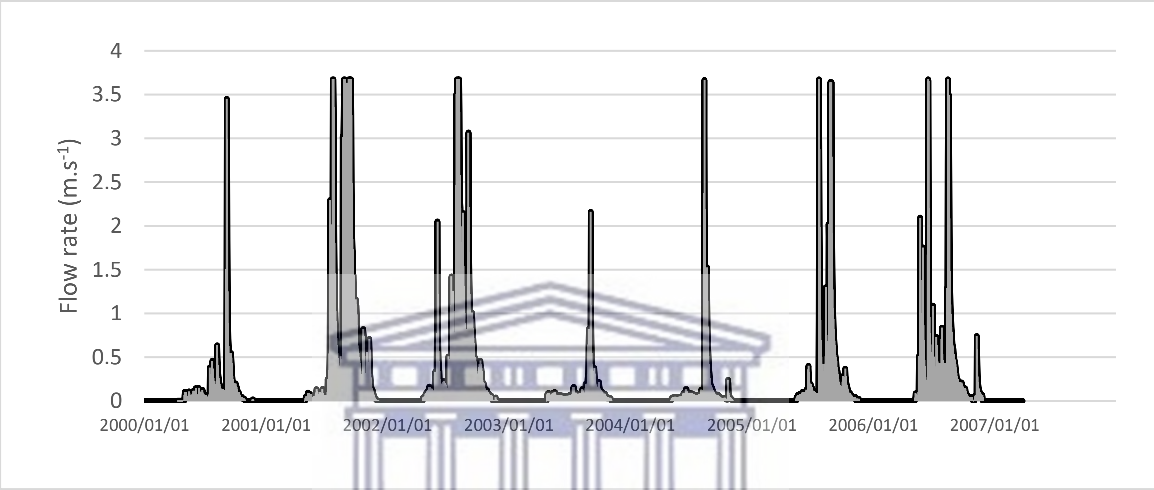


Figure 6: Long term river monitoring of the Kruismans river from 2000 to 2007 (DWS station: G3H001)

Continuous monitoring of the Verlorenvlei water level occurs at DWS station G3T001. A 17-year ongoing record provides insight into the wetland's hydrological character. The average water level of the Vlei is between 0.6 – 1.8 m per annum as seen in Figure 7. The record of the continuous monitoring indicates three periods of below-average water level where levels have dropped below 0.5 m and to even 0 m during the period of this current study (Figure 8).

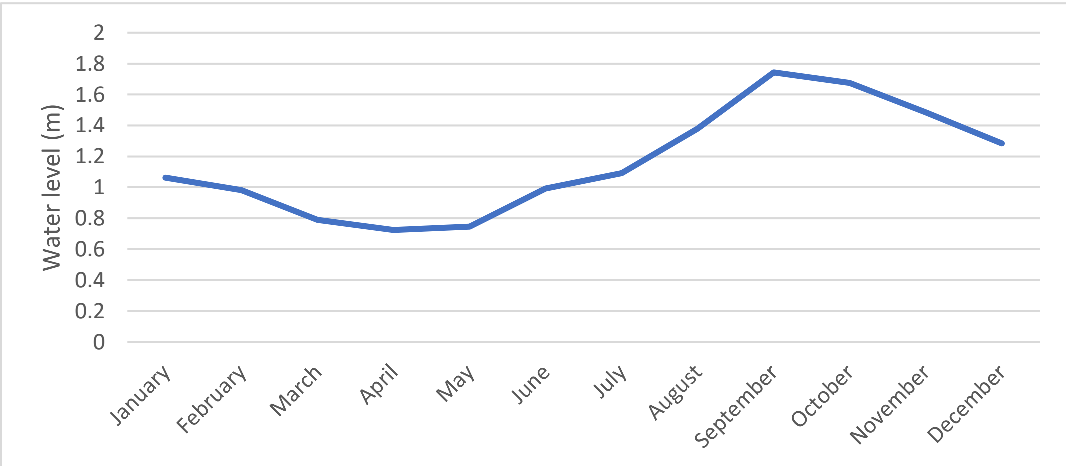


Figure 7: Average monthly water level of the Verlorenvlei wetland estuary in metres. DWS Station G3T001, 2000-2018.

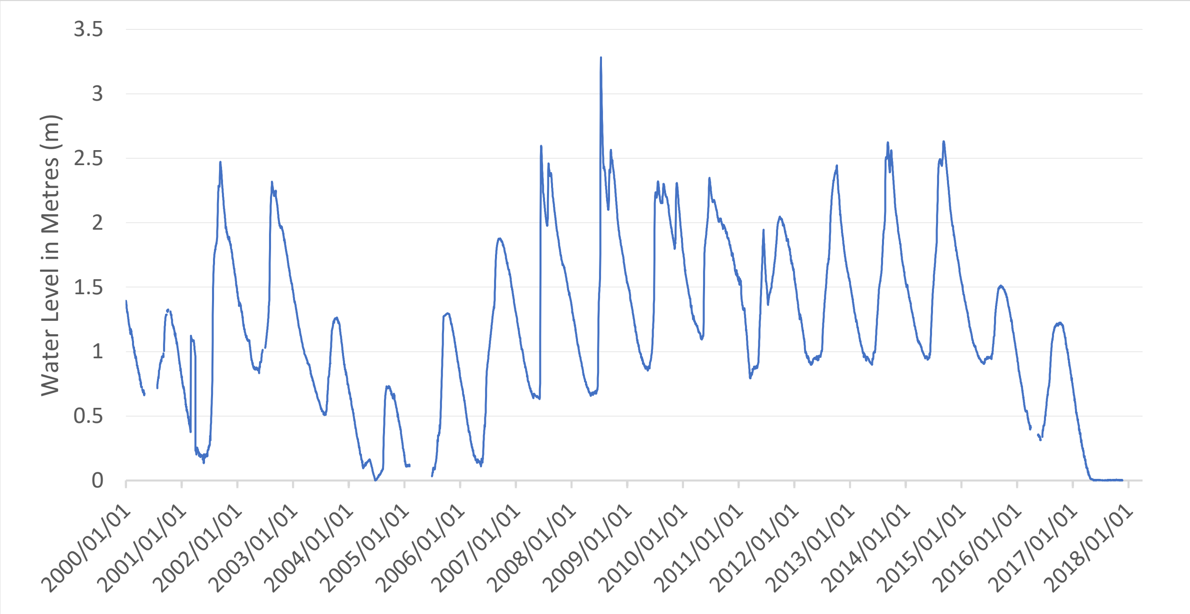


Figure 8: Hydrological monitoring of Verlorenvlei's daily average water level from 2000 to 2018 (DWS station: G3T001)

3.5 Geology and Hydrogeology

The movement of subsurface water through aquifer systems is determined by the geology of the area. The geology of the Verlorenvlei area is presented in Figure 9.

The geologic character of Verlorenvlei can be subdivided into four major formations: The Proterozoic Malmesbury Formation, the Cambrian Klipheuwel Formation, Palaeozic Cape System and the Cenozoic Sandveld group. Tertiary to Quaternary sand deposits cover the area making mapping of actual geology difficult. The geological information presented here is therefore an inferred geology for the study area.

The unexposed basement Proterozoic Pre-Cambrian (535-750 Ma) Malmesbury formation, of the Pan-African Saldania Belt, forms the foundation for the Verlorenvlei lithostratigraphy. Low permeability, clay-like metavolcanic and metasedimentary rocks of this formation can be subdivided into distinctive terranes by major fault zones across South Africa's Western coast (Buggisch, et al., 2010). The Piketberg-Wellington major fault subdivides the Boland and Swartland zones and the Colenso fault further subdivides the Swartland zone from the Tygerberg zone (Rozendaal *et al.*, 1999; Frimmel *et al.*, 2013). Outcrops of the Porterville and Piketberg formation (of the Boland Terrane) and the Moorreesburg formation (of the Swartland terrane) are found within Verlorenvlei (Conrad *et al.*, 2019).

Following the Malmesbury formation, an unconformity exists between the Malmesbury group formation and the Cape System which succeeds it. This unconformity, the Cambrian Klipheuwel formation, outcrops intermittently causing its full extent to remain unknown. Isolated outcrops can be found near Redelinghuys as well as along the eastern edge of the mountains which surround the Eendekuil basin, as indicated in red in the figure below (Figure 7). The Klipheuwel formation is characterised by interbedded shale mud-rock, sandstone and intermittently developed conglomerate (CGS, 1973; CGS, 2008).

Above the Malmesbury formation rests the Table Mountain Group (TMG) which forms part of sedimentary rocks that characterise the Cape Supergroup that outcrop along the southwestern, southern and south-eastern margins of SA; the majority of which lie within the Cape Fold belt found predominantly within the Western Cape. The original thickness of the Cape succession is unknown due to the prevalence of thrusting that complicates measurements. Cape Supergroup sediments were deposited during shallow marine and non-marine braided fluvial conditions (de Beer, 2002). This formation has high groundwater quality and exploitation potential due to its medium to coarse grain size and inert nature of the quartz arenite that it is composed of, combined with its characteristic fracturing and folding (de Beer, 2002). The stratigraphy of the Cape Supergroup can be divided into three distinctive groups of which TMG forms the earliest division. The TMG is further subdivided into the following formations: the Piekenierskloof, Peninsula and Graafwater Formation. As the TMG is mainly composed of hard sandstone of little primary porosity, the groundwater occurrence within this formation is attributed to heterogenous fractures including faults, joints, and bedding planes which create secondary porosity (Xu *et al.*, 2009). The faults occurring in the western portion of the TMG show north-westerly trends, most notably the De Hoek Fault, the Redelinghuys Fault and the Clanwilliam Fault, all of which are characterised by wide breccia zones (de Beer, 2002). Geological contacts are known to be associated with groundwater discharge which support aquifer dependent ecosystems such as springs, riverine and wetland ecosystems (CSIR, 2009).

The Cape system is overlain by tertiary to recent Cenozoic deposits of unconsolidated, coastal sand which make up the Sandveld Group and its subdivisions. The thickness of the accumulations of these sands is controlled by the basement topology (Nel, 2005). This unconsolidated well-sorted, coarse-grained sand of Cenozoic deposits constitutes the coastal primary aquifer of the Sandveld. The secondary aquifer is substantial in the area and has been noted to extend west underneath the sand of varying thickness found further towards the Atlantic coast (Conrad, *et al.*, 2004). This secondary aquifer is made up of fractured rock found towards the headwaters of the catchment.

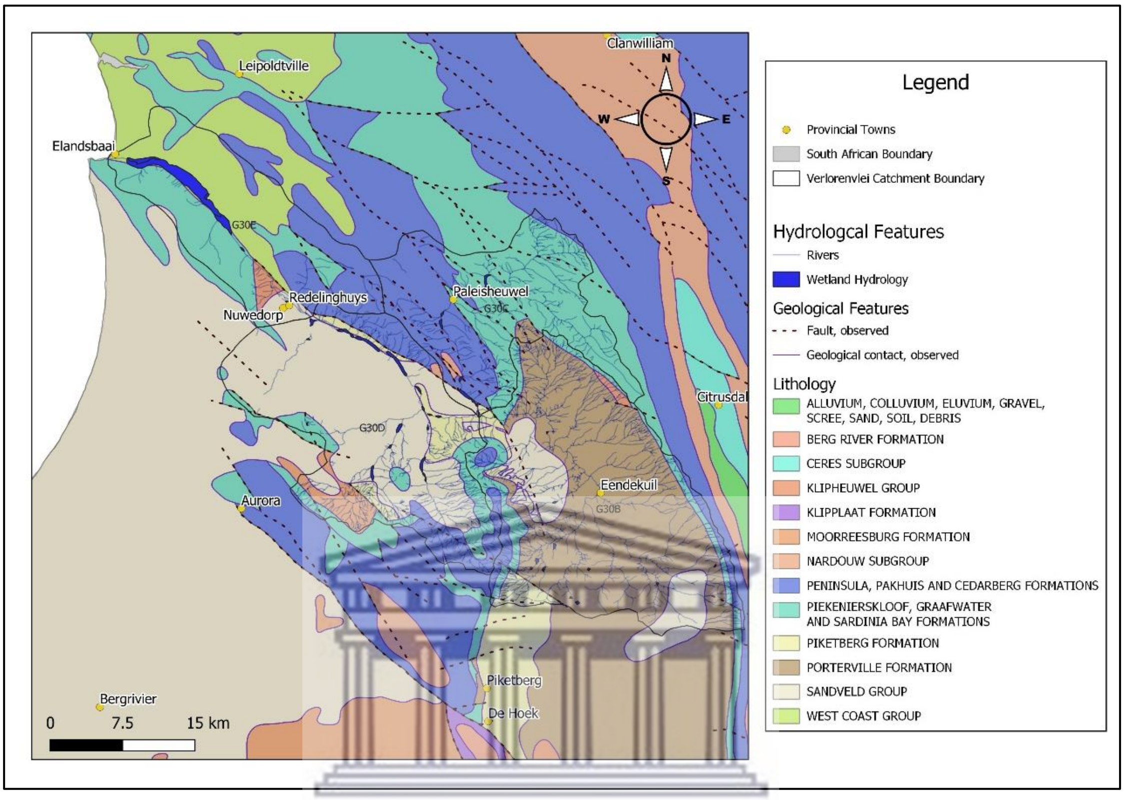


Figure 9: Map displaying the geology of the Verlorenvlei catchment, Western Cape, South Africa. (Source: Council of Geoscience, 2019)

Groundwater flow in the Sandveld occurs from an inland direction generally at high angles to the coastline and discharges either directly into the ocean as diffuse discharge along the coastline or into river reaches (Department of Water Affairs and Forestry, South Africa, 2008). Groundwater flow within the secondary aquifer flows preferentially along various fault planes, weathered zones and bedding surfaces typical of TMG aquifer flow (de Beer, 2002; Xu *et al.*, 2009). A strong link between the primary and secondary aquifer systems has been identified through establishment of a recharge relationship between the two systems and potentiometric pressure head of the secondary aquifer elevated higher than the water table (Conrad *et al.*, 2004; Watson et al., 2018). The Olifants-Doorn area has experienced isolated declining water levels, especially in parts of the Sandveld, but these are usually caused by individual boreholes being over-abstracted and not the aquifers entirely (Department of Water and Sanitation, 2015).

Table 1: Geological Succession and Lithology of Verlorenvlei and surrounding Sandveld area (adapted from Geological Council of South Africa 1:250 000 geological series 3218 Clanwilliam (CGS, 1973) and Simplified Geology of the Republic of South Africa (CGS, 2008).

Era	Period	Formation	Group	Subgroup	Lithology
Cenozoic	Tertiary to Quaternary	Tertiary to Recent	Sandveld		Sand, alluvium, calcrete
Palaeozoic	Denovian, Silurian, Ordovician	Cape System	Witteberg Group		Quartzitic sandstone, mudrock
			Bokkeveld Goup		Mudrock, sandstone
			Table Mountain Group		Quartzitic sandstone
Palaeozoic	Cambriam	Klipheuwel Formation			Brightly coloured shale, sandstone, graywacke and conglomerate
Proterozoic	Late Namibian	Nama System	Malmesbury Group	Mooreesburg	Lower arenaceous units upper part consists of a series of greywackes and pelites and are typified by a well-laminated quartz-muscovite-biotite schist.
				Piketberg	Strongly foliated and lineated feldspathic quartzites, greywackes, sericite schists, feldspathic grits and conglomerates, and minor impure marly limestones
				Porteville	Phyllitic shale, schist and fine- to medium-grained greywacke, minor limestone, quartzitic sandstone and conglomerate.

3.6 Water Quality

Verlorenvlei is predominantly a closed freshwater estuary. The estuary mouth provides minimal sea water input to the wetland when high sea levels breach the shores. However, it remains closed during periods of lower water levels, stopping the outflow of water to the ocean, leaving behind a stagnant water body. Verlorenvlei is thus more susceptible to salt build-up through evaporative concentration due to the reduced exposure to freshwater dilution associated with greater runoff (CSIR, 2009). The tributaries that flow into the Verlorenvlei main river each contribute variable salt loads. The Krom Antonies is characterised by lower electrical conductivity (EC) levels below

300mS/m, while the Kruismans and Hol River have high EC of less than 1500mS/m. Moderate EC levels of between 500 – 800mS/m characterises the Bergevallei River (Sigidi *et al.*, 2017). Contributors to the salinity profile of Verlorenvlei has been identified to be evaporation (Sigidi *et al.*, 2017), but water quality profiles of the tributaries suggest other sources may contribute to variable EC values (Sigidi *et al.*, 2017). Relatively fresh groundwater (EC 30 – 70 mS/m) contributes to the Verlorenvlei system from the north and, in some areas, is suspected to originate from deep groundwater flow from high lying recharge areas surrounding the catchment. (CSIR, 2009).

3.7 Chapter Summary

The aim of this chapter has been to describe the study area characteristics relevant to this current study. By describing the study areas hydrological, climatological and hydrogeological character we may create a background understanding of the chosen study area that may contextualise the investigations done within this area. The research design and methods followed to achieve the study's investigative aim is detailed in the following chapter.

4.1 Chapter Introduction

This chapter provides a detailed description of the research design and methodological approach followed in order to conduct this study. The methods followed in order to achieve the study objectives outlined in Chapter 1 are described in this chapter.

4.2 Research Design

4.2.1 Study Design

This study is a mixed method design of both qualitative and quantitative research. The problem and research question are conceptual in nature, however quantitative research methods are employed to address and answer the question. In this study, local observations and measurements contribute to the overall understanding of the system at a regional level. Measurements were made to identify, describe and validate findings of observations and their relation to a known theory.

4.2.2 Research design method

This study follows an inductive approach whereby observations are made, and data is obtained before a theory or concept is attributed to the findings of the research. This approach is applied to this study as it is difficult to discern which groundwater – surface water connectivity type (i.e., disconnected, losing, gaining or a combination of these) is applied to the river system without conducting preliminary observation of various parameters. Once these observations are made, patterns in these observations are acknowledged and a known principle can be applied to the patterns observed.

4.2.3 Sampling design and site description

Following a purposeful sampling design, sample sites were chosen based on accessibility, representation and availability of water. An initial field visit was undertaken in 2017 in order to choose sites for sampling. Sites were chosen that followed the hydrology of the Verlorenvlei and reflected changes in geology as indicated by available geological mapping of the area. For the groundwater component of this study, existing boreholes and spring-fed farm dams were sampled where possible. Several sites easily accessible on the Verlorenvlei were chosen to obtain a representative sample of the wetland itself. In total: 3 wetland sites, 5 spring-fed dams, 11 river sites and 20 boreholes were sampled across the Verlorenvlei and its contributing catchments as indicated in Figure 1. One anti-evaporation rain gauge was installed in the lower reaches in the catchment for isotope sampling of precipitation.

Sites were chosen during the wet season of 2017. When water was present, samples were taken in the same locations seasonally between July 2017 and February 2019. The influence of drought and the nature of non-perennial rivers meant that on occasion – mostly during the dry summer months – samples could not be obtained at the same revisited sites. The site type, elevation, and locations within the catchment is provided in Figure 10.

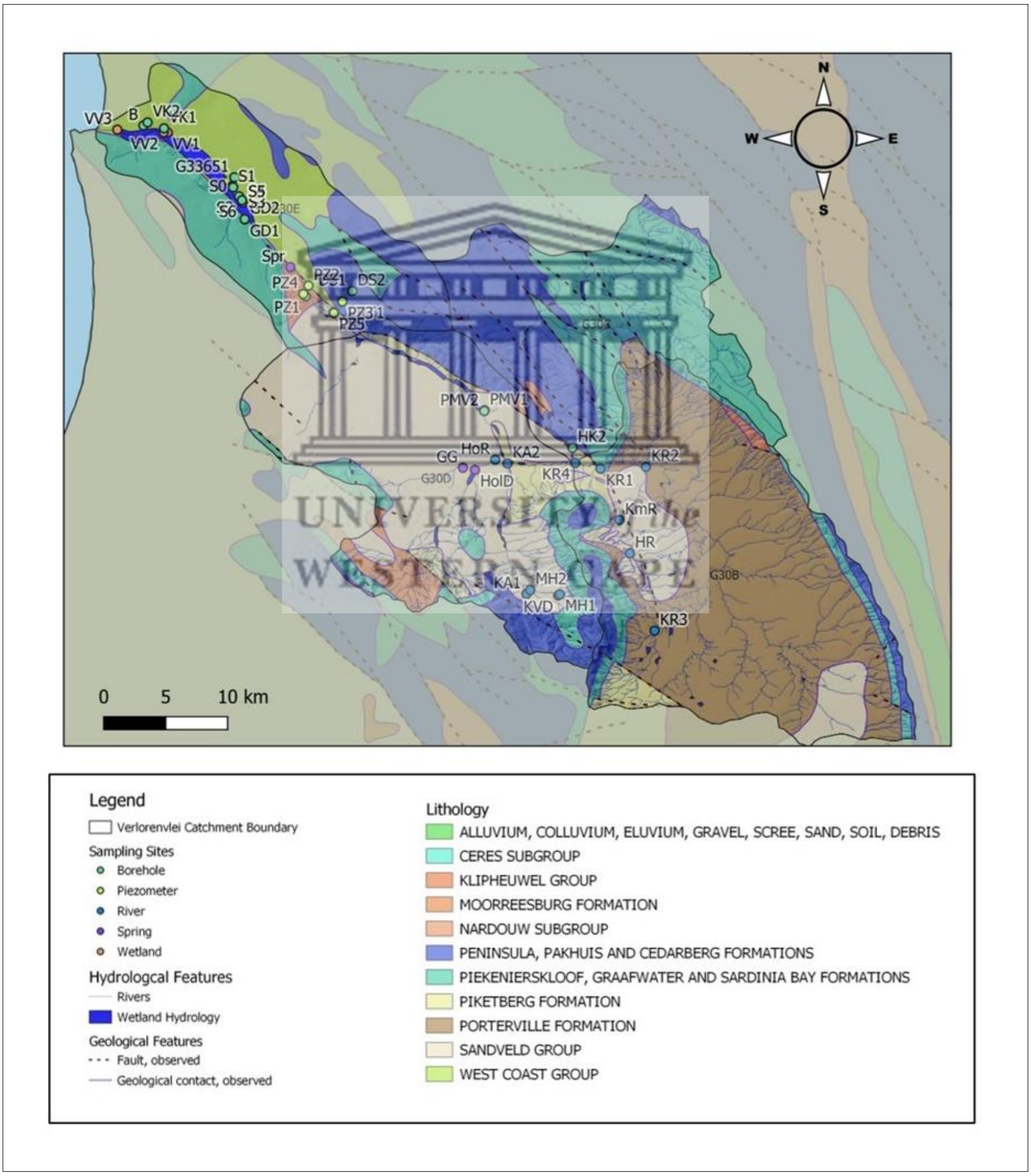


Figure 10: Map indicating the location of sampling sites selected for this current study within the Verlorenvlei, Sandveld river system in relation to the area's geological features and lithostratigraphic groups. (Source: Council of Geoscience, 2019)

Table 2: Location and basic details of selected sites

Site Type	Site	Location/ Farm Name	Latitude	Longitude	Elevation (m)
Wetland	VV1	Verlorenvlei	18.39866	-32.3175	3
	VV2		18.39533	-32.3175	5
	VV3		18.35534	-32.3151	0
Spring	GG	GoerGap Farm	18.65326	-32.6059	56
	HolD	Hol River	18.66357	-32.6077	46
	Spr	Klaarfontien	18.50447	-32.4333	8
	KVD	Kromvlei Farm	18.73535	-32.7157	161
River	HoR	Hol River	18.68111	-32.5989	41
	KA1	Krom Antonies River	18.70812	-32.7143	92
	KA2		18.69167	-32.6022	42
	KmR	Krom River	18.78822	-32.6508	119
	KR1	Kruismans River	18.77181	-32.6067	53
	KR2		18.81099	-32.6051	73
	KR3		18.81852	-32.746	99
	KR4	Kruis River	18.75008	-32.6017	44
	VR1	Verlorenvlei River	18.54185	-32.4721	9
	VRT1	De Schuur Farm	18.54907	-32.463	26
	MH1	Krom Antonies River Tributaries	18.73677	-32.7147	167
	MH2		18.71116	-32.711	93
Piezometer	PZ1	Redelinghuys	18.51762	-32.4582	5
	PZ2		18.52009	-32.4493	8
	PZ3	De Schuur Farm	18.54933	-32.4629	27
	PZ4	Van Gill Farm	18.51566	-32.4564	38
	PZ5	Van Zyl Farm	18.54198	-32.4727	7
Borehole	B	Bontheuwel	18.37784	-32.3116	13
	DS1	Die Schuur Farm	18.55746	-32.4539	43
	DS2		18.55795	-32.4539	48
	G33651	Uithoek Farm	18.45624	-32.3561	34
	GD1	Grootdrif Farm	18.46518	-32.3923	5
	GD2		18.46511	-32.392	8
	HK1	Het Kruis Farm	18.74771	-32.5888	65
	HK2		18.74771	-32.5888	65
	PMV1	Palmietvlei Farm	18.67185	-32.5564	42
	PMV2		18.6716	-32.5571	39
	S0	Sebulon Farm	18.45442	-32.3635	6
	S1		18.45515	-32.3647	6
	S2		18.46027	-32.3724	10
	S3		18.46379	-32.3773	12
	S4		18.46338	-32.3775	4
	S5		18.46344	-32.3776	5
	S6		18.46275	-32.3758	6
	VK1	Vensterklip	18.39559	-32.314	15
	VK2		18.38139	-32.3089	24

- River Sites

River sites were selected on each of the inflowing tributaries to the Verlorenvlei river. In the upper catchment, sites MH1, MH2, and KA1 and KA2 were selected. MH1 and MH2 were both indicative of upper catchment headwater tributaries which feed into the Krom Antonies catchment. These sites were accessible and constant as they were selected near road crossings. KA1 and KA2 were selected as representative sites for the Krom Antonies river. KA1 was located upstream of KA2. The riverbed was sandy at both of these sites with few cobbles as indicated in Figure 11 and Figure 12. In-stream cattle grazing was observed during a few of the sampling campaigns in the wet and dry seasons.

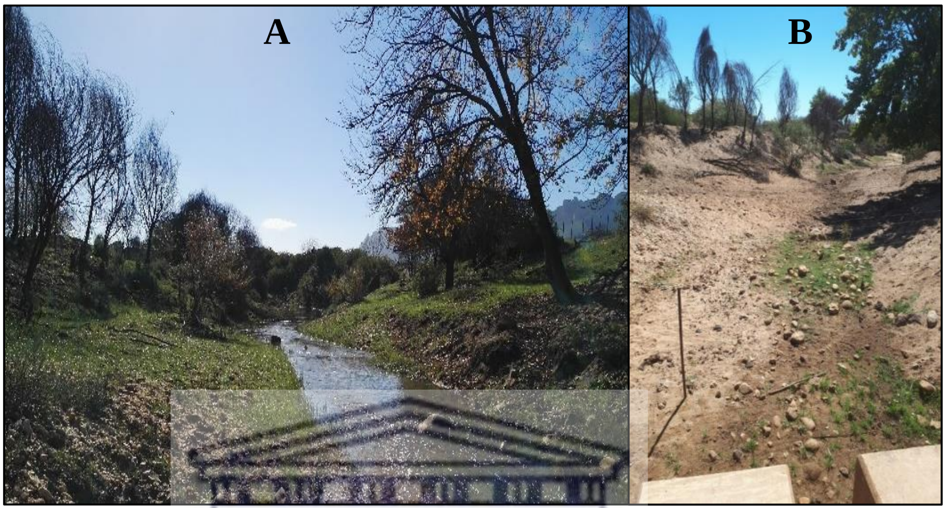


Figure 11: Photographs taken at site KA1 during both the wet season (photograph A, July 2017) and dry season (photograph B, March 2018) sampling campaigns indicating site KA1's temporal conditions and characteristics.

Figure 12: Photograph depicting river conditions and characteristics at site KA2 during the dry season (October 2017).

For the Krom River, Site KmR was chosen as the representative sample. This site was accessible via a road crossing. The Krom river drains the Piketberg Mountains on the northeast facing slope. Here the river drained into a reed bed before pooling into channelled rivers. Water was sampled at the point before the river entered the channels. Site characteristics for KmR are depicted in Figure 13.

Figure 13: Photograph taken at site KmR during the wet season (July 2018) depicting site KmR's conditions and characteristics.

Along the Kruis River, the sites: KR1, KR2, and KR3 were selected. KR4 was selected at the transition of the Kruismans River to the Kruis River at the location of the previously operating weir (DWS station: G3H001). This site is accessible under the overpass bridge which leads into quaternary catchment G30C. KR4 is characterised by sandy soils with many reeds growing in the wide riverbed. Wetland conditions were present for most of the sampling campaigns. KR3 is located at the headwater of this river ~18km from the town of Piketberg. This site is accessible via a road crossing. Water pools below the road crossing bridge as it drains the southeastern slopes of the Piketberg mountains. KR2 was selected at the confluence of the Krom and Kruismans rivers at it narrows to the Eendekuil basin mouth. KR1 was selected as it was accessible via a road crossing and was situated at the mouth of the Eendekuil basin. Water accumulates here as the topography gradually flattens creating wetland conditions along this stretch of the river tributary.

HolR was selected as the sampling site for the Hol River tributary. This site was selected near (~700m) the confluence to the Verlorenvlei river. The site was accessible via a service road on private property with permission from the landowner. The flowing river was lined with riparian vegetation and reedbeds. The site condition and characteristics can be seen in Figure 14 below.

Figure 14: Photograph indicating site conditions and characteristics for river site HolR during the dry season (October 2017)

In the lower catchment, two river sites were chosen. A site near Redelinghuys was chosen as a representative sampling site for the Verlorenvlei River. VR1 was chosen as it was accessible via a road crossing. This site was the active channel for the Verlorenvlei river in this river reach. The river was filled with reeds however small pools of water were found in between the reeds and below the road crossing bridge. The north-easterly adjoining tributary at this Redelinghuys Verlorenvlei reach (unnamed tributary) was selected as an additional sampling site location. VRT1 within the De Schuur Farm boundary was chosen as a representative sample of this inflowing tributary. This site was accessible via a dirt road into the Kruisfontein Valley. Reeds were present within the channel of the tributary. Samples were taken in the active channel running (~2m) parallel to the dirt road.

- Spring Sites

Springs sites included the following spring fed dams: KVD, HolD, GG, and a spring fed stream, Spr. Site KVD was located in the upper catchment near MH1. This site is a farm water supply dam. Later it was determined that the origin of this dam was pumped groundwater from the farm's boreholes and not a spring as originally suspected. Site HolD is found along the Hol River in a reach of the river that is relatively dry upstream of site HolR. This site was also later determined to be a farm supply dam within which water pumped from groundwater was stored for later use. Site GG is located west of HolD. This site is a dammed spring which is used for water supply on the neighbouring farm. Site Spr is a small stream that is fed by a north easterly off-road spring near Redelinghuys (~6km towards the coast). This stream forms a furrow that is then channelled into the Verlorenvlei river floodplain via tunnels under the road. The water was sampled at the entry of the tunnel below the spring's eye before it drained into the Verlorenvlei river.

- Boreholes

A total of 17 boreholes were chosen as representative groundwater sites within the study area. These sites were chosen due for their location, accessibility and potential for measurement repeatability. Several boreholes were sampled from frequently used taps which were taken to be representative of their respective geosites. The boreholes sampled can be grouped according to their geological locations.

Table 3: Descriptions of boreholes chosen as representative groundwater sites within the study area grouped according to their geological locations.

Geology		Site Name	Location	Depth	Description
Table Mountain Group	Pennisula, Pakhuis and Cederberg Formations	HK1	Near Kruis river and Bergvallei confluence.	36-40 m	Lies along the observed NW-SE fault which runs through the mouth of the Eendekuil basin across into the Verlorenvlei floodplain along the Verlorenvlei river. It is unknown if the borehole intercepts the fault at this depth.
		PMV1	Situated along elevated area which borders the Verlorenvlei catchment and adjacent Langvlei catchment	(Sampled from tap)	These boreholes are drilled into the primary sedimentary sand aquifer. No water depth was taken for these sites as they were only accessible via the taps sampled.
		PMV2			
		DS1	North of Redelinghuys. Adjacent to the Kruisfontein river tributary, ± 1 km North of the VRT1 river site.	(Sampled from tap)	lithology typical of the Peninsula, Pakhuis and Cederberg formations
		DS2			
	Piekeniersloof, Graafwater and Sardinia Bay Formation	GD1	Situated along the Southern side of the Verlorenvlei	(Sampled from water supply dam)	Located within a pivot field and is actively used for irrigation.
		GD2			
West Coast Group		B	Northern shoreline of the Verlorenvlei wetland	50 – 60 m	Drilled into geology characteristic of the West Coast Group Formation. This borehole is the furthest North-West borehole sampled in this study for the Verlorenvlei catchment, closest to the mouth of the Verlorenvlei estuary. The borehole is located next to the road in a grazing field.
		VK1	northerly edge of the Verlorenvlei wetland	±23 m	Sampled via taps with permission from the landowner
		VK2		±76 m	Sampled via taps with permission from the landowner
		G33651	northern side of the Verlorenvlei Wetland	drilled to a total depth of 65m, but has since collapsed to 33.5m	The lithology of G33651 is characterised as unconsolidated sand to a depth of 15m, thereafter unconsolidated gravel at 21m and silt at 41m.
		S0	Situated along the north side of the Verlorenvlei wetland	(Sampled from tap)	Sampled from a tap so no depth to water level could be taken for this borehole. Located within a few metres of S1 and S2.
		S1			Located within a few metres of S0 and S2
		S2			Located within a few metres of S0 and S1
		S3			Production Borehole Drilled into sedimentary sand, pumped into nearby storage dam
		S4		±30 m	Production Borehole drilled into sedimentary sand
		S5		±30 m	Production Borehole drilled into sedimentary sand

- Piezometer Sites

For the purpose of observing the local scale interaction, 5 piezometers were installed in the study area. The location of these piezometers is indicated in Figure 15. Piezometers 1, 2, 4 and 5 are situated in the Verlorenvlei floodplain and riverbed, PZ3 is located adjacent to the Redelinghuys tributary which flows into the Verlorenvlei from the North. The soil was characterised as predominated sandy soil with layers of clay reached in PZ1 and PZ5. The water strikes of the piezometers were found to be between 2 to 3.5 m below mean sea level. The installation of the piezometers proved difficult due to pressure which resulted in the piping being forced upward continuously, especially in PZ1 and PZ5. Due to tampering and/or natural damage to the installations, only PZ5 was able to be sampled for physicochemical parameters and stable isotopes.

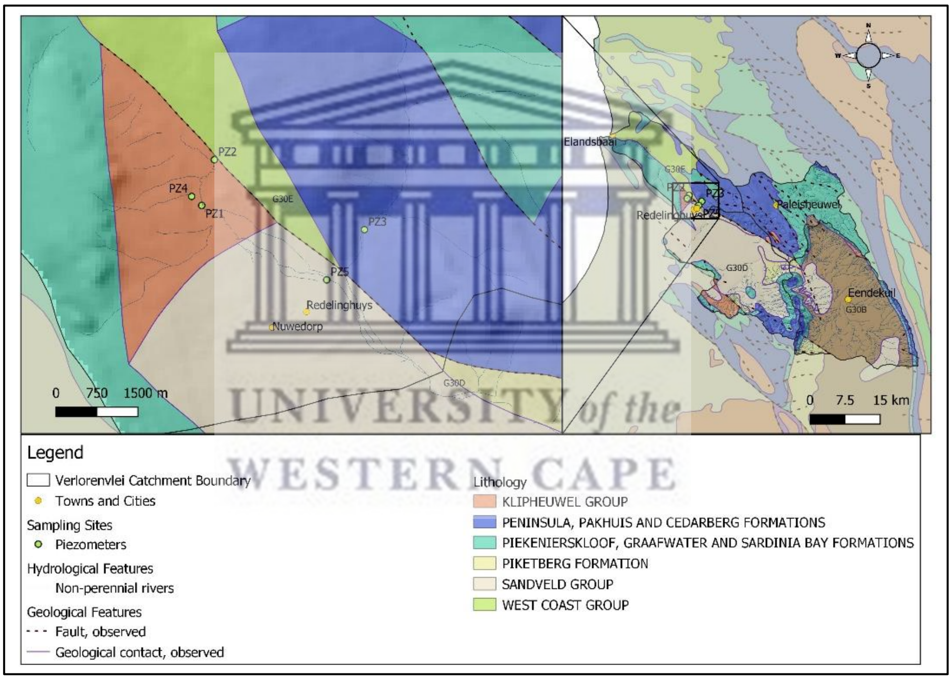


Figure 15: Map indicating location of installed piezometers in relation to Geology of Verlorenvlei (Source: Council of Geoscience, 2019)

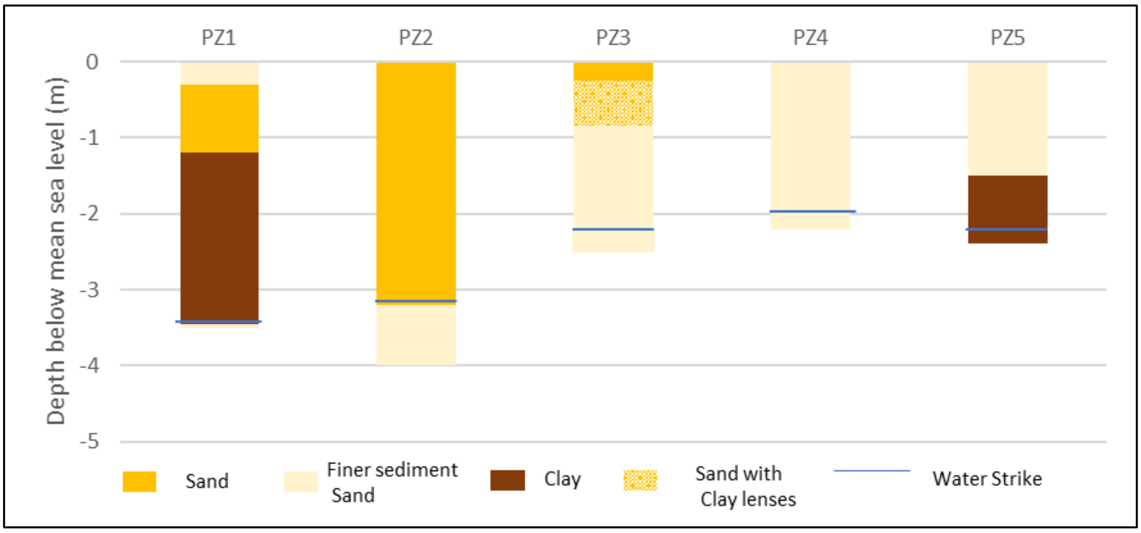


Figure 16: Sediment logs and water strikes of the installed exploratory Piezometers

- Wetland Sites

The Verlorenvlei wetland was accessed at three sites (VV1, VV2 and VV3) according to presence and availability of water during the duration of the study as the water level of the wetland receded considerably during the drier months of the drought. Water from the Verlorenvlei was sampled for hydrochemical and physiochemical properties from the wetland shore for the purpose of this study. The wetland comprised of saturated sand material. All three sites were dry in late 2017 and remained dry for the remaining sampling trips for this study.

Figure 17: Photograph indicating site conditions and characteristics for wetland site VV2 during the wet season (July 2017)

- Meteorologic monitoring and sampling Sites

Meteorological data was obtained from three meteorological monitoring sites. The locations of these are displayed in figure 8. Two South African Weather Service meteorological station are situated at Porterville and Redelinghuys. Rainfall, temperature and air pressure measurements are available from these stations. The Redelinghuys weather station falls in the G30E catchment, closest to the Verlorenvlei wetland. The Porterville weather station, although outside of the bounds of the Verlorenvlei extent, gives an indication of the regional, inland precipitation patterns that may affect a regional water source. Records from as early as the year 2000 are available for the Redelinghuys and Porterville monitoring site. Another rain gauge is situated within the Verlorenvlei catchment (within G30D) managed by South African Science Service Centre for Climate and Land Management (SASSCAL). This monitoring site was recently set up within the catchment for measurement of rainfall and began monitoring rainfall data in 2017.

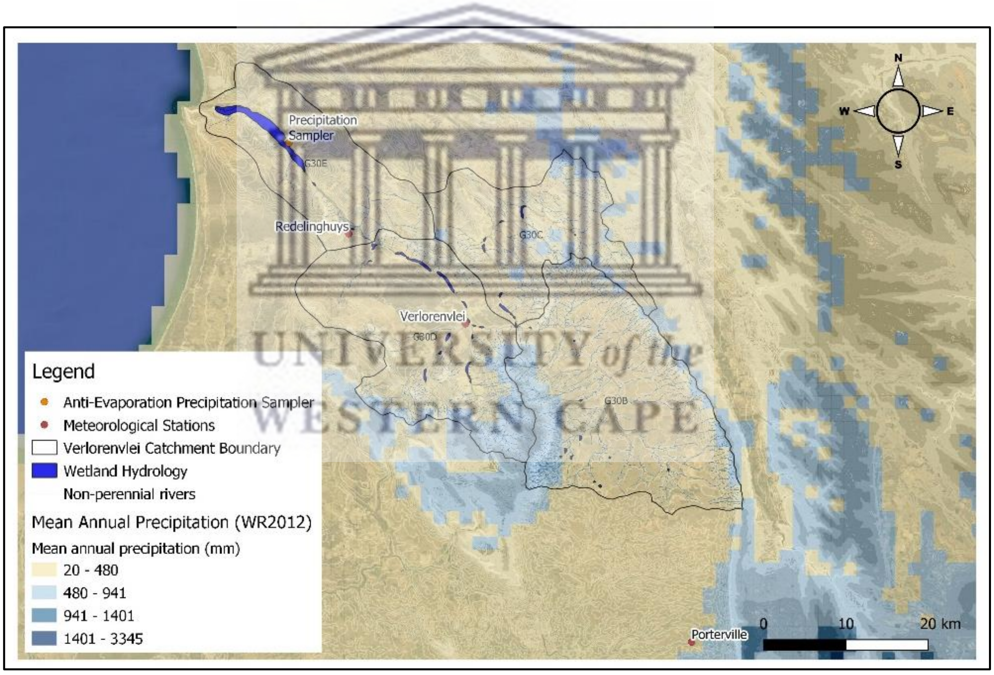


Figure 18: Map indicating location of Meteorological monitoring stations relative to the Mean Annual Precipitation for South Africa (WR2012).

An anti-evaporation precipitation sampler was installed within G30E in 2018 as part of this current study in order to obtain rainfall samples suitable for stable isotope analysis. The precipitation water sampler is an unpublished experimental design, based on published designs, which was utilised for the purpose of the Environmentally Sustainable Management of Non-perennial Rivers Project, of which this study forms a part. The precipitation water sampler was placed on privately owned land alongside the Verlorenvlei wetland with permission and enthusiasm from the landowner. Care was taken to ensure the rain gauge was securely placed in an open area, unobstructed by trees or vegetation and away from any cattle that may alter or disturb the collected samples.

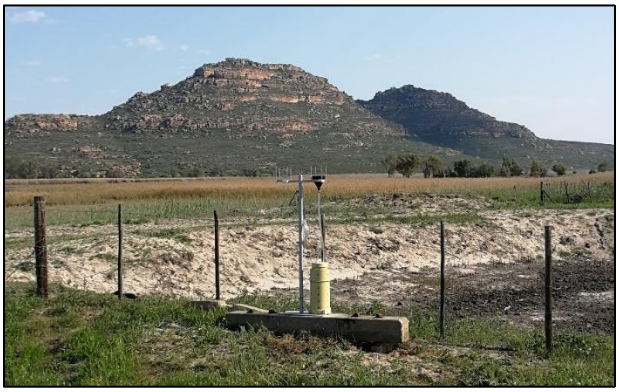


Figure 19: Anti-evaporation precipitation sampler installed within G30E at S 32.36263, E 18.45327 in 2018.

4.2.4 Study Parameters

To achieve objective one, three criteria were used to determine the applicability of methods for assessment of interaction in non-perennial rivers. These criteria were: the scale of interaction the method could determine, whether water presence was a prerequisite for the application of the method and the comparative limitations, achievements and applications of the method in investigating interaction. To achieve objective two, primary measurements of environmental tracers of water chemistry and physio-chemical parameters (namely: EC, pH and temperature, and major anions and cations, and alkalinity) are investigated to explore groundwater – surface water interaction mechanisms within the Verlorenvlei. In order to achieve objective three, aquifer parameters, water balance components and groundwater – surface water processes inform the conceptual model of the study area that is then refined by objective two. For local investigations, geophysical surveys were also conducted to refine the conceptual model.

4.2.5 Data and Data Sources

Meteorological data for the study area were gathered from two different sources, namely SASSCAL and South African Weather Service. Detailed geological mapping of Verlorenvlei and extended Sandveld area has been undertaken by the Geological Council of South Africa in the form of a 1:250 000 geological map (CGS, 1973) and as a part of the 1:200 000 Simplified map of the Geology of the Republic of South Africa (CGS, 2008). Geological logs, water chemistry and water level information were also obtained from Department of Water and Sanitation (DWS) and the groundwater consulting company, Geohydrological and Spatial Solutions (GEOSS) South Africa (Pty) Ltd, who have conducted multiple hydrogeological studies in the Verlorenvlei area. Primary sampling of water chemistry and water level information was undertaken to further investigate the groundwater- surface water interaction processes in the Verlorenvlei catchment. Desktop review of previous local study's conducted provided information into the inputs and outputs of the water budget and aquifer parameters for this investigation.

4.3 Data Collection Methods

4.3.1 Desktop Survey of existing information

Hydrological data in the form of daily flow in ms^{-1} were obtained from Department of Water and Sanitation databases for the weir within the Kruismans river (G3H001), a tributary of the Verlorenvlei river. Water level data were also obtained from Department of Water and Sanitation databases for within the Verlorenvlei itself (G3T001). To establish the location of geological features within the study area, a 1:250 000 geological map covering the study area was obtained with permission from the Council of Geoscience for use in this study. Further to this, rainfall data were obtained with permission from SASSCAL. Hourly rainfall, temperature and pressure data were also obtained from SA Weather Service for the town of Redelinghuys, a low-lying area within the catchment. Information regarding aquifer properties of those aquifer units within the catchment were obtained through literature review. Data to fulfil requirements of a water balance were also sourced from literature and previous projects conducted within the study area to develop a conceptual understanding of the study area's environment.

4.3.2 Methods for Assessment of Groundwater-Surface Water Interaction

To achieve the first objective, information on the current methods for assessing groundwater - surface water interaction was obtained from available published literature. Review papers which presented the comparative achievements and drawbacks of available methods were especially invaluable. The utilisation of these methods was further explored by reviewing their application in published research which aligned with the context of this current study.

4.3.3 Hydrochemical Analysis

To achieve the second objective, in-field sampling trips were undertaken during the wet and dry seasons from 2017 to 2019 which consisted of sampling for chemical, isotopic and in-situ physical parameters of both groundwater and surface water bodies. To obtain samples of surface water sampling sites, the 'grab' sampling technique was used to obtain a sub-surface sample (WRC, 2000). This method involves obtaining samples by submerging sampling bottles into a body of water with the bottle neck facing down, turning it to face the surface and allowing it to fill up.

Sample bottles are then capped below the surface of the water body to minimise the air retention within the bottle itself. To obtain samples of the Verlorenvlei wetland, a bailer was used to fill sample bottles with water from the wetland itself.

Several sampling methods exist to obtain a representative sample of groundwater for chemical analysis. These can be categorised into purge or no-purge methods. Purging is an active method of groundwater sampling which aims to ensure that a sample is taken after standing water is removed from the water column (Sundaram *et al.*, 2009; WRC, 2017). When standing for an extended period of time, water in the borehole column becomes stagnant which modifies the chemical character of the water from the formation, influencing the validity of the sample taken. To alleviate the problem, groundwater is pumped from a borehole until field chemical parameters (such as: pH, EC, Dissolved Oxygen (DO), Eh, temperature, and turbidity) stabilise (WRC, 2017). The accepted recommendation to remove all standing water is three or more times the volume of the borehole water column (Weaver, 2007; Sundaram *et al.*, 2009; WRC 2017). This method results in turbulent conditions which may be associated with mixing, dilution effects, high turbidity and several other undesirable effects (WRC, 2017). Another active method is low-flow sampling which reduces the disturbance to the borehole and hydrogeological formation by pumping water at lower rates creating laminar flow conditions. Passive or no-purging methods present an alternative to purging methods. This involves sampling at discrete depths within the borehole column where water from the flow zone continuously supplies water to the water column through the casing screen. Prior knowledge of the depth of the screen is needed in order to execute this method accurately and reliably. In this current study, boreholes were sampled using the traditional purging method as many of the existing boreholes measured directly were unsealed and therefore required removal of water for a representative sample. Several boreholes in the study area were accessible via taps which were used instead of directly sampling from the borehole when available. In the case of sampling from taps, a similar procedure to the traditional purging method was followed in that the tap water was allowed to run until water chemistry parameters stabilised.

Both surface water and groundwater samples were taken in 250ml high density polyethylene bottles and stored in an ice chest (cooler box with ice) in the field to standardise the temperature before being transferred to a fridge for short term storage prior to analysis. Time and date of measurement as well as other field observations such as water presence and riparian vegetation condition were made con-currently during sampling trips. Thorough labelling protocol was adhered to, preventing misinterpretation during analysis. In addition to samples taken for further chemical analysis, field determinants of EC, pH, temperature and DO were measured in-situ by means of a standard multi-parameter probe at each site. Two instruments were used to measure field determinants, the HACH Portable Multi Meter Probe and the YSI 6-Series Multiparameter Water Quality Sonde. Both instruments share a detection range of between 0.01 μS/cm - 200.0 mS/cm for Conductivity. Prior to use in the field, equipment was calibrated as per the specifications for the type of environment expected according to the user manual prior to use in the field. As this study focuses on non-perennial rivers, it was noted when sites were dry upon returning during sampling trips.

4.3.4 Stable Isotopes

Following the same procedure as in the hydrochemical sampling, separate samples were collected for isotope analysis representing wet and dry seasons between 2018 and 2019. Double capped 50ml polyethylene bottles were used following the grab – sampling technique at both surface water bodies and groundwater sites for analysis of stable isotope ratios of Oxygen-18 and Deuterium. Bottles were capped below the surface to ensure airtight conditions and prevent potential alteration to the isotopic ratio of the samples. The same quality control measures were followed as with the hydrochemical sampling for major ion analysis. An anti-evaporation rainfall collector was installed locally within the study area to obtain local isotopic precipitation data for analysis.

4.3.5 Hydrogeological Monitoring

The potentiometric surface of the aquifer is represented by the water level measurements as a general reflection of the aquifer pressure (WRC, 2017). At selected borehole sites, standing water levels of the water column were measured as depth to water level or meters below ground level. This is later converted to meters above mean sea level. through comparison to a known datum – in this case elevation above sea level. Two types of water level measurements can be used: manual water level measurement or automatic digital measurements whereby a data logger is fitted to a borehole to measure and record water levels at predetermined intervals to be later downloaded for analysis (WRC, 2017).

In this current study the manual water level measurement with a Dip meter method was chosen. Dip meters are electronic water level meters that consist of an open circuit which takes advantage of the conductive properties of water to indicate its presence. The dip meter is inserted into a borehole column and lowered until it comes into contact with water, closing the circuit, at which point a light or Amp meter indicates to the user that it has come into contact with water. Attached to the probe is a tape measure. When the dip meter indicates that the probe has made contact with the water, the depth to water level is measured by taking a reading from where the tape meets casing of the borehole at this point. Due to the salinity profile of the area, this measurement was repeated up to 3 time at a given borehole for improved accuracy of the measurement. A GPS was used to measure the elevation and co-ordinates at each borehole to ensure accurate conversion of depth to water level to meters above mean sea level for analysis.

4.3.6 Geophysical Survey

Geophysical techniques are applied to obtain information of the geophysical nature of the subsurface (McLachlan *et al.,* 2017). Electrical resistivity methods are governed by Ohms law (Loke *et al.,* 2013). The apparent resistivity of a medium is established using this technique by passing low frequency currents directly into the earth's surface and measuring the resulting voltage difference (Loke *et al.,* 2013; McLachlan *et al.,* 2017). The following formula is used to convert measurements of current and voltage to apparent resistivity:

$$\rho_{\alpha} = K\frac{\Delta V}{I} \quad (2)$$

An in-depth description of the basic principles which govern this process is given by Loke *et al.* (2013). Geophysical resistivity surveys can be applied in a multiple dimensional capacity which account for increasing variation in the subsurface. 1-D surveys form the basic survey types which assumes there is no lateral variation in resistivity, 2-D imaging surveys create a 2-dimensional subsurface profile of vertical and lateral variation in a single direction, and a combination of spaced orthogonal 2-D surveys create a 3-D image survey (Loke *et al.,* 2013; Kirsch, 2009; Gharibi & Bentley, 2005). 3-D imaging surveys may benefit the researcher in creating a more detailed investigation but remains less widely applied compared to 2-D resistivity surveys (Loke *et al.,* 2013).

For this current study a 2-D multi-electrode resistivity survey was conducted. This method is cost-effective, unobtrusive and offers high vertical and lateral resolution of the evaluation of underground formations. As this technique involves a computer-driven data acquisition, only a small field team is necessary to obtain field measurements making it easy to conduct in-situ assessments. This method assumes that resistivity varies only in the vertical and one horizontal (lateral) direction along the profile and essentially no resistivity variation perpendicular to cross section will be observed (Loke *et al.,* 2013; Kirsch, 2009). To combat this draw back, 2D resistivity surveys may be conducted in various directions in order to create a more detailed understanding of the resistivity variation, often by arranging multiple survey lines or arranging line directions orthogonally (Loke, *et al.*, 2013). This technique consists of many electrodes (usually metal stakes) connected to a resistivity meter by means of a multi-core cable with fixed spacing. Current and potential electrodes are placed equidistant from each other and are progressively moved along the surface of a cross section (Samouelian, et al., 2005). Inversion modelling creates a 2-D profile of the subsurface along the cable with resolution and depth constraints related to the electrode array configurations. Array configurations may be altered to match the appropriate method for the site characteristics such as geology, altitude and vegetation and the purpose of the investigation.

Two sites were identified for geophysical survey, the main river stem and a tributary near Redelinghuys. For the main river, a 700m NE - SW survey line was chosen to ensure the full width of the river was investigated. This resulted in a 2D profile for the river to a maximum 60 m depth. For the adjoining tributary a crossline survey arrangement was chosen to improve the lateral resolution of the investigation. Two perpendicular survey lines were set up, one 600 m survey line with a maximum depth of 60 m followed the length of the tributary from SW to NE and was intersected by a 200 m NW – SE cross profile of the tributary's subsurface to a maximum depth of 30 m. The intersecting survey was created with 5 m spacing to create a more accurate representation of the shallow below-ground profile as opposed to the wider spacing used for the longitudinal profile survey at the tributary. To minimise poor electrode contact, a small amount of water was poured into the holes where electrodes were inserted to allow for better conductivity due to the dry sediment conditions.

4.4 Data Analysis Methods

4.4.1 Applicability of Assessment Methods

The methods to assess groundwater-surface water interaction applicable for use in non-perennial river systems was determined through literature review. The review was guided by three main criteria based on the environmental context and scope of the current study. These guiding criteria included: the scale of interaction the method could identify, the method's ability to still be used during periods of no flow or when dry riverbeds occur, and how the method fairs according to the standard methods of interaction shown to be successful in previous groundwater – surface water interaction studies. Fulfilment of the first objective of this current study informs the methods utilised in the proceeding objectives. From this review of literature, a multi-method approach was adopted to investigate interaction within the chosen case study area for this study.

4.4.2 Environmental Tracers

- Physicochemical Constituents

By establishing the relationship between different chemical constituents in water samples we identify the interactions the water may have undergone with rock since entering the hydrological cycle. During rock-water interaction, different chemical processes arise which are responsible for changes to the chemical make-up of the water sampled. Chemical processes that occur during rock-water interaction include ion exchange processes, dissolution and precipitation, and oxidation and reduction processes which give rise to differing chemical compositions of water through a change in the concentration of ions present, changes to the water's pH and changes to the mobilisation of dissolved constituents in the water.

- Major Ion Chemistry

Collected samples from surface water and groundwater were analysed for chemical constituents through Elsenburg's analytical services for soil, plant and plant diagnostics using an ICP (Inductively Coupled Plasma) spectrometer (Analytical Services | Agriculture, 2020). Chemical constituents analysed for included major cations of: Ca^{2+}, Mg^{2+}, Na^{2+}, K^{+} and major anions of SO_4^{2-} and Cl^{-}. At the time of sampling, an in-field titration was conducted to measure alkalinity (in mg/l $CaCO^3$) of samples at selected sampling sites that would be analysed further for major ion analysis. $CaCO^3$ measurements obtained in field was later calculated as mg/l HCO^{3-} as per Younger (2007).

For groundwater – surface water interaction to occur, we assume hydro-chemically similar water composition in all sources of water sampled. To highlight similarity or differences in water signatures we plot the chemical composition in different graphical representations to visualise their similarity or dissimilarity. Standard Piper plots indicate the geochemical origin of water samples, as well as provide an analysis of the chemical character of the water samples through establishing the hydrochemical facies of water samples. The chemical character of water moving through aquifers is affected by the lithology and mineralogy of the rocks it encounters along its flow path. Due to a change in the composition of ion exchange minerals from the recharge to discharge area, a hydrochemical facies gradient from recharge to discharge zone is observed (Walton, 1970). The hydrochemical facies of a water sample can as a result indicate the water-rock interaction that may have taken place and also reveal the groundwater flow pattern through the distribution of the facies in the drainage basin as this is influenced by the groundwater head distribution and flow direction (Walton, 1970).

Following analysis of the major ionic composition of water samples taken the credibility of the analysis was tested by means of ensuring Pauling's principle of electroneutrality was met. This principle emphasises that water cannot carry a net positive or net negative electrical charge. Each sample was tested to ensure that the sum of the negatively and positively charged species present within a water sample were balanced to convey a cation-anion balance (CAB), or charge balance error, that approaches zero for no charge, and thus electrically neutral (Younger, 2007). This was calculated using the following formula:

$$\text{CAB (\%)} = 100 \times \frac{[\sum cations] - [\sum anions]}{[\sum cations] + [\sum anions]} \qquad (3)$$

As expressed by Younger (2007), those water samples that were analysed to have a CAB% that was between 0 to 5% were identified as sufficiently accurate for use in scientific studies. Those which exhibited a CAB % of between 5 to 15 % were deemed suitable but were to be used with caution. Water samples which were calculated to have a CAB % greater than 15% are deemed unreliable for the use in scientific studies. A decision was made to include those which were to be used with caution conjunctively with those samples which indicated reliable water analysis in order to increase the points of reference for the study during drier months. To remain true to the integrity of the data upon which conclusions are drawn in this study, those that offered incomplete results were excluded.

- Stable Isotopes

Samples collected were analysed in the University of the Western Cape Earth Sciences Soil laboratory for stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$) by means of a mass spectrometer. Repeat analysis of the samples was employed to ensure reliability of the analysis results. Isotopic compositions are presented in delta notation (δ value) which is the deviation of the sample relative to the Vienna Standard Mean Ocean Water (VSMOW) (Wang *et al.*, 2018) derived from ocean water. Ocean water has $\delta^{18}O$ and $\delta^{2}H$ (δD) values of 0 or close to 0 while negative values have been observed as signatures for most fresh waters (Geyh, 2000).

For interpretation of results, the Global Meteoric Water Line (GWML) was set according to Craig (1961) using the formula:

$$\delta D = 8\delta^{18}O + 10‰ \quad (4)$$

To create a local meteoric water line (LMWL) for the Western Cape of South Africa, freely available local long-term monthly isotope data for Cape Town from the Global Network of Isotopes in Precipitation (GNIP) (Project GNIP/M/ZA/02; 33°58′11.99″S, 18°36′0″E) were used (IAEA/WMO, 1998-2020). The long-term precipitation isotopic data were plotted on a scatter plot to which the LMWL was fitted using an equal weighting, ordinary least squares regression method (Wang *et al.*, 2018). Deuterium excess (or d-excess), defined by d (‰) = δ 2H - 8. δ 18O (Froehlich *et al.*, 2002), is also calculated for analysis and interpretation of results. To interpret the d-excess value we consider the samples deviation from the d-excess at the GMWL (d = +10). In cases where the d-excess is reduced below +10 water is lost by evaporation is enhanced, and in cases where d-excess is above +10, moisture recycling is enhanced (Froehlich, et al., 2002).

By observing the isotopic make up of water we are able to discern valuable information about the water's origin and history (Gat, 1996; Gat et al., 2000; Geyh, 2000). Isotopic and chemical compositions of groundwater give an indication of the lithological and mineralogical composition of the rocks in the aquifer due to water-rock interaction processes which give rise to the waters chemical character. Analysing this data can be used to determine recharge zones and determine the groundwater origin. Isotopic compositions are analysed according to the isotopic species fractionation theory as described by Gat (1996). Stages of the hydrological cycle can be isolated by isotopic signature's representative of that phase in the cycle. This is possible due to evaporative and rain formation processes which alter the isotopic species within water through fractionation.

Certain effects are applied to fractionation processes through change in altitude, latitude, and distance from coast which may affect the enrichment and depletion of heavier isotopes within the water. Due to the altitude effect, the isotopic composition of precipitation changes may become more depleted in $\delta^{18}O$ and δ^2H at higher elevations (more negative) creating an orographic gradient of these constituents in water. This gradient allows us to make inferences of the recharge area of groundwater discharge sites such as springs through comparison of the sample site water chemistry with that of sites at a greater elevation which may have a different composition due to this effect. Greater enrichment of heavy isotopes (more positive isotopic composition) is characteristic of the evaporation effect. Evaporation and condensation of water leads to greater fractionation in evaporative systems such as lakes, rivers, plants and soil water resulting in greater enrichment of isotopic species relative to meteoric water which is often deficient of heavy isotopic species (more negative). As water moves further inland from the coast, the continental effect results in a progressive depletion of the $\delta^{18}O$ species in precipitation (Gat, et al., 2000). This effect may be negligible at relatively smaller scales at the local catchment level as in the case of this study but should be considered when comparing isotopic composition of water from coastal areas to areas several kilometres further inland.

4.4.3 Conceptual Model Development

To achieve objective three of this study, graphical representation of the Verlorenvlei system was developed through interpretation of existing information. The model developed presents the components of the groundwater – surface water interaction water balance equation and describes the conceptual functioning of the study area's groundwater system.

Processes which form the groundwater – surface water interaction water balance equation are generally unable to be measured directly except at small scales (Tanner and Hughes, 2015). As a result, these processes are estimated through extrapolations of local scale observations. The relative importance of each of these processes and components is determined through careful examination of information pertaining to the topography, regional groundwater gradient, hydraulic conductivity and other related aspects of the environment (Tanner and Hughes, 2015). Interpreting existing information and observations to determine simplifying assumptions that describe a groundwater system is termed hydrogeological conceptual modelling. This method employs the interpretation of information to determine system boundaries, properties and processes relevant to the research question being addressed (Enemark et al., 2019). By producing an understanding of the groundwater system, often graphically, conceptual modelling forms an essential first step in groundwater assessments and research.

Several approaches to the development of conceptual models exist. A study by Enemark et al., (2019) provides a review on the current approaches and uncertainty avoidance techniques. A framework for hydrogeological conceptual modelling is presented by Brassington et al (2010), simplified here in Figure 20. Developing conceptual models involves interpreting available geological and hydrological information from observed data, such as: water levels, borehole information and tracer concentrations. Soft knowledge, such as geological insights or expert interpretation also provide valuable insight in conceptual modelling (Enemark et al., 2019).

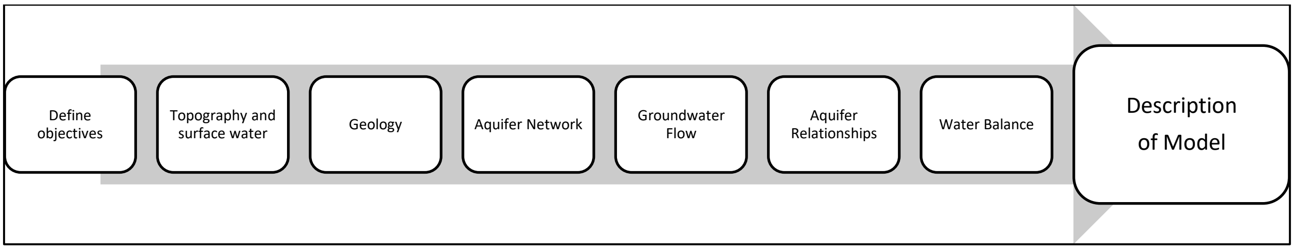


Figure 20: A flow diagram of the simplified steps of the proposed framework for conceptual modelling (Adapted from Brassington et al. (2019)).

The research question of this study is related to the interaction of groundwater and rivers within the study area. A water balance approach was employed to ensure the relevant components of the catchment's water balance equation were accounted for. Existing information from previous studies and climatic observational data was reviewed to characterise these components. Available data obtained from primary measurements and desktop survey was consolidated into a representation of the hydrogeological units, groundwater surface water interaction, relevant processes and water balance of the Verlorenvlei catchment. Geological information was used to conceptualise lithostratigraphic units, their hydraulic properties and links to the Verlorenvlei system. Direction of groundwater flow was assessed through hydrogeological survey of local boreholes and findings from previous groundwater studies in the study area.

In addition to the assessments of the groundwater – surface water interaction conducted to complete objective two, the presence of water within the channel was surveyed upon visitation of the site during field sampling trips. Through repeat monitoring of water presence, the mechanism that allowed water to remain present in the Verlorenvlei catchment at these sites can be conceptualised. Applying the concept of a water balance to a non-perennial river pool, the change in pool water storage would be resultant of net inflows less the net losses of water. With net losses being infiltration of water to groundwater and evaporation, the inflows would consist of either upstream inflow of water and inflow of water from other sources such as precipitation, groundwater from spring flow or baseflow. For the water presence survey, no distinction was made to determine the quantity of water present at sites but rather the water presence was determined according to a simple observation of whether water was present at that site, whether pooling or flowing or if there was visual evidence of a dry riverbed. This may not present a quantitative indication of how much water were at these sites, but it does give a qualitative indication of where the net losses may have exceeded the inflow of water or where water outflow was balanced by water inflow so as to allow water to remain at that site. To create more robust evidence of water presence within the Verlorenvlei river, Google Earth continuous imagery which coincided with the field sampling trips were consulted as a secondary observation of the wetness conditions on site.

4.5 Research Integrity

4.5.1 Quality assurance

- Reliability

Reliability of results is obtained through achieving consistency across the measures taken to obtain and analyse the data to generate results. To this end, sample sites were chosen which were intended to be repeatably sampled. Procedures outlined for data collection were repeated upon returning for field campaigns at each site in the same way it was collected when visiting that site previously. Resampling of sites was made difficult to achieve in highly variable river sites due to seasonal variation in water presence across the catchment. However, groundwater monitoring sites were repeatably monitored upon each field visit. A standard route to reach all sampling sites within the stipulated time allocated to field campaigns was developed and followed upon returning in each campaign. To ensure consistency of data analysis of hydrochemical and isotopic constituents, water samples were analysed at the same research lab for each sampling campaign.

- Validity

The methods selected to achieve the aim of this study were chosen according to their previously proven use in similar studies to meet aims similar to this study. The methods that were chosen have been shown to measure variables which have been identified as representative of the processes that are of interest in this study according to proven theories. Previously published literature was studied to understand how the research question may be answered in contexts similar to that of this study and determine the applicability of methods of assessment to these conditions. By reviewing previous studies in a similar context or environment it is ensured that the current study's findings can be cross-checked with expected results to highlight possible concerning outliers. This cross-check at this stage can highlight data that needs to be re-analysed to ensure its accuracy or data that may represent an anomaly in the variable being measured. Results obtained by following these methods will be interpreted based on identified patterns in theory and previous studies. Characteristics that cannot be directly measured in this study have been accounted for through the measurement of indicators that may give us more information about these characteristics as identified by known theory, such as the water balance and the application of Darcy's law.

4.5.2 Statement of Ethical Consideration

The four principles of ethical consideration applied in this study are the principles of justice, beneficence, autonomy, and non-maleficence (do no harm). To ensure the autonomous principle is upheld, landowners were made aware of the nature of the research being undertaken prior to accessing privately owned land to allow opportunity of refusal on site as well as refusal of participation in the research being conducted. To ensure the justice principle, where possible the opportunity was given to stakeholders in the area to collaborate in the research being conducted to facilitate partnership and generate awareness of the nature of the research. Interaction with all peoples in the catchment was done with respect for their personal knowledge of the area that may pertain to the research study and the interest they may have in the research as it relates to them. As field campaigns were conducted in a group, all co-students, field assistants and field technicians were treated fairly. Activities conducted in field were shared with a multidisciplinary team with equal opportunity to learn new techniques and field skills. In ensuring the principle of beneficence and autonomous principle, consideration was given to data sharing obligations and retaining data integrity. All secondary data sources utilised in this study were ethically sourced with clear communication of the nature of the intention for the data use in this study. As this study forms part of the Environmentally Sustainable Management of Non-perennial Rivers Project conducted by the Institute of Water Studies, data agreements pertaining to any and all primary data generated by this current study were adhered to regarding data sharing and data ownership. To ensure the principle of non-maleficence (or the 'do no harm' approach) was adhered to, the study was largely observational, requiring no ethical clearance. Only small volumes (50 to 250ml) of water were taken from water sources as samples with care not to disturb the environment unnecessarily.

4.5.3 Technical Consideration

To determine the natural functioning of the Verlorenvlei system, a simple water balance approach was chosen to build on the information already existing within the study area. Geohydrologists that work closely with farmers, the Department of Water and Sanitation and various stakeholders in the Sandveld area were consulted for their insight into the hydrogeology of the Verlorenvlei and surrounding area and their input into the conceptual model of the system. Chemical analysis of the water samples taken were outsourced to expert accredited laboratory facilities to conduct an accurate analysis of the water samples for use in the major ion analysis for this study. To complete the geophysical survey for the assessment of the local interaction mechanisms, an expert in geophysics was consulted to assist in the conducting the geophysical surveys of the profiles as well as the compilation of the inversion model of the apparent resistivity used in the data analysis.

4.5.4 Legal Consideration

The South African National Water Act prohibits water use activities that may potentially harm or have an adverse impact on water resources. Care was taken to ensure samples of water taken were according to research guidelines in conjunction with officials from the Department of Water and Sanitation who manage the water resources in the area and other local water management authorities to ensure legal consideration was taken when conducting data collection field campaigns. Any entering of private property for field observations, installation of equipment or sampling of water for water analysis was done with the informed consent of the owner. It was ensured that due notice was given to landowners on the purpose of our visit, the intention of our research and our affiliation as post-graduate research students at the University of the Western Cape, Institute of Water Studies prior to embarking on these field campaigns. All rights to enter private property was reserved for the landowner's discretion.

4.5.5 Limitations of the study

The high variability of non-perennial systems may pose challenges in designing the field sampling regimes for these systems (Seaman *et al.*, 2013). No standard data collection method has been developed for the collection of data on non-perennial rivers in the different disciplines (Seaman *et al.*, 2016). Uncertainty in groundwater-surface water measurements is a key limitation of this study as heterogeneity and inconsistencies over varying temporal and spatial scales can significantly affect the results obtained. In this study this can be overcome with careful consideration of the scale for which each method is applicable, both temporal and spatial when applying the method of choice (Kalbus, *et al.*, 2006). That means that frequent data at intervals is required however, this was not possible due to various limitations such as time, budget and/or water availability at sampling sites as in the case of this study.

In recent years, the Western Cape of South Africa experienced a drought period with the lowest annual rainfall reported in 2017 (Department of Water and Sanitation, 2018). Previous studies of non-perennial rivers have identified drought as a natural disturbance to these unique systems as it may alter the duration, extent and frequency of river floodplain linkages and disrupt both physicochemical conditions in pools downstream and their characteristic vertical and lateral linkages (Rossouw *et al.*, 2005). These conditions resulted in the Verlorenvlei exhibiting exaggerated desiccation characteristics which created difficulty in the site selection process as the difference between areas that were naturally dry or dry as a result of the drought conditions was difficult to discern. Several boreholes were unable to be re-sampled for certain field campaigns due to borehole collapse due to increased water usage during the drought period or as a result of inaccessibly due to absence of landowners. Continued and increased active groundwater use during the duration of this study may skew results and reduce certainty.

Present day water quality monitoring of groundwater data was constrained to accessible private boreholes with little to no geohydrological information which results in a low confidence interpretation of results obtained from these sites.

The Verlorenvlei area is largely transformed area with much of the original natural landscape being altered through agricultural practises, this causes difficulty in assessing the natural functioning of this system due to its alteration from its original state. It is as a result, difficult to provide a description of the natural functioning of the catchment with greater certainty at this level of study.

4.6 Chapter Summary

The research design and a detailed description of the method followed to obtain the results of this study is provided in this chapter.

5.1 Chapter Introduction

This chapter presents the results obtained from the application of the approaches described in the previous chapter. By applying this approach and methodology, the groundwater – surface water interaction within the Verlorenvlei river network may be explored as a case study to further the knowledge on groundwater's role in sustaining non-perennial rivers.

5.2 Applicable Methods

The first objective of this study is to establish the applicability of methods for assessing groundwater – surface water interaction for use in non-perennial environments. The applicability of current assessment methods was determined through review of available literature. The review which gave rise to the chosen methods utilised in this study is presented in Chapter 2. This review provides the supporting argument of a multi-method approach for assessment of interaction in this current study and outlines the specific methods which would be beneficial for the environmental context and scope of this current study. As a result, a combined assessment utilising hydrochemical analysis of environmental tracers, geophysical survey techniques and hydrogeological monitoring was deemed applicable for the assessment of interaction mechanisms and processes within the chosen case study area.

5.3 Interaction Processes

The second objective of this study is to investigate the processes and mechanisms of groundwater -surface water interaction within the Verlorenvlei catchment at regional and local scales. The results of the methods that were undertaken to achieve an understanding of these multi-scale processes. A geophysical survey was conducted to determine the interaction mechanisms and an environmental tracer-based study was undertaken to identify water origin and spatial potential for interaction.

5.3.1 Geophysical Survey Results

Three geophysical cross-sectional surveys were constructed to assess the local groundwater - surface water mechanisms near Redelinghuys within the study area. The surveys were conducted during November 2017, with additional survey data obtained from September 2015. Geophysical Resistivity Inversion Surveys (RIS) for the sites of cross-sectional surveys are presented by Figures

21, 22 and 24. Resistivity - depth values are colour graded from 10.0 to 1111 Ω.m for geo-electric models 1- 4 and from 5.0 to 908 Ω.m for geo-electric model 5. The corresponding colours are as follows: blue indicates the lower end of the resistivity values, red to purple indicate the upper limit of the higher resistivity values, and green and yellow representing the median values of the resistivity spectrum.

Resistivity profiling of a cross-section of the Verlorenvlei river (Geo-electrical model 1) during the dry season of 2017 is presented in Figure 21. The resistivity profile of this cross-section ranges from 38.4 – 148 Ω.m with the two comparatively more resistive areas of ±289 Ω.m between 400 to 600m along the profile. A low resistivity layer of sediment is found immediately below the surface of the river's flood plain to a depth of ~10 m with the least resistive material found between 400 - 600 m of the profile length. A band of low resistivity material is evident at the SW end of the profile (between 620 - 700 m) which corresponded with field observations of a furrow at this location.

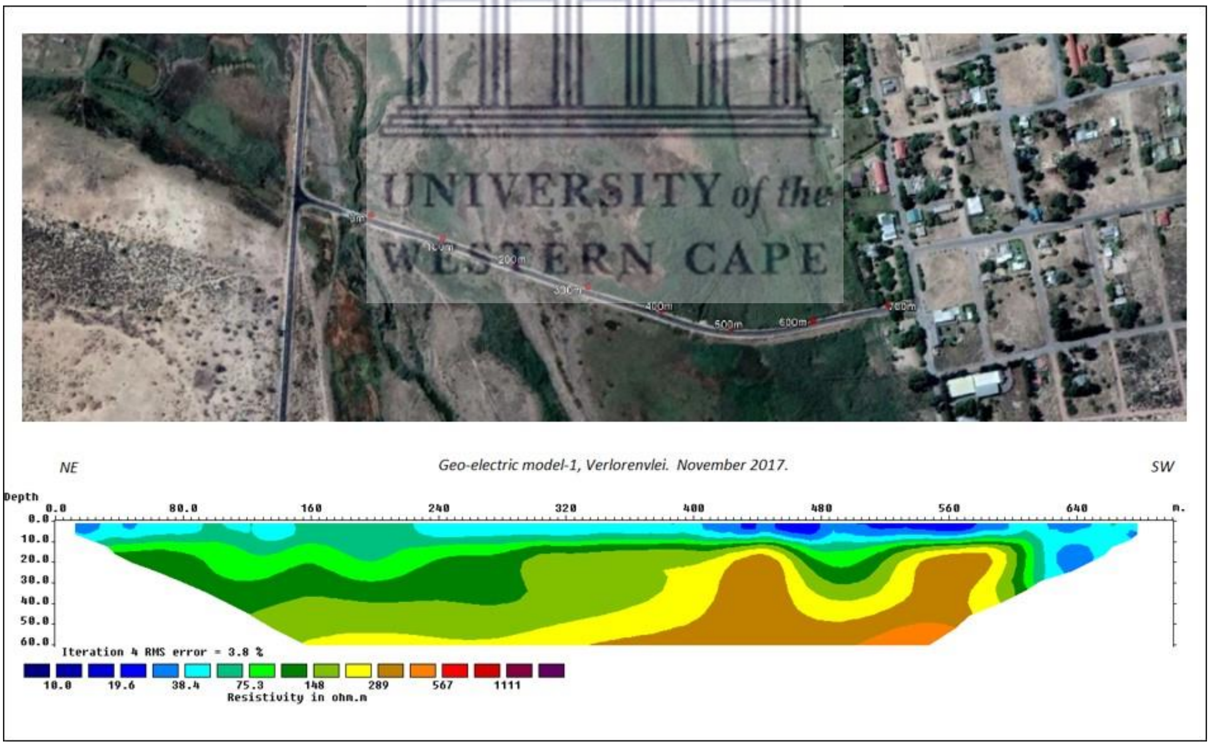


Figure 21: 2D Apparent Resistivity Survey across the Verlorenvlei River (November 2017)

Orthogonal RIS transects across the Redelinghuys tributary surveyed during the same field campaign in 2017, is presented in Figure 22. For both transects (Geo-electric model 2 and 3) a clear division is evident in the inversion model between a layer of low resistivity material until approximately 10 to 15 m below the surface followed by a highly resistant foundation layer with modelled resistivity values in the upper limits of the inversion model between 567 and 1111 Ω.m. Observation of the soil characteristics of the first 2 – 3 metres along the transect of Geo-electric Model 3 through auger investigations indicated sandy soil conditions (Figure 23). The modelled resistivities increase gradually below the ground until a threshold is reached at 30m, thereafter a resistive body of rock is evident with resistivities at ~1111 Ω.m which extends for a further 30m past the boundary of the model at 60m (Geo-electric model 2, Figure 22).

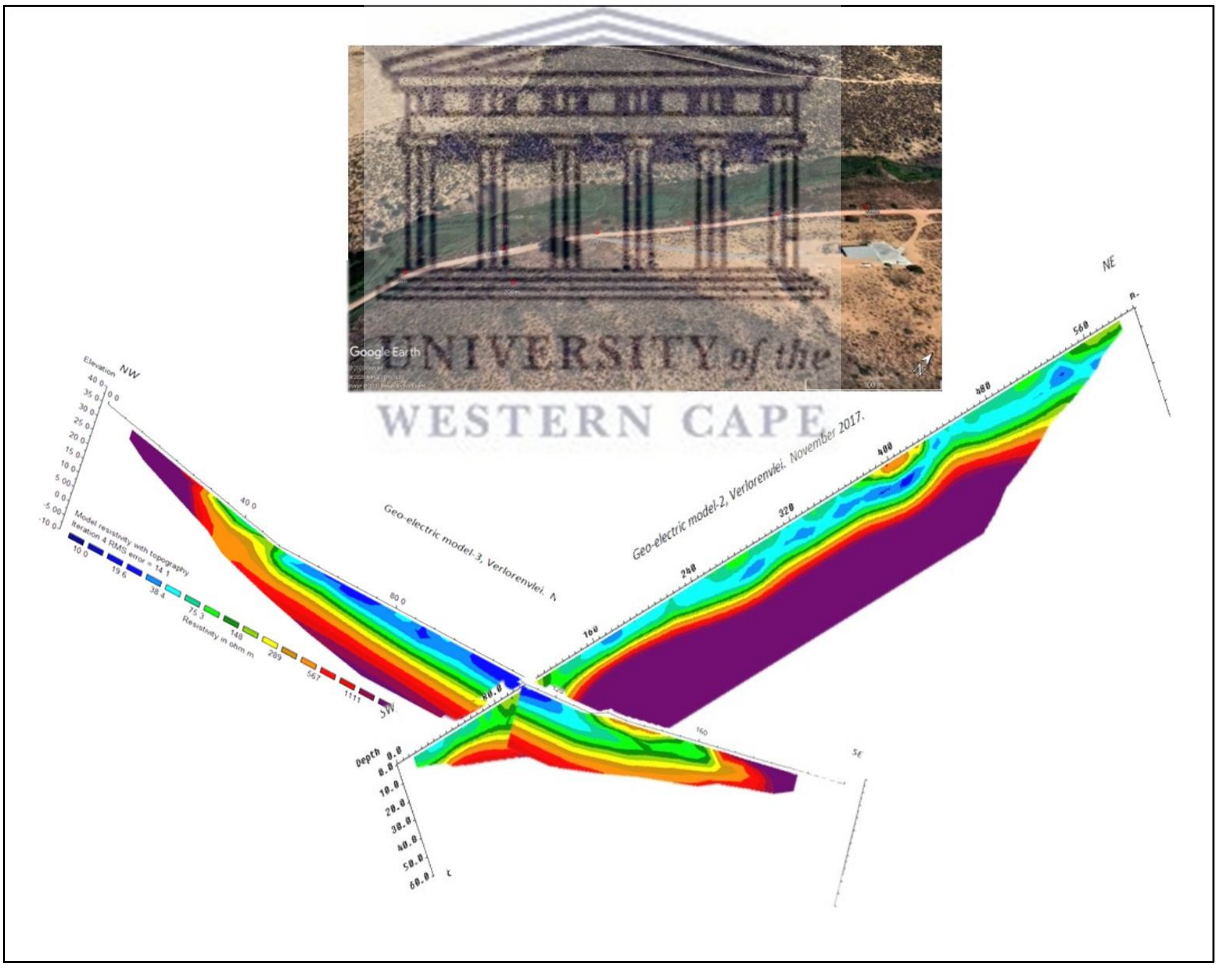


Figure 22: Orthogonal 2D Apparent Resistivity Survey of a Redelinghuys tributary to the Verlorenvlei (November 2017).

Figure 23: Photo depicting observations of sandy soil sediments via auger investigations at S 32.44930°, E 018.52009°, Elevation: 8m.

Figure 24 shows an orthogonal transect (Geo-electric models 4 and 5) further north along the Redelinghuys tributary surveyed during the early dry season of 2015. The resistivity profile of this cross-section ranges from 5 to 1111 Ω.m, showing high variation in the resistivity along both Geo-electric models 4 and 5 profiles. Geo-Electric model 4 indicates that the same distinction can be made between a low resistivity shallow layer of sediment and a more resistive harder rock below as in Geo-Electric model 2 and 3, however, the distinction is less definte than further South along the tributary towards Verlorenvlei. The resistivity profile of Geo-electric Model 4 shows us the below ground resistivity along the length of the tributatry. A shallow low resistivity layer extend along the entire length of this profile to an approximate depth of 20-25 m. Two low resistivity zones about 40 m thick are observed between 160 and 400 m along the profile length which extend the low resistivity shallow layer to a depth of ~50 m in these areas. In this transect, a resistive rock layer was modelled between 260 to 320 m at a depth of 60 m as well as between 640 and 880 m at a depth of 50m. Geo-electric Model 5 provides an indication of the below ground resistivity transecting the tributary. In this profile a low resistivity layer was observed below the surface to a depth of ~20 m. A layer of highly resistive rock with apparent resistivities of approximately 908 Ω.m is found at depths below ~20 m which is interupted by a more conductive zone (~46.5-97.7 Ω.m) between 270 and 310 m along the transect. A low resistivity zone of ~5 to 10.5 Ω.m indicating very conductive substratum was modelled between 30 and 80m and 120 to 150 m.

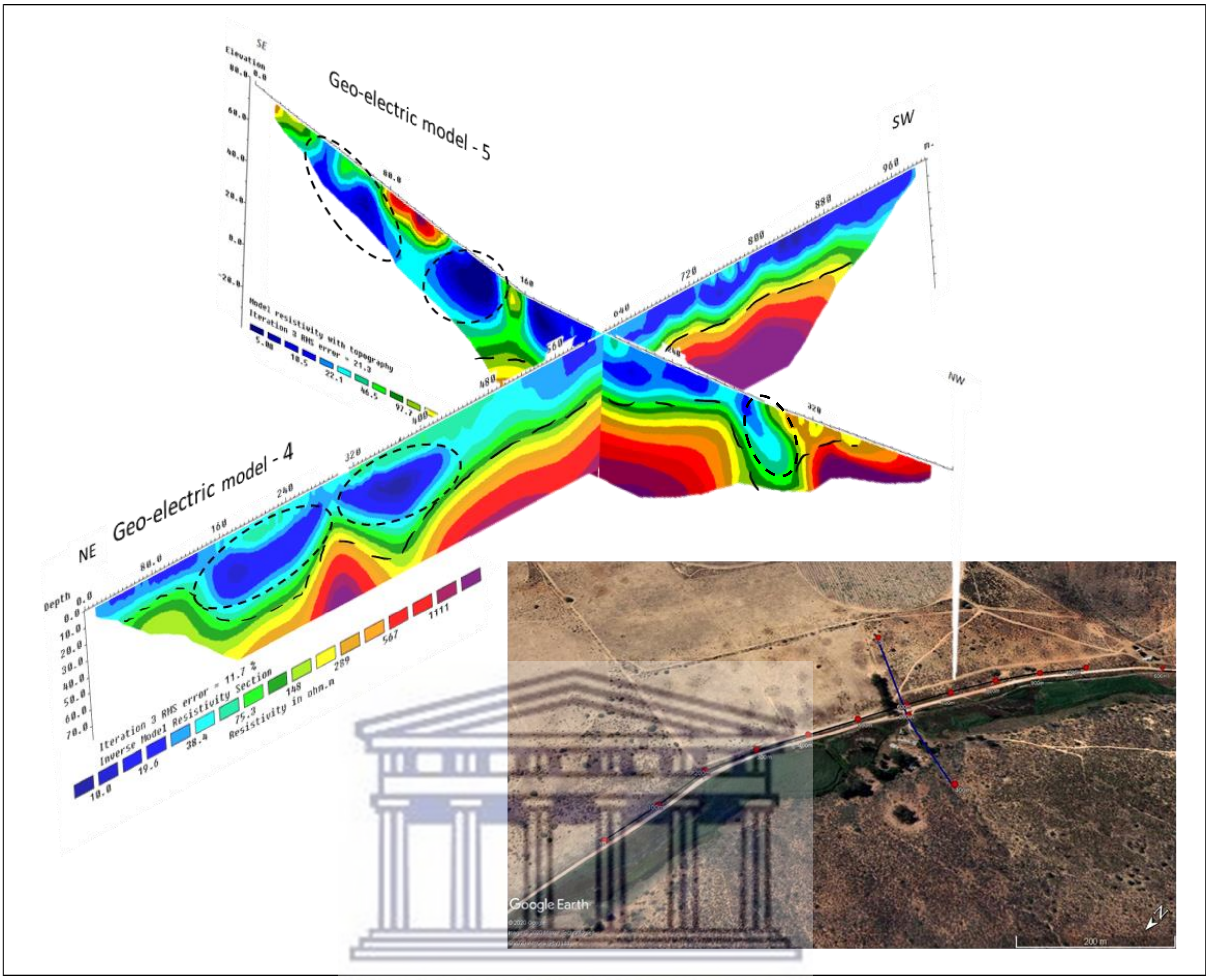


Figure 24: Orthogonal 2D Apparent Resistivity Survey of a tributary to the Verlorenvlei near Redelinghuys (September 2015).

Field observations of the Verlorenvlei river tributary near Redelinghuys during the dry season of 2018 identified a possible spring at the source of this tributary (Figure 25) which seems to correspond with geological contacts previously mapped in the area. The low EC and pH of water sampled at this seep as indicated in Table 4 is comparable with the characteristic profile expected from the TMG sandstones, suggesting that the presence of water in this location was due to groundwater upwelling and discharge to the surface.

Figure 25: Photo of groundwater upwelling North of Redelinghuys taken May 2018

(S 32.41772° E 018.54982°, Elevation 77m).

Table 4: Physicochemical values of groundwater upwelling North of Redelinghuys, May 2018 (S 32.41772° E 018.54982°, Elevation 77m)

Electrical Conductivity (µS/cm)	Temperature (°C)	pH
223.9	23.3	4.81

5.3.2 Environmental Tracer Results

Water samples taken were analysed for naturally occurring environmental tracers and physico-chemical water quality parameters to identify the main origin of the water at various sites and determine their potential interaction. The main hydrochemical and isotopic constituents analysed from these samples included; Concentration of major ions of: Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, and HCO^{3-}; in mg/l, stable isotopes of Oxygen (^{18}O) and Deuterium (^{2}H) and physico-chemical parameters of: electrical conductivity (µS/cm), temperature (°C) and pH. Chemical character of water from representative samples from both groundwater and surface water samples are compared to identify possible linkages and evidence of interaction. A quality assurance check was conducted on all samples by applying a Charge Balance Error (CBE) assessment to the major ion analysis to ensure the quality of samples for application to research. Table 5 presents the 75 water samples of the hydrochemical analysis which were deemed acceptable for use in research and used in this current study, the rest were rejected to retain analysis accuracy.

Table 5: Hydrochemical and physiochemical data from groundwater, river and wetland samples collected along the Verlorenvlei

Site	Date	EC (µS/cm)	pH	Temp (°C)	Ca (mg/l)	Cl (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	SO_4 (mg/l)	HCO_3^- (mg/l)	CBE %
B	Jul-17	1487.00	5.39	13.9	30	307.71	15	30	186	73	40.8	7
	Feb-19	1162.67	6.34	26.68	90	1297.88	9	92	541	193	7.2	-6
DS1	Jul-17	1128.00	5.12	14.6	11	289.54	2	24	166	10	19.2	6
	Mar-18	1267.00	5.82	27.5	8	222.51	1	19	124	12	40.8	1
	Jul-18	1109.00	7.4	20.4	11	276.47	2	24	163	13	14.4	8
	Feb-19	1202.00	6.28	29.6	11	297.35	2	28	170	11	2.4	9
G33651	Mar-18	1001.00	6.5	21.4	14	277.33	3	29	124	12	21.6	1
	Jul-18	965.00	6.36	21.7	19	248.78	3	27	114	11	19.2	4
	Feb-19	936.00	6.35	23.95	13	244.1	4	31	118	1	2.4	8
GD1	Jul-17	1287.00	5.73	18.8	20	307.86	8	34	167	59	28.8	4
	Oct-17	1209.00	5.82	23.9	21	325.46	2	33	169	54	76.8	-2
	Mar-18	1337.00	6.42	22.56	20	351.17	3	36	181	56	43.2	1
	Feb-19	1350.00	6.39	26.50	22	330.15	5	41	181	62	14.4	7
GG	Jul-17	413.00	7.57	17.6	8	93.72	1	7	41	9	33.6	-10
	Oct-17	388.00	8.49	25.6	11	112.32	1	10	58	11	86.4	-10
	Mar-18	443.00	7.705	23.1	10	128.08	1	12	63	8	16.8	2
	Jul-18	436.00	7.58	21.5	10	113.46	1	11	61	14	31.2	1
	Feb-19	517.00	7.18	27.7	11	136.6	1	16	78	8	7.2	12
HK1	Oct-17	878.00	6.39	20.5	13	239.84	1	29	133	32	72	1
	Mar-18	905.00	6.15	26.52	12	202.07	1	25	96	30	52.8	-2
	Feb-19	942.00	6.82	29.1	15	218.54	3	32	122	35	26.4	9

HolD	Jul-17	5710.00	7.62	15.4	58	1364.34	5	120	680	168	0	1
	Oct-17	4820.00	7.78	22.3	55	1407.79	1	130	802	109	144	4
	Mar-18	514.00	7.06	26.02	11	139.02	1	13	65	10	31.2	-2
	Feb-19	1389.00	8.09	31.6	25	345.34	2	40	187	32	38.4	7
HoR	Oct-17	5390.00	8.47	25.7	42	931.8	1	82	570	109	204	3
KA1	Jul-18	121.00	8.73	16.5	3	41.46	1	3	17	9	12	-14
	Feb-19	494.00	6.91	21.7	28	101.1	1	14	51	26	72	10
KmR	Jul-17	809.00	5.94	17.2	38	156.2	1	25	91	142	33.6	0
	Oct-17	324.00	6.93	27.8	11	79.09	1	7	47	27	28.8	-1
KR1	Jul-17	7730.00	7.5	16.2	68	1222.34	10	110	619	255	38.4	0
	Jul-18	5580.00	7.72	15.1	64	1035.46	12	110	523	132	196.8	-1
KR2	Jul-17	2156.00	7.68	16.3	48	595.12	4	53	283	70	151.2	-4
KR3	Jul-18	163.00	8.5	15.7	8	44.45	1	5	14	23	12	-14
	Feb-19	719.00	7.17	24	23	146.83	3	24	102	50	96	6
KR4	Jul-17	7940.00	7.26	13	81	1383.36	12	140	654	282	153.6	-3
	Oct-17	7910.00	7.63	20.7	78	2575.88	16	220	967	294	300	-13
KVD	Jul-17	282.00	7.44	14.2	27	44.02	2	6	25	14	84	1
	Oct-17	337.00	6.61	25	16	54.24	1	7	31	11	96	-10
	Feb-19	416.00	7.25	23.55	41	64.04	3	9	40	15	163.2	-2
MH1	Jul-18	93.30	8.4	17.6	4	29.39	2	2	11	5	16.8	-15
MH2	Jul-17	783.00	6.97	11.4	24	167.13	1	24	105	37	151.2	-1
	Jul-18	134.80	8.49	18.3	8	32.94	1	3	15	15	19.2	-8
	Feb-19	669.00	7.01	21.5	52	103.8	1	18	66	5	304.8	-7
PMV1	Oct-17	453.00	6.06	29.3	18	136.6	2	12	56	11	55.2	-7
	Mar-18	545.00	6.47	29	19	142.57	2	13	61	12	43.2	-3
	Jul-18	435.00	7.3	20.8	15	107.35	3	11	47	9	28.8	1
	Feb-19	498.00	7.08	33.6	17	124.11	4	13	55	9	9.6	7
PMV2	Oct-17	460.00	6.02	24.10	18	141.43	2	13	58	11	60	-7
	Mar-18	512.00	6.23	25.49	18	138.45	2	13	60	11	45.6	-3
	Jul-18	444.00	7.20	18.30	17	119.14	3	11	50	8	24	1
	Feb-19	1400.50	6.35	27.55	36	331.57	8	40	179	57	7.2	10
PZ5	Feb-19	854.00	6.7	24.9	12	229.33	16	27	133	117	96	-8
S0	Jul-17	1034.00	4	18.7	26	209.31	15	14	114	49	0	6
	Oct-17	676.00	3.67	22.1	14	178.35	6	15	91	19	0	5
	Mar-18	650.00	4.36	20.75	8	144.13	2	12	79	7	0	7
	Jul-18	894.00	4.67	19.1	20	205.76	11	18	103	27	0	6
	Feb-19	665.00	4.63	26.8	9	152.93	4	15	90	7	12	10
Spr	Jul-17	1701.00	6.94	12.9	20	324.75	2	29	168	9	60	2
VK1	Jul-17	669.00	4.3	13.4	14	168.55	6	12	93	17	4.8	6
	Oct-17	636.00	3.78	19.6	16	169.83	4	11	89	18	124.8	-12
	Jul-18	663.00	6.4	18	16	165.71	5	11	89	18	2.4	6
	Feb-19	675.00	5.61	21.15	14	157.19	6	12	95	17	7.2	10
VK2	Jul-17	4840.00	5.95	17.5	56	1054.49	19	75	595	198	24	2
	Oct-17	3080.00	5.12	22.7	49	756.29	5	52	475	132	81.6	4
	Mar-18	7484.00	7.44	21.21	86	1588.98	7	79	1001	291	349.2	3
	Jul-18	4870.00	6.3	21.2	89	1390.75	10	92	721	216	12	0
VR1	Jul-17	1343.00	7.02	14.5	23	303.6	5	33	179	70	48	4
	Oct-17	1053.00	8.2	19.2	13	301.47	1	29	189	53	96	0
	Mar-18	1154.00	6.27	21.4	14	264.26	1	25	143	26	69.6	-1
	Jul-18	2051.00	7.31	16.7	36	492.03	7	52	254	89	69.6	1
	Feb-19	904.00	6.75	24.2	13	47.43	92	11	35	62	36	5
VRT1	Jul-18	1755.00	7.43	14.6	35	650.22	5	56	314	14	76.8	1
	Jul-17	1649.00	7.31	12.8	102	1198.76	3	120	791	703	33.6	-6
VV2	Jul-17	200000.00	7.57	8.9	86	1931.77	20	160	869	220	237.6	-6

5.3.2.1 Physiochemical survey

Table 6 presents a statistical summary of results of the hydrochemical and physicochemical water quality analysis for samples taken during the assessment period averaged according to seasonality. In general, groundwater samples varied less in their levels of electrical conductivity than those of surface water samples in both the dry and wet seasons while temperature and pH varied more in groundwater samples than in surface water samples.

EC values for groundwater were observed to range from 282 to 7484 µS/cm, Surface water EC values were more extreme, with a range of 93.3 to 200000 µS/cm. The lowest values of EC in both groundwater and surface water were observed during the wet season. During the dry season, the lowest EC values were ±300 µS/cm with the highest EC values exceeding 5710 µS/cm in either group of dry season samples. Site VV2 was measured to have an EC signature of more than 200000 µS/cm - the upper limit of the measurement equipment – during the wet season. This site was measured to have the highest electrical conductivity across the study area.

Considering the standard deviation from mean, temperature measurements were most variable in groundwater sites during the dry season and least variable in surface waters during the wet season. The pH of the samples ranged from a low of 3.67 to a high of 8.49 in the groundwater samples while the pH of surface water samples ranged from a pH of 5.94 to 8.73.

Table 6: Comparative statistical summary of hydrochemical and physiochemical parameters in groundwater and surface water sampling sites

Parameters	Groundwater				Surface water			
	Range	Median	Mean	Std. Deviation	Range	Median	Mean	Std. Deviation
	Wet Season (July-17 & July-18) n=18				Wet Season (July-17 & July-18) n=15			
Ca^{2+} (mg/l)	8-89	19.50	25.94	20.47	3-102	36.00	41.87	30.89
K^{+} (mg/l)	1-19	4.00	6.28	5.36	1-20	4.00	5.67	5.41
Mg^{2+} (mg/l)	6-120	21.00	30.89	31.02	2-160	52.00	59.73	52.45
Na^{+} (mg/l)	25-721	114.00	199.06	214.97	11-869	254.00	315.93	290.22
Cl^{-} (mg/l)	44.02-1390.75	229.05	377.32	411.86	29.39-1931.77	492.03	618.95	581.46
SO_4^{2-} (mg/l)	8-216	15.50	51.22	66.87	5-703	70.00	137.73	175.18
HCO_3^{-} (mg/l)	0-84	21.60	23.73	21.36	12-237.6	48.00	83.36	72.10
EC (µS/cm)	282-5710	999.50	1575.94	1646.85	93.3-200000	1649.00	15487.21	49378.76
Temp (°C)	12.9-21.7	18.15	17.67	2.86	8.9-18.3	15.70	14.99	2.46
pH	4-7.62	6.38	6.29	1.16	5.94-8.73	7.50	7.59	0.70
	Dry Season (Oct-17, Mar-18, Feb-19) n=33				Dry Season (Oct-17, Mar-18, Feb-19) n=9			
Ca^{2+} (mg/l)	8-90	16.00	22.82	19.87	11-78	23.00	30.44	21.55
K^{+} (mg/l)	1-16	2.00	3.48	3.08	1-92	1.00	13.00	28.31
Mg^{2+} (mg/l)	7-130	19.00	29.06	26.02	7-220	24.00	47.78	64.39
Na^{+} (mg/l)	31-1001	96.00	175.91	214.13	35-967	102.00	241.11	300.69
Cl^{-} (mg/l)	54.24-1588.98	202.07	326.84	372.37	47.43-2575.88	146.83	505.74	775.54
SO_4^{2-} (mg/l)	1-291	15.00	43.06	61.25	5-294	50.00	72.44	83.23
HCO_3^{-} (mg/l)	0-349.2	40.80	55.60	66.96	28.8-304.8	96.00	134.13	101.75
EC (µS/cm)	337-7484	854.00	1200.07	1395.05	324-7910	904.00	2068.56	2531.60
Temp (°C)	19.6-33.6	25.00	25.19	3.33	19.2-27.8	21.70	22.91	2.56
pH	3.67-8.49	6.39	6.33	1.09	6.27-8.47	7.01	7.26	0.67

Figure 26 presents the distribution of the range of physicochemical data measured at the surface water and groundwater sites selected for this study. In surface water samples, the greatest EC values occurred near the mouth of the Verlorenvlei wetland while lower EC values were found in higher elevation areas where pooled and flowing water was found only during high rainfall periods. The lowest EC values occurred in tributaries to the Krom Antonies river within Moutonshoek, with site MH1 having the lowest EC value.

No distinct relationship between the geology present and the physical parameters can be determined in groundwater sites. The groundwater sites selected were comprised of boreholes, open air dams and springs. The environments of each site may cause their physiochemistry to vary.

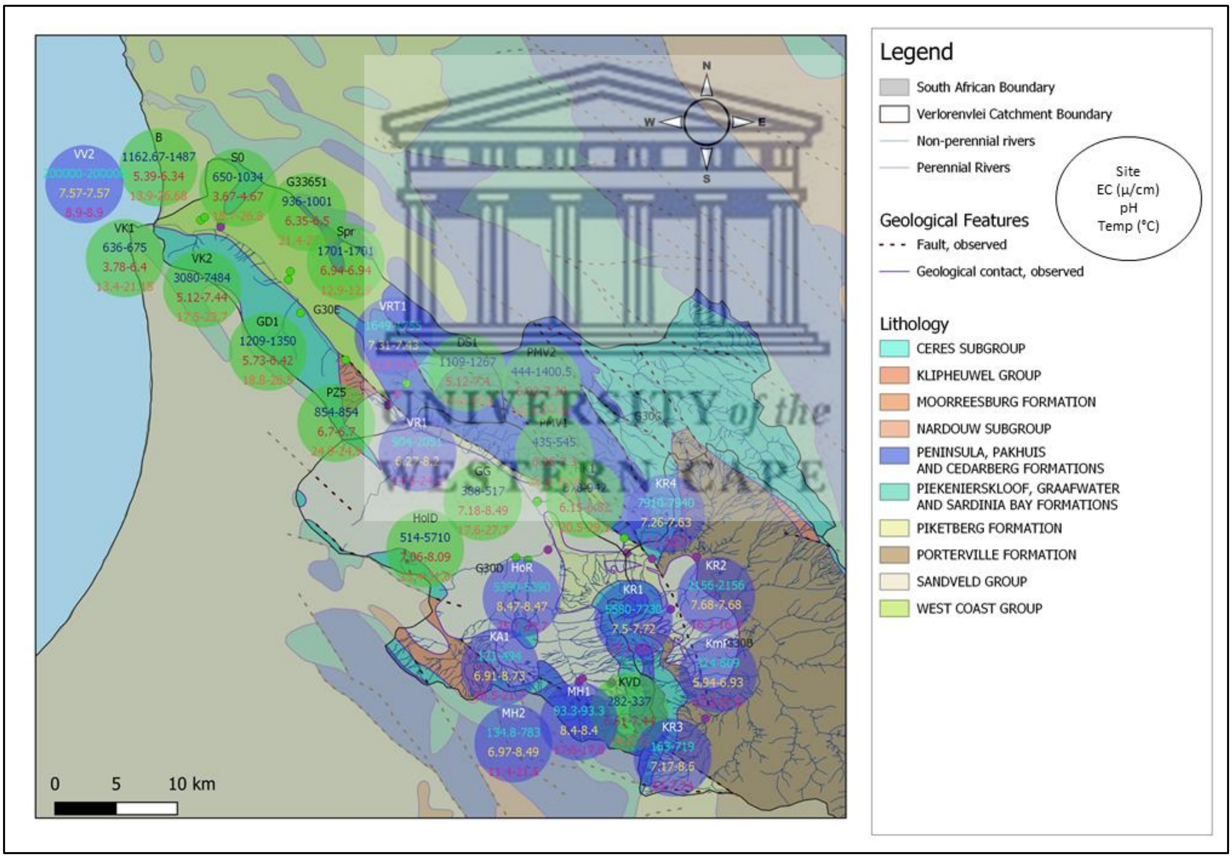


Figure 26: Distribution of the range of physicochemical results obtained at groundwater and surface water sites chosen for this study.

5.3.2.2 Hydrochemical facies and distribution of salts

The results of the major ion analysis are provided below. The results are arranged graphically in piper diagrams and stiff diagrams to observe the hydrochemical facies, grouping and hydrochemical distribution in the groundwater and surface water through analysis of the dissolved chemical constituents. The hydrochemical facies of the water samples across all the samples analysed is characterised as Na-Cl which is typical of discharge waters (Karroum, et al., 2017). The dominant constituents in the hydrochemical analysis are observed to be $Cl^- \geq Na^+ \geq Mg^{2+}$ as indicated in the piper diagrams in Figures 27, 28 and 30. Two exceptions to this were found: 2018 wet season surface water sites exhibit a dominant trend of $Cl^- \geq Mg^{2+} \geq Na^+$ and 2017 dry season groundwater samples exhibit a dominant trend of $Cl^- \geq Na^+ \geq HCO^{3-}$.

The hydrochemical facies of the wet season samples are indicated in Figure 27 for both July 2017 and July 2018. For July 2017 (Figure 27.1 a.), the majority of the samples, both groundwater and surface water samples, are of Na-Cl water type, with sample KVD being Ca-HCO_3 water type and MH1 was observed to have a mixed Ca-HCO_3 to Na-Cl hydrochemical facies. Similarly, the samples for July 2018 are observed to have a hydrochemical facies of Na-Cl water type (Figure 27.2. a). By arranging the major ion concentrations into stiff diagrams according to the location of each sampling site we are able to evaluate spatial distribution of hydrochemical facies. From Figure 27.1. b we can interpret the following similarities in ionic composition; sample B, DS1, SO, and Spr, samples VV2 and HolD, samples KVD, MH1, and GG.

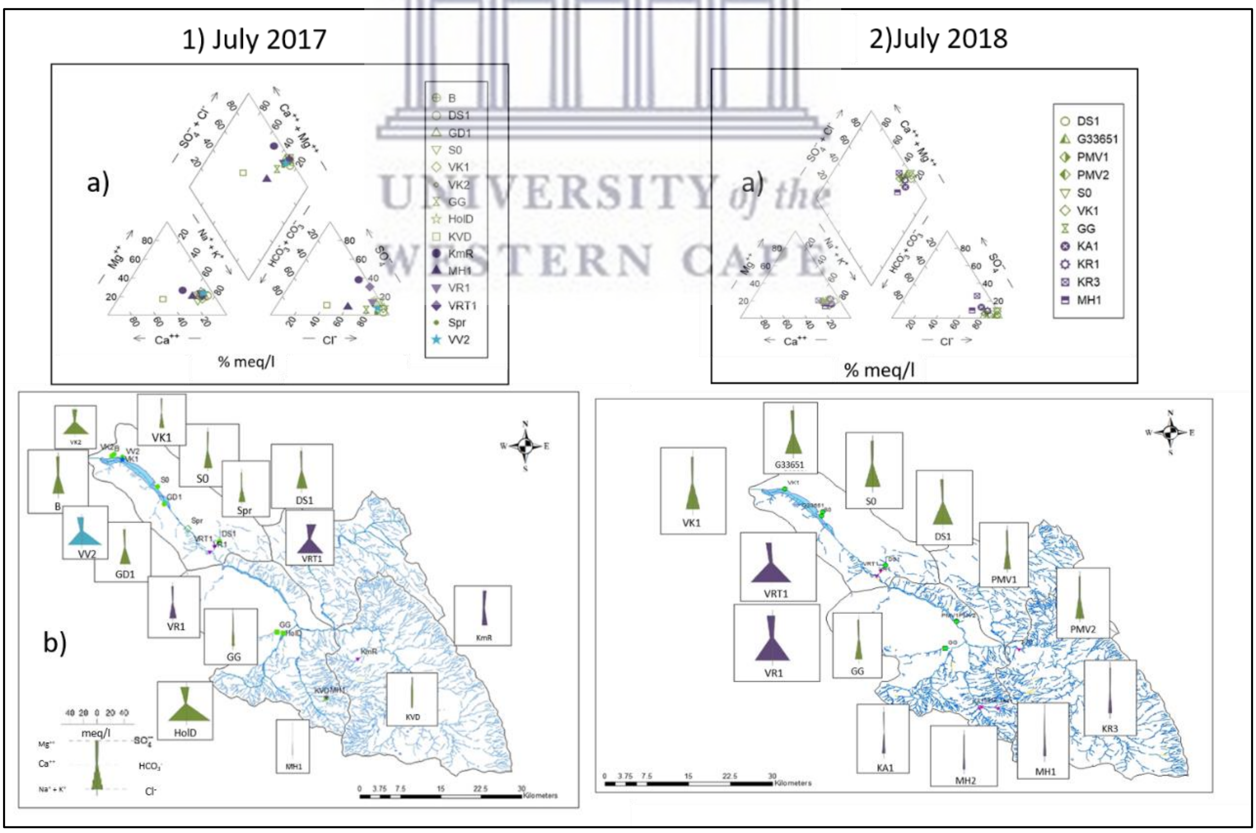


Figure 27: 1 a) Piper Diagram depicting hydrochemical facies composition of samples for July 2017. b) Map indicating the distribution of chemical character for the October 2017 sampling campaign through stiff diagram representation.2 a) Piper Diagram depicting hydrochemical facies composition of samples for July2018. b) Map indicating the distribution of chemical character for the March 2018 sampling campaign through stiff diagram representation. Here the green samples indicate groundwater sample origin, purple indicates surface water samples and blue indicates the wetland estuarine sample.

Dry season water type composition and distribution for October 2017 and March 2018 are indicated in Figure 28. Similarly, to the wet season, the dominant water type for these samples is Na-Cl. KVD continues to show a chemical character of Ca-HCO_3 and samples of VK1 & GG exhibit a combined water type of Na^+-Cl -Mg^{2+}. Although most river sampling sites were dry upon return in the dry season, similarities in the ionic composition are evident between the groundwater sites and the few remaining pools in both 2017 and 2018 (Figure 28.1 b & Figure 28.2 b).

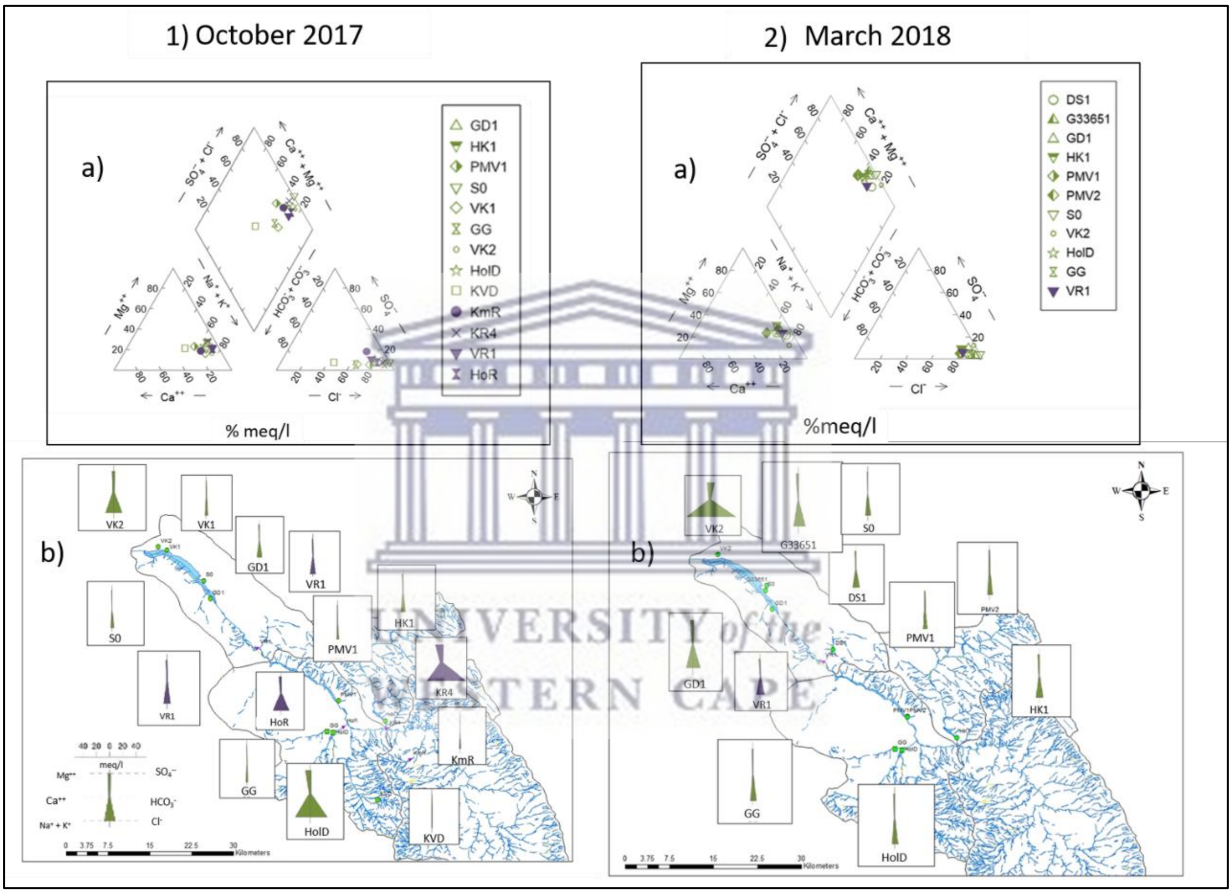


Figure 28: 1 a) Piper Diagram depicting hydrochemical facies composition of samples for October 2017. b) Map indicating the distribution of chemical character for the October 2017 sampling campaign through stiff diagram representation.2 a) Piper Diagram depicting hydrochemical facies composition of samples for March 2018. b) Map indicating the distribution of chemical character for the March 2018 sampling campaign through stiff diagram representation. Here the green samples indicate groundwater sample origin, purple indicates surface water samples and blue indicates the wetland estuarine sample

The wet season of 2018 brought some relief to the Western Cape in terms of the drought. February 2019 samples represent the hydrochemical character of the Verlorenvlei system as a result of a wet period after an extended period of less than average rainfall. The dominant water type of samples taken during the February 2019 dry period were found to be Na-Cl for both surface water and groundwater sources. Several tributary sites (KR3, MH2 and KA1), the shallow piezometer (PZ5), and a groundwater site (KVD) are observed to have increased concentrations of HCO^{3-} during this sampling campaign. Site MH2 indicated a water type of Na-HCO_3 and KVD continued to be classified as a Ca – HCO^3 water type.

Although the dominant water type was found to have no change, an increase in concentration of the relative constituents in the water sources is evident (Figure 30). Cyclic wetting and drying of soil in semi-arid to arid areas may cause salts to precipitate on the riverbeds of rivers. Heavy rainfall following a dry period may leech accumulated salts into the water to be transported out of the soil and into the water ways of non-perennial rivers (Drever & Smith, 1978). A greater concentration of salts was measured during the February 2019 sampling campaign compared to the previous samples which may be attributed to the initial flood conditions following the drought conditions flushing salts that may have built up in the soils and aquifer through the catchment, similar to results obtained by Skoulikidis *et al.* (2017). An indication of some precipitated salts is given in the photograph provided in Figure 29.

Figure 29: Salt precipitates left behind on the Kruis River tributary riverbed in March 2018

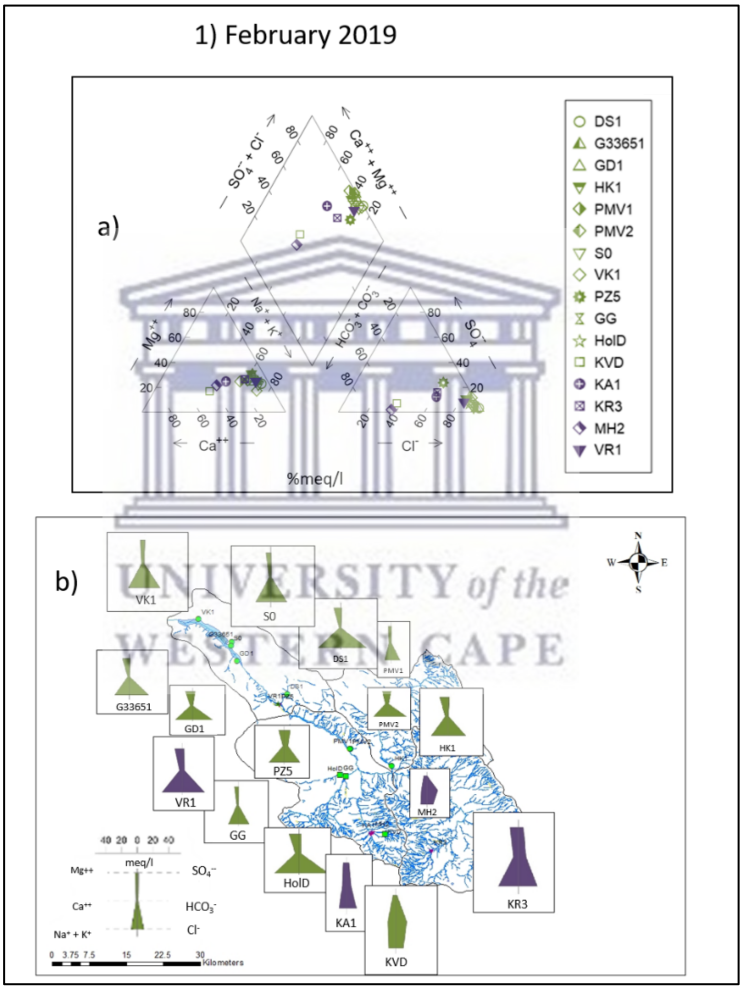


Figure 30: 1 a) Piper Diagram depicting hydrochemical facies composition of samples for February 2019. Groundwater samples are indicated in green whilst surface water samples are indicated in purple. A blue marker is used for the Verlorenvlei wetland sample. b) Map indicating the major ion composition of each site for the February 2019 sampling campaign through stiff diagram representation. Here the green samples indicate groundwater sample origin, purple indicates surface water samples and blue indicates the wetland estuarine sample

A correlation matrix of the groundwater and surface water samples is presented in Table 7 and Table 8. Constituents that indicate a correlation value of one or approach one is considered to be directly correlated such that an increase or decrease in one constituent leads to a comparative increase or decrease in the compared constituent.

Table 7 presents the correlation of physicochemical parameters for surface water samples and shows that strong positive correlations exist between several constituents including Ca-Cl, Ca-Mg, Ca-Na, Ca- SO_4^{2-}, Mg-Cl, Na-Cl, Mg-Na and Na- SO_4^{2-}. The correlation between these values is calculated as above 0.7 which means that we can expect the concentration of these major ions to match their partner constituent.

Table 7: Table indicating the correlation matrix of surface water physiochemistry and hydrochemical constituents. Positive correlations are indicated in bold.

	Ca (mg/l)	*Cl^- (mg/l)*	*K (mg/l)*	*Mg (mg/l)*	*Na (mg/l)*	*SO4 (mg/l)*	*HCO^{3-} (mg/l)*	*pH*	*EC (µS)*	*temperature (°C)*
Ca (mg/l)	1									
Cl^- (mg/l)	**0.83741733**	1								
K (mg/l)	0.013814292	0.081801255	1							
Mg (mg/l)	**0.874776435**	**0.992797099**	0.085557	1						
Na (mg/l)	**0.896613454**	**0.970814036**	0.050615	**0.976721854**	1					
SO4 (mg/l)	**0.818739276**	0.654951185	0.043511	0.69611723	**0.764141056**	1				
HCO^{3-} (mg/l)	0.548894159	0.592920366	-0.00902	0.593733683	0.53401488	0.10955442	1			
pH	-0.226679827	0.040288539	-0.2474	-0.011889722	0.036239087	-0.145253865	-0.053023267	1		
EC (µS)	0.550652312	0.656155091	0.150394	0.620026502	0.635526476	0.282996266	0.454259821	0.028580536	1	
temperature (°C)	-0.407808666	-0.313869964	0.164335	-0.330567415	-0.344471662	-0.343524962	-0.023675481	-0.056695972	-0.425782527	1

Table 8 presents the correlation of physicochemical parameters for groundwater samples. The correlation values show that several constituents display a strong positive correlation, namely: Ca-Cl, Ca-Mg, Ca-Na, Ca – SO_4^{2-}, Na-Cl, Cl- SO_4^{2-}, Mg-Na, Mg- SO_4^{2-} and Na- SO_4^{2-}. There is also evidence that EC is positively correlated with several major ions of the groundwater samples, namely: Ca, Cl^-, Mg, Na and SO_4^{2-}.

Table 8: Table indicating the correlation matrix of groundwater physiochemistry and hydrochemical constituents. Positive correlations are indicated in bold.

	Ca (mg/l)	*Cl^- (mg/l)*	*K (mg/l)*	*Mg (mg/l)*	*Na (mg/l)*	*SO4 (mg/l)*	*HCO^{3-} (mg/l)*	*pH*	*EC (µS)*	*temperature (°C)*
Ca (mg/l)	1									
Cl^- (mg/l)	**0.904395216**	1								
K (mg/l)	0.418984649	0.335140544	1							
Mg (mg/l)	**0.812313553**	**0.95121211**	0.283062288	1						
Na (mg/l)	**0.878506071**	**0.986940539**	0.333192809	**0.923196674**	1					
SO4 (mg/l)	**0.901587319**	**0.914982293**	0.553097408	**0.813792128**	**0.91795432**	1				
HCO^{3-} (mg/l)	0.369062713	0.335252958	-0.074033414	0.205231028	0.423014959	0.410465175	1			
pH	0.122365211	0.145787578	-0.362678789	0.195961963	0.1418744	0.077769029	0.246305019	1		
EC (µS)	**0.781982714**	**0.917996871**	0.333148391	**0.853480607**	**0.956578919**	**0.868435838**	0.442216861	0.1430279	1	
temperature (°C)	-0.095512387	-0.125227592	-0.264622866	-0.07729276	-0.139800821	-0.120718254	-0.018979571	0.211070101	-0.205050496	1

5.3.2.3 Stable isotope Results

Various water sources were analysed for stable isotope (^{18}O and Deuterium) signatures. A total of 58 stable isotope samples were taken and used in this study. Table 9 presents the results from the stable isotope analysis for the samples collected for this study across 3 field campaigns between 2018 and 2019 for this study Isotopically enriched sea samples were taken for July 2018 and

February 2019 for reference. A LMWL was established to represent the Western Cape of South Africa from precipitation data available for the nearby Cape Town area. The LMWL is described by the equation $\delta D = 4.0153\delta^{18}O - 0.7058$. The isotopic composition of local, low altitude rainfall ranged from -15.9 to -3.2 δ^2H, -3.59 to -2.62 δ^{18}O in isotopic character. Local rainfall isotope samples taken between July 2018 and February 2019 plot above the LMWL and indicate that rainfall in this area varies regionally from rainfall further towards Cape Town.

Sampled pools within the Verlorenvlei river and its tributaries were found to have a more isotopically enriched character (-5.5 to 43.2 δ^2H, -3.56 to 9.4 δ^{18}O). Boreholes were found to comparatively present a more isotopically deficient character (-19.7 to -11 δ^2H, -4.45 to -2.35 δ^{18}O). Spring sites and groundwater fed dams were found to have an isotopic character which plotted between the river and groundwater sources indicative of the mixing occurring at these sites (-18.8 to -7.2 δ^2H, -2.78 to -1.6 δ^{18}O).

Table 9: Stable isotopic data from field campaigns along the Verlorenvlei

Sample	Field Campaign	δ^2H (‰)	δ^{18}O (‰)
DS1	Mar-18	-12.3	-3.09
	Jul-18	-14.2	-2.35
	Feb-19	-11.7	-2.85
DS2	Mar-18	-13.8	-3.21
	Feb-19	-13.7	-3.64
G33651	Mar-18	-16.9	-4.42
	Jul-18	-16.1	-3.46
	Feb-19	-15.2	-3.77
GD1	Mar-18	-15.3	-3.44
	Jul-18	-15.1	-2.42
	Feb-19	-15.9	-3.44
GG	Mar-18	-15.5	-3.45
	Jul-18	-12.7	-2.56
	Feb-19	-11.5	-2.77
HK1	Mar-18	-18.8	-4.19
	Feb-19	-19.7	-4.4
HolD	Mar-18	-14.2	-3.07
	Jul-18	-8.6	-1.6
	Feb-19	-8.3	-2
HoR	Jul-18	-6.7	-1.92
KA1	Jul-18	-9.7	-2.56
	Feb-19	-8.5	-1.12
KA2	Jul-18	-10.1	-2.64
KmR	Jul-18	-8	-2.5
KR1	Jul-18	-10.3	-2.59

KR3	Jul-18	-12	-2.55
	Feb-19	14.9	2.77
	Mar-18	-12.4	-3.56
KVD	Jul-18	-7.2	-2.47
	Feb-19	-11.8	-2.78
MH1	Jul-18	-8.7	-2.18
MH2	Jul-18	-5.7	-1.89
	Feb-19	-6.4	-1.95
	Feb-19	-19.2	-4.19
PMV1	Mar-18	-17.1	-3.93
	Jul-18	-18.2	-4.14
	Mar-18	-19.3	-3.91
PMV2	Jul-18	-18.8	-4.45
	Feb-19	-17.9	-3.35
	Jul-18	-3.2	-2.62
Rain	Feb-19	-15.9	-3.56
	Feb-19	-10.4	-3.59
S0	Feb-19	-12.3	-2.92
S1	Mar-18	-13	-3.1
	Jul-18	-12.6	-2.9
Sea	Jul-18	1.7	0.38
	Feb-19	2.1	0.77
	Mar-18	-13	-3
VK1	Jul-18	-12.9	-3.02
	Feb-19	-11	-3.41
	Mar-18	-15.1	-3.13
VK2	Jul-18	-14.8	-2.55
	Feb-19	-14.1	-3.36
	Mar-18	-12.2	-3.53
VR1	Jul-18	-7.4	-2.2
	Feb-19	-12.2	-3.5
VRT1	Jul-18	-5.5	-1.75
VV3	Feb-19	43.2	9.4

The results of the March 2018 isotope analysis are presented in Figure 31. The March 2018 sampling campaign had groundwater samples closely related to the spring and river sites. Spring sites were isotopically depleted and plotted closely to site VR1, a river site towards Redelinghuys. Boreholes along the NE edge of the Verlorenvlei catchment (G33651, PMV1, PMV2 and HK) plotted at the extreme end of isotope depletion. The results of March 2018 have a positive average d-excess value of 12.8 for the borehole and spring sites indicating the low importance of evaporation at these sites. The origin of the water at these sites is likely to be more isotopically depleted rainfall possibly from further inland or recharged at higher altitudes than those in the studied local catchment. River site VR1 may be contributed to through groundwater discharge due to its similarity in isotopic signature to the borehole samples as well as the spring and groundwater fed dams.

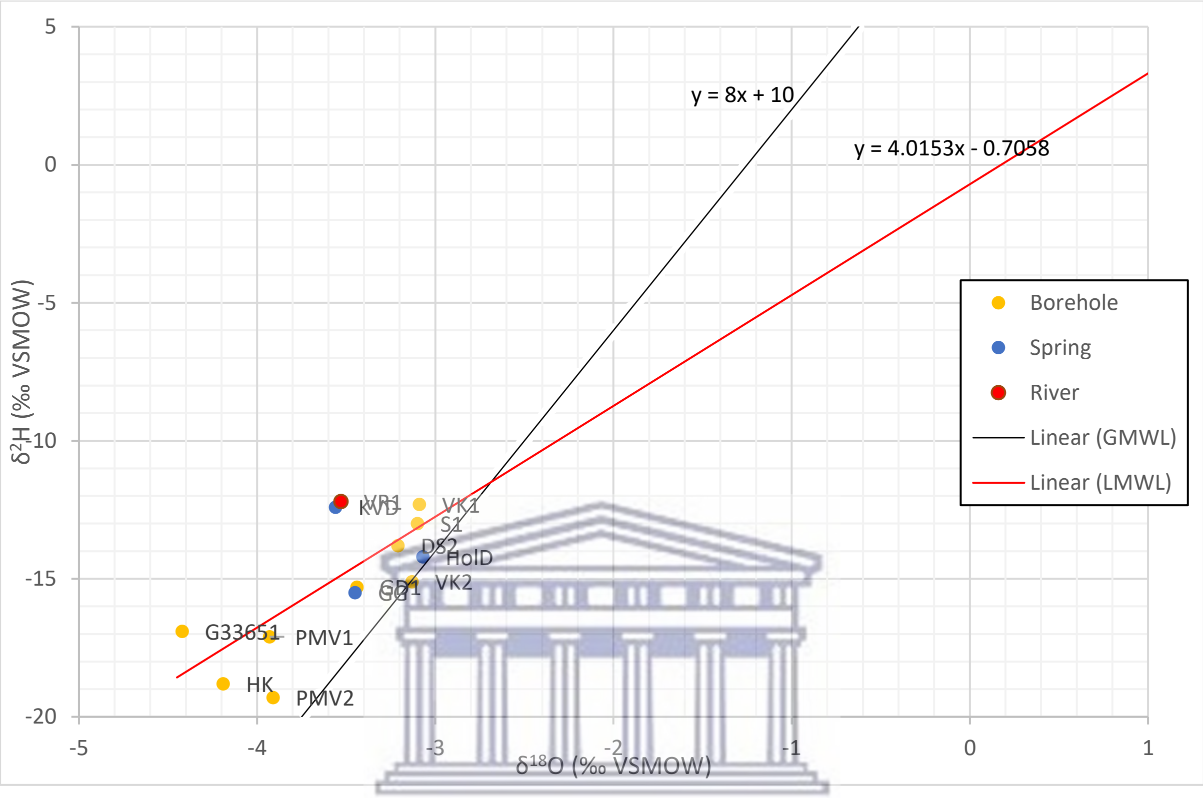


Figure 31:Relationship between Oxygen-18 and Deuterium from groundwater, springs and rivers in the Verlorenvlei river system in relation to the Local Meteoric water line (LMWL) and Global Meteoric water line (GMWL). (March 2018)

Table 10: Statistical summary of isotopic composition of water sources (March 2018)

	Borehole (n = 10)			Spring (n = 3)		
	δ²H‰	δ¹⁸O‰	d-excess	δ²H‰	δ¹⁸O‰	d-excess
Min	-19.3	-4.42	9.94	-15.5	-3.56	10.36
Max	-12.3	-3	18.46	-12.4	-3.07	16.08
Mean	-15.46	-3.54	12.88	-14.03	-3.36	12.85

During the July 2018 sampling campaign, there was more wetness present in the catchment and therefore a wider variety of samples were able to be obtained for isotopic analysis. The results of the July 2018 isotope analysis are presented in Figure 32. River samples collected during July 2018 are more enriched and plot closely to the KVD and HolD spring samples. Local rain samples and rivers in the catchment seem to show similar isotopic abundance. Spring sample GG plots closer to the groundwater samples however, groundwater sites: G33651, PMV1 and PMV2 again represent isotopic depletion and seem to have no relationship to local springs and the local, low altitude, rainfall. VR1 is clustered with the other river sites in this sampling campaign.

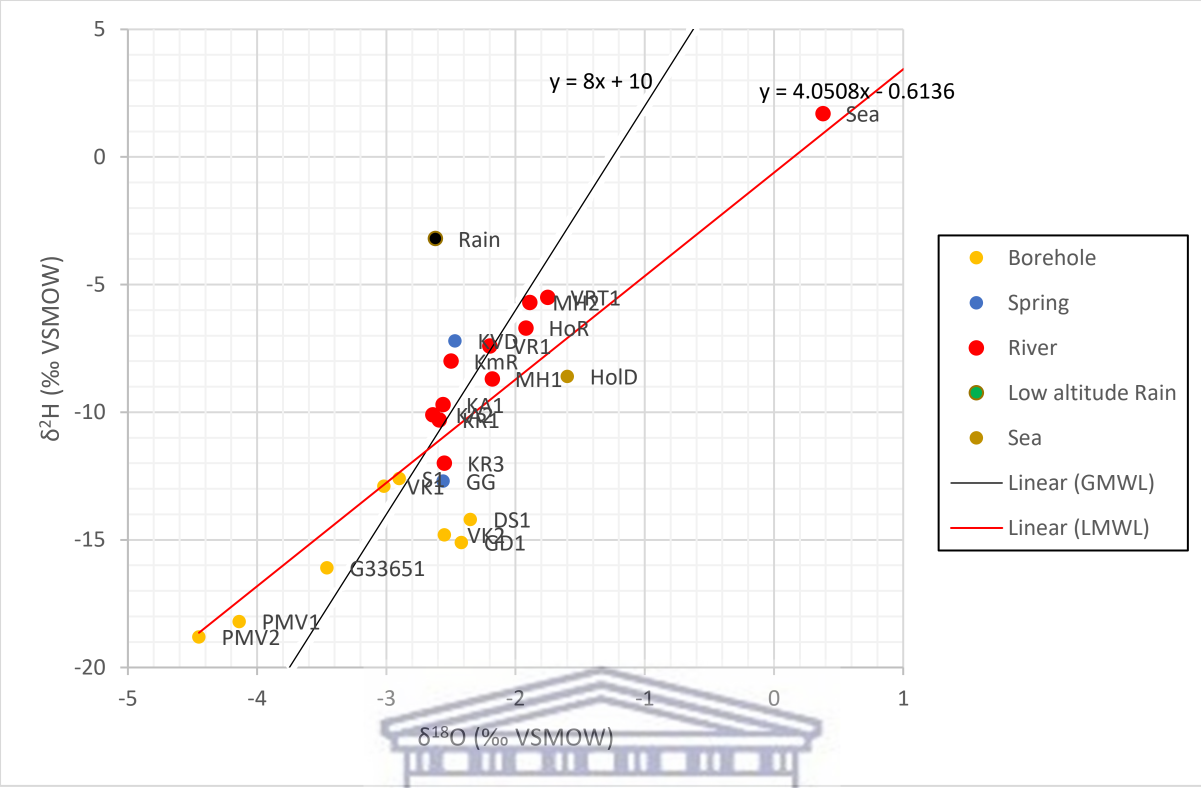


Figure 32:Relationship between Oxygen-18 and Deuterium from groundwater, springs, rivers, local rain and sea in the Verlorenvlei river system in relation to the Local Meteoric water line (LMWL) and Global Meteoric water line (GMWL) (July 2018)

By comparing the d-excess value of the types of water sources within the July 2018, we are able to determine that evaporation processes are prominent in the isotopic abundance of these sites. The river samples indicated a minimum d-excess value of -2.38 while the average d-excess value of the river sites was 8.71 which is similar to that of the borehole and spring sites. This would suggest that some river sites are more susceptible to enhanced evaporative water loss than others. Local rainfall may influence the isotopic make-up of the groundwater and spring fed dams through local recharge and direct rainfall. However, site GG may plot closer to the borehole sites with more depleted isotopic abundance due to a constant input of isotopically depleted groundwater.

Table 11: Statistical summary of isotopic composition of water sources (July 2018)

	Borehole (n = 8)			Spring (n = 3)			River (n = 12)		
	δ^2H‰	$\delta^{18}O$‰	d-excess	δ^2H‰	$\delta^{18}O$‰	d-excess	δ^2H‰	$\delta^{18}O$‰	d-excess
Min	-18.8	-4.45	4.26	-12.7	-2.56	4.2	-12	-2.64	-2.38
Max	-12.6	-2.35	16.8	-7.2	-1.6	12.56	-5.5	-1.14	12
Mean	-15.34	-3.16	9.95	-9.50	-2.21	8.18	-8.69	-2.17	8.71

Figure 33 provides a plot of the results from the stable isotopes analysis from samples obtained in the dry season of 2019. The samples were obtained from boreholes, the sea, low altitude local rainfall, springs and river sites within the study area. Groundwater samples obtained have more negative ^2H and ^{18}O values, indicating the samples have been depleted of heavy isotopes. Samples HolD, KA1, KR3, and MH2 are more enriched than both those samples obtained in this sampling campaign as well as those previously obtained during March 2018 and July 2018. These sites may be more enriched due to pooling of water in the riverbed and open water spring fed dams which accumulate heavy isotopes through the evaporation effect (Gat, et al., 2000). The signature of wetland sample VV3 is more enriched than the sea water sample that was taken for reference with isotopic values of +9.4‰ $\delta^{18}O$ and +43.2‰ δ^2H and a d-excess value of -32 indicating the prominence of the evaporation process (Gat, et al., 2000). The VV3 site is a pool situated at the mouth of the Verlorenvlei estuary. This pool was measured to be the most saline point of the system with EC values that were out of bounds of the upper limits of the instrument used in these insitu measurements, i.e., greater than 200 mS/m.

VR1 plots close to the borehole sites similarly to the isotopic signature exhibited during the March 2018 campaign. The isotopic signature of GG plots closely to the borehole sites with some enrichment occurring placing it further up the LMWL. This is expected due to its source of water being groundwater, depleted of isotopes while being exposed to the atmosphere in the standing pool, thereby becoming enriched due to on-going evaporation through the evaporation effect (Gat, et al., 2000). Sites such as MH2, HolD, KA1 in February 2019 and the river sites in July 2018 show more enriched isotopic signatures.

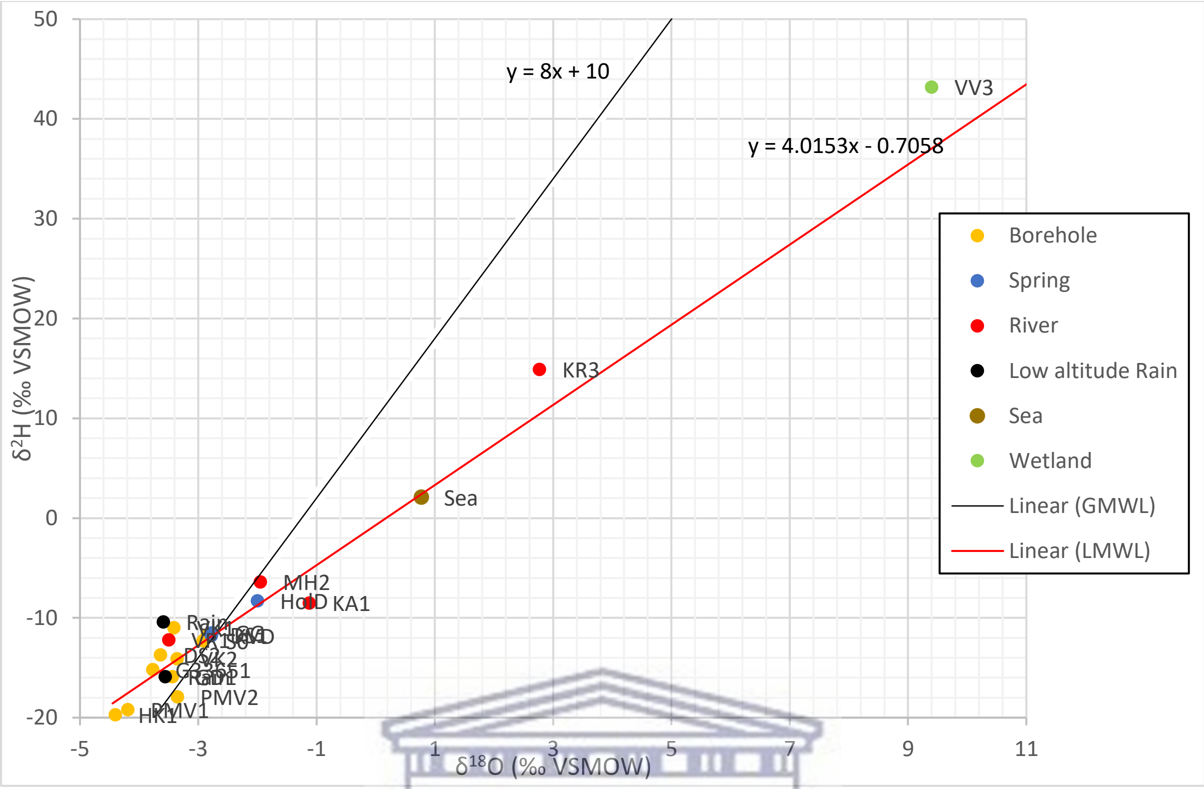


Figure 33: Relationship between Oxygen-18 and Deuterium from groundwater, springs, rivers, local rain and sea in the Verlorenvlei river system in relation to the Local Meteoric water line (LMWL) and Global Meteoric water line (GMWL). (February 2019)

Table 12: Statistical summary of isotopic composition of water sources (February 2019)

	Borehole (n = 10)			Spring (n = 3)			River (n = 4)		
	δ^2H‰	$\delta^{18}O$‰	d-excess	δ^2H‰	$\delta^{18}O$‰	d-excess	δ^2H‰	$\delta^{18}O$‰	d-excess
Min	-19.7	-4.4	8.9	-11.8	-2.78	7.7	-12.2	-3.5	-7.26
Max	-11	-2.85	16.28	-8.3	-2	10.66	14.9	2.77	15.8
Mean	-15.07	-3.53	13.19	-10.53	-2.52	9.60	-3.05	-0.95	4.55

5.4 Driving Components of Groundwater

To achieve objective three of this current study, the conceptual water balance of the Verlorenvlei and the water movement through the catchment is described through literature review and survey of water presence and groundwater level monitoring. The following section presents the key results in developing a conceptual understanding of the natural functioning of the interconnected Verlorenvlei groundwater and surface water system. A water balance approach was undertaken to ensure all components within the system were recognised. A universal water balance of a given aquifer can be expressed through the equation:

$$\Delta S_{gw} = RE - {}_{gwoff}Q + {}_{gwon}Q - Q_{bf} - ET_{gw} \qquad (5)$$

This equation simply states that water retained in storage (ΔS_{gw}) is the result of all water arriving at the water table ($RE + {}_{gwon}Q$) which then either flows out of the basin as groundwater flow (${}_{gwoff}Q$), is discharged to surface (Q_{bf}) or lost via evapotranspiration (ET_{gw}). According to previous studies in the Verlorenvlei and surrounding Sandveld areas, the groundwater balance of this catchment can be expressed as:

$$\Delta S = RE_{p} + RE_{river} + GW_{in} - GW_{spring} - GW_{baseflow} - ET - GW_{use} \qquad (6)$$

According to this equation, change in groundwater storage is the result of inputs of groundwater recharge both from precipitation (*REp*) and surface flow (*REriver*) in the upper parts of the catchment (Conrad *et al.*, 2004; Watson *et al.*, 2018), regional groundwater inflow from neighbouring aquifer systems and fault driven flow (*GWin*) (Nel, 2005). Total groundwater storage (ΔS) is reduced by fault driven spring flow where groundwater daylights at the surface (*GWspring*), groundwater discharge to rivers (*GWbaseflow*), agricultural and municipal groundwater use (*GWuse*), and evapotranspiration to the atmosphere by natural and agricultural vegetation (*ET*). The relevant components of the water balance for the study area are visualised in Figure 34.

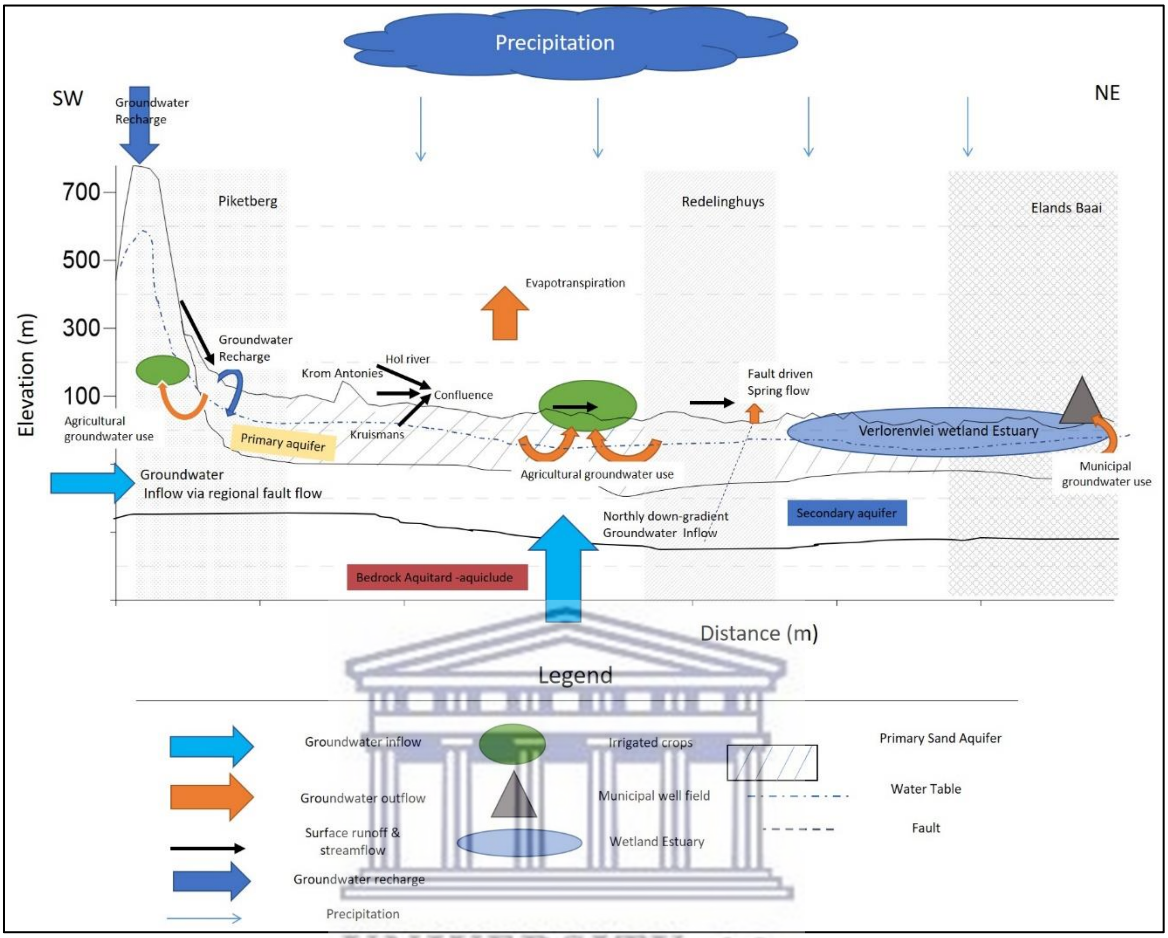


Figure 34: Conceptual model of water balance components of the Verlorenvlei catchment (Quaternary catchments: G30E, G30C, G30D and G30B)

5.4.1 Recharge and Groundwater Inflow

Potential recharge of the Sandveld primary aquifer has been estimated to be between -4 to 30% with areas of large recharge potential being found in high lying areas with lower lying, discharge areas associated with irrigated agriculture along the coast revealing a negative or net zero potential recharge similar to that of neighbouring coastal aquifers (Münch *et al*, 2013). Although there is no evidence of runoff occurring over the sand of the Sandveld area (Nel., 2005), the primary sand aquifer of the Sandveld receives a limited amount of direct recharge due to low rainfall and high soil temperatures as well as low soil moisture (Conrad *et al.*, 2004). Much of the groundwater in the primary aquifer has been suggested to be derived from water originating from underlying faults (Conrad, *et al.*, 2004, Nel., 2005). The major sources of water to the Sandveld aquifers were conceptualised by Münch *et al.* (2013) to be derived from major faults and recharge through the upper reaches of the Sandveld catchments.

Recharge is confined to the upper reaches of the catchment along high lying areas associated with sub-formations of the Table Mountain Aquifer group namely, the Pennisula, Pakhuis, Piekenierskloof and Graafwater Formation. The surface of the TMG is conducive to infiltration as it is made up of joints, faults and blocky rock with minimal soil cover which create preferential pathways that readily receive water during rainfall (Rosewarne, 2002). The TMG forms the majority of the bulk regional hydrogeology within the Cape which is a result of large-scale geological deformation responsible for the mountainous Cape Fold Belt and major faults which characterise the Cape. The groundwater character of the greater Cape Town area is influenced by this geology. Mountainous altitudes facilitate significant recharge which is then transported to coastal discharge points via regional systems of groundwater flow (Rosewarne, 2002). The Gydo-Verlorevlei Megafault (Hartnady and Hay, 2002), the Wellington-Redelinghuys major fault and several minor faults enter the Verlorenvlei catchment at Piketberg in a north westerly direction towards the coast.

5.4.2 Springs and Baseflow

De Beer (2003) reports the importance of faults to the Verlorenvlei river are two-fold: they bring a vital groundwater contribution to the main river flow, and are believed to have shaped the Verlorenvlei river course. Later work by Watson et al (2019) estimated that 19% of the total Verlorenvlei reserve flow was attributed to other sources with about 12% being contributed to by secondary aquifer flow and 28% contributed to by primary aquifer flow. The Verlorenvlei river system is evidently not perennially supported by groundwater via baseflow, but receives groundwater through external freshwater supply to the Verlorenvlei through connection to fractured aquifers (Watson et al., 2020). A closer look at the hydrological character of each tributary of the Verlorenvlei river explains their varying contribution to the flow regime of the main river stem. The Kruis River flows during the wet season with extended no flow periods between high rainfall periods (refer to Figure 6). The southwest Hol River tributary flows year-round and provides a steady baseflow to the Verlorenvlei system which is believed to be of groundwater origin (Watson et al., 2019). The eastern Krom Antonies tributary is situated within the Moutonshoek basin characterised by steep slopes of TMG sandstones and a basin of Quaternary sediments which drains the Piketberg Mountains. Runoff from topographical rainfall is generated through quickflow and local runoff accumulating into drainage lines to form the Krom Antonies. Conductive TMG sandstones and Quaternary sediments in the Krom Antonies and Bergvallei limit the flow attenuation of these tributaries to a quick baseflow response which does not reach the main river stem (Watson et al., 2019).

Previous groundwater studies estimate the lower section of the Verlorenvlei basin to receive an inflow contribution of 12 000 m^3d^{-1} from neighbouring groundwater bodies (DWAF, 2003). Further work by Nel (2005) estimated that approx. 6.5Mm^3/a of external inflow from regional groundwater contributes to the groundwater budget of the lower Verlorenvlei at G30E via fault flow. In the lower reaches of the Verlorenvlei catchment springs occur which support rivers and wetlands. Within the Sandveld, spring water occurs as groundwater daylights at the surface as it seeps from primary aquifers which are fed fault driven groundwater from underneath (Nel. 2005). Several types of springs are associated with the TMG aquifer. Over the regional scale, fault-controlled springs bring characteristically high temperature water over large distances to discharge at the surface. Water within these springs generally have long residence times and are of very high groundwater quality with low EC character (Meyer, 2002). Springs also occur at regional scales due to water encountering the contact of interbedded layers of differing permeability within the lithology of the formation. Local springs may occur due to shallow circulating water in the upper layers of the TMG Formation as well as water encountering shallower contacts with interbedded shale layers within the unconformity of the TMG Formation.

5.4.3 Water Presence Survey Results

For the duration of this study limited baseflow was observed in the Verlorenvlei tributaries. A survey of water presence was done for the sites visited during in-field sampling trips to investigate which areas within the catchment remained wet or developed dry conditions during the dry season of the study duration. The results of the water presence survey are presented in Table 13.

Along the Verlorenvlei river, site VV3 and site VR1 remained wet while the adjoining northern tributary was found to be dry at site VRT1. Site VR1 and VV3 along with the spring sites: GG and HolD along the Hol River, remained wet. Sites that remained wet during the drought are suggested to have direct contribution from groundwater sources or subsurface flow. During dry periods, water was unexpectedly found to be present within a few smaller tributaries to the Krom Antonies River at sites MH1 and MH2. Local runoff from high altitude rainfall in Moutonshoek could be responsible for the water presence at these tributaries as they are the only tributaries that remained wet. Certain sites along the Krom Antonies tributaries had water present at the site sampled while water was absent further downstream as seen in Figure 35 (B). In this case, water may evaporate or infiltrate before reaching the main river stem due to low total high altitude rainfall during the dry season. Only after receiving adequate rainfall does pool connectivity and river flow occur as seen in Figure 35 (C).

Figure 35: Site conditions of the Krom Antonies river at site KA1 during March 2018 (A). July 2018 (B) and February 2019 (C).

Table 13: Indication of water presence at sites during infield sampling trips from July 2017 to February 2019.

Site	Jul-17	Oct-17	Mar-18	Jul-18	Feb-19
GG	WET	WET	WET	WET	WET
HolD	WET	WET	WET	WET	WET
Spr	WET	WET	DRY	WET	DRY
HoR		WET	DRY	WET	WET
HR			DRY	WET	DRY
KA1	WET	WET	DRY	WET	WET
KA2		WET	DRY	WET	DRY
KmR	WET	WET	DRY	WET	DRY
KR1	WET	WET	DRY	WET	DRY
KR2	WET	DRY	DRY	DRY	DRY
KR3	WET	WET	DRY	WET	WET
KR4	WET	WET	DRY		DRY
MH1	WET	WET	WET	WET	DRY
MH2	WET	DRY	WET	WET	WET
VR1	WET	WET	WET	WET	WET
VRT1	WET	WET	DRY	WET	DRY
VV1	WET	DRY	DRY		DRY
VV2	WET	DRY	DRY		DRY
VV3	WET	WET	WET	WET	WET

5.4.4 Groundwater Level Survey Results

A hydrogeological survey of groundwater water levels was conducted over 5 field campaigns between July 2017 to February 2019. Table 14 presents the groundwater level data collected during this survey in metres below ground level (m.b.g.l.).

Water levels of boreholes near to the Verlorenvlei river at lower elevations, (B, S0, S1, S2, S4, S5, S6), have shallower water levels compared to boreholes at higher elevations further from the wetland. Boreholes at higher elevations (G33651, VK1, VK2) tend to have deeper measured water levels. Water levels measured at borehole HK2 are shallower than expected for a high elevation borehole given the observed trend in this data. This borehole is situated near the confluence of the Bergvallei and Kruis Mans River tributaries so although its elevation is high, it follows the trend of shallower water levels near to the river.

Production borehole, S3, is an exception to this trend with deep measured water levels due to active pumping. Abstraction during sampling surveys dropped the water level at some measured boreholes. Water levels measured for GD1 and GD2 display variable changes due to abstraction most notably during the drought period. These boreholes were actively used for pivot irrigation during the study. Measured water levels in GD1 decreases as far as ±50 m.b.g.l. during October 2017. Water levels then seem to recover following the wet period with GD1 measured to have a water level of 2.96 m.b.g.l. during the July 2018 wet period. Further indication of the influence of abstraction patterns on groundwater levels is unable to be investigated in this study without time series water level and abstraction data.

Within the valley of the Redelinghuys tributary, variable water levels were measured at borehole DS2 across the sampling campaigns. The water levels measured at this site show a rising water level trend. During the initial measurement of water level at this site during the October 2017 survey the water levels were measured at 15 m.b.g.l. and experienced a rapid rise in water level to 2.2 m.b.g.l. in March 2018. Lastly, during the February 2019 survey, water levels had risen above ground level to the surface of the borehole collar indicating artesian conditions.

Table 14: Water level data from hydrogeological survey across the Verlorenvlei

Site	Latitude	Longitude	Elevation (m)	Collar (m)	Field Campaign	Groundwater level (m.b.g.l.)
B	18.3778	-32.3116	13	0.41	Jul-17	3.8
					Oct-17	3.89
					Mar-18	4.09
					Jul-18	3.94
					Feb-19	4.19
DS2	18.5579	-32.4539	45	0.29	Oct-17	14.71
					Mar-18	1.91
					Jul-18	0.67
					Feb-19	0
G33651	18.4562	-32.3561	16	0.45	Oct-17	14.28
					Mar-18	14.63
					Jul-18	14.52
					Feb-19	15
GD1	18.4652	-32.3923	-4	0.15	Jul-17	2.285
					Oct-17	49.845
					Mar-18	3.745
					Jul-18	2.805
					Feb-19	19.205
GD2	18.4651	-32.3920	8		Jul-17	2.78
					Oct-17	14.94
HK2	18.7477	-32.5887	65		Jul-17	7.59
					Mar-18	8.2
S0	18.4544	-32.3635	0	0.6	Oct-17	3
					Mar-18	7.19
					Feb-19	7.34
S1	18.4551	-32.3647	1	0.61	Feb-19	5.73
S3	18.4638	-32.3773	1	0.35	Jul-17	13.45
					Oct-17	11.83
					Mar-18	8.6
					Jul-18	11.85
					Feb-19	10.35
S4	18.4634	-32.3775	-4	0.55	Jul-17	4.57
					Oct-17	5.84
					Mar-18	5.37
					Jul-18	5.59
					Feb-19	6.01
S5	18.4634	-32.3776	-3	0.346	Jul-17	4.534
					Oct-17	5.944
					Mar-18	5.754
					Jul-18	5.554
					Feb-19	6.124
S6	18.4627	-32.3758	6	0.32	Jul-17	11.68
VK1	18.3956	-32.3140	14	0.32	Jul-17	14.24
					Oct-17	14.08

					Jul-18	14.68
					Feb-19	14.98
					Jul-17	19.29
					Oct-17	23.76
VK2	18.3814	-32.3089	21	0	Mar-18	22.9
					Jul-18	22.18
					Feb-19	23.03

A proxy for the hydraulic gradient may be established through investigating the relation between elevation and groundwater level. Groundwater may flow from higher elevation to lower elevation areas due to the potential difference according to gravity. A comparison between the elevation and measured water levels relative to mean sea level indicated a positive correlation (Figure 36, $r^2 = 0.7766$). This suggests that the groundwater level distribution follows the topography of the Verlorenvlei catchment and groundwater may drain towards areas of lower topography. We can also see this in how the water levels measured are shallower near rivers and deeper at higher elevations. Topographically higher areas will in this case form groundwater flow divides for the shallow aquifer where the groundwater flow then is directed towards the river down the topographic gradient.

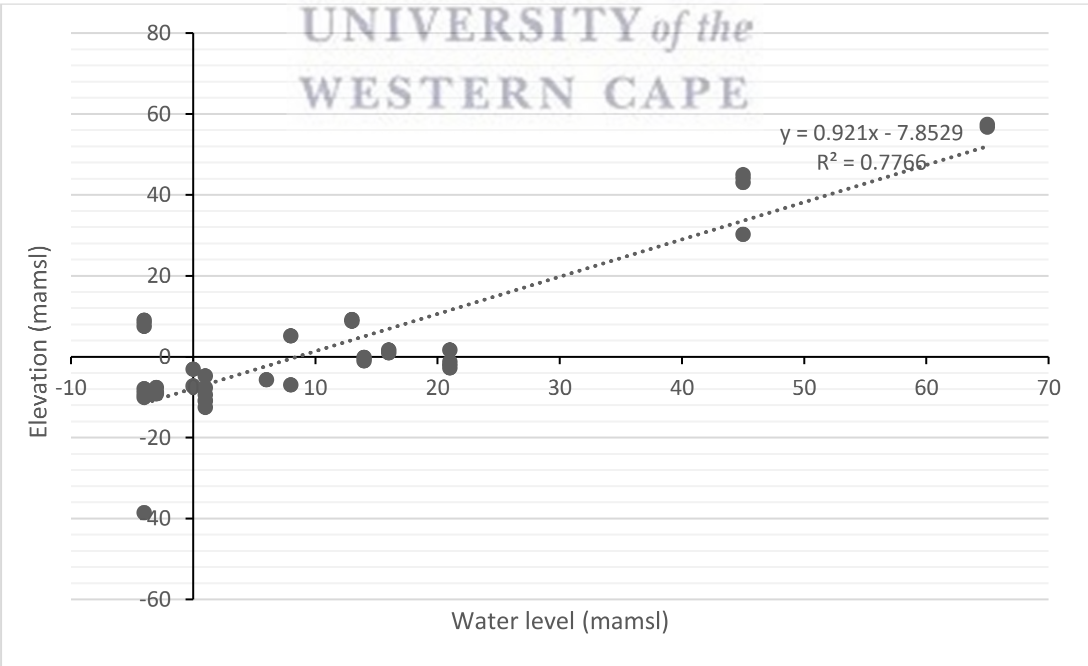


Figure 36: Relationship between elevation and groundwater level above mean sea level at sampled boreholes (n =51, $r^2 = 0.7766$). Positive correlation observed

5.4.5 Evapotranspiration

The root water uptake and loss of water to the atmosphere is a considerable portion of the water balance of a semi-arid area such as the Verlorenvlei, Sandveld area. Evaporation along the West Coast has been estimated to be in excess of annual rainfall for the area with estimated evaporation rates of between 2482 and 1800 mm/a (DWAF, 2003). Evaporation from water bodies within the area has also been estimated to be relatively high in comparison to the water input into the area via rainfall. During the in-field sampling campaign of this study, salt precipitates were observed to accumulate on dry river beds during the hot dry periods of the study as seen in Figure 29.

5.4.6 Groundwater Use

Minimal surface water, if any, is used for domestic or agricultural purposes in this area. As mentioned previously in Chapter 1, the groundwater use in the Verlorenvlei area is predominantly set aside for agricultural uses at 20% of recharge with 1% of total annual recharge being set aside for domestic, municipal use (Archer, et al., 2009). The area is dependent on groundwater for its water supply due to its dry conditions and limited supply of surface water. At full capacity, the Verlorenvlei wetland is utilised for recreational use and is renowned for its thriving ecological benefit for bird life and aquatic animals such as certain fish species and other animals.

5.5 Chapter Summary

The aim of this chapter has been to present the key results obtained for the multimethod approach adopted to investigate the processes and mechanisms of groundwater – surface water interaction in the Verlorenvlei. The intention was to achieve an understanding of the multi-scale interaction potential and processes of the Verlorenvlei by conducting a combined method of several physical and chemical in-field surveys in addition to a desktop review of records to derive the driving processes of groundwater in the study area, and thus achieve the study objectives.

By applying these methods, their applicability to the study of interaction in the context of non-perennial rivers may be determined to achieve objective one. In-field surveys of geophysical properties (geophysics, water presence and groundwater levels) provide evidence for the interaction potential and mechanisms that may take place at the various scales (local and regional) in the study area to address the second objective of this study. Thirdly, the presentation of information from desktop records review creates a conceptual understanding of the natural functioning of the Verlorenvlei which establishes the driving components of the groundwater balance to achieve objective three, thereby contextualising the study results within the case study setting.

Results were described to highlight and establish key trends and patterns in the data. The geophysical resistivity image surveys provided information about the subsurface properties along a reach of the Verlorenvlei case study area. Environmental tracer surveys of hydrochemical and physico chemical constituents provided insight into the flow of water within the catchment as well as the spatio-temporal variability of the chemical character within the system. Stable isotopes provided information on the water source origin and mixing and a water presence survey provided insight into areas more likely to remain wet during the dry season within the study area. An understanding of the natural functioning of the environment and the contribution of groundwater to the Verlorenvlei river system was developed as informed by a field survey of the hydrogeological flow within the catchment and desktop investigation of available information from literature and previous studies.

The following chapter discusses the results obtained from the local case study to build on the conceptual understanding of groundwater's role in non-perennial rivers.

6.1 Chapter Introduction

The previous chapter presented the results for the multi-method analysis of interaction for the case study. These results are discussed in this chapter and is presented in terms of what the results reveal about the nature of multiscale interaction within the Verlorenvlei case study. Environmental tracers reveal the potential for interaction. Insight into the interaction mechanisms is gained through geophysical survey results. Results from the water presence survey and hydrogeological monitoring is discussed in conjunction with the natural functioning of the Verlorenvlei in order to develop a conceptual model of the interaction at multiple scales. These interaction models are then presented and described. To tie the results in to the main focus of this study, the results obtained in the Verlorenvlei case study and the developed interaction model are then used to facilitate an understanding of the role of groundwater in non-perennial rivers and the implications thereof for the management of water resources in non-perennial river environments.

6.2 Interaction potential

6.2.1 Water origin

Stable isotope composition of water presents the signature of water movement within the environmental landscape. Evaporative and rain formation processes alter the enrichment and depletion of isotopic species within water. Greater enrichment of heavy isotopes occurs in evaporative systems such as lakes, rivers, plants and soil as a result of greater fractionation of isotopic species relative to rain water as characteristic of the evaporation effect. Meteoric water in comparison is often deficient of heavy isotopic species (Gat, et al., 2000).

For the duration of the seasonal stable isotope survey conducted along the Verlorenvlei stream network, the river and its tributaries had ceased flow and was characterised by disconnected pools susceptible to evaporation. Some evidence of runoff was present during the wet season however streamflow was observed to be minimal. From samples of groundwater and surface water, a general trend was observed: groundwater (borehole) samples were depleted of isotopes, surface water samples were isotopically enriched, and spring-fed damns had a mixed isotopic character.

6.2.1.1 Surface water trends

Seasonal water presence survey within the Verlorenvlei revealed several persisting pools across the Verlorenvlei drainage network. During the dry season persisting wet conditions were observed for several isolated pools along the Krom Antonies river and its tributaries (MH2 and KA1), a pool within the Verlorenvlei main river stem (VR1), and a pool at the mouth of the Verlorenvlei wetland (VV3). Severe drought conditions during the March 2018 survey caused most pools within the stream network to have dried, site VR1 was only the exception. A site along the Kruis river (KR3), while dry during the drought conditions, remained wet during the February 2019 dry season. Seasonal isotope analysis of pools may elucidate the pool water origin during periods of minimal rainfall.

In-stream pools within the upper Krom Antonies tributary present during the February 2019 dry season (MH2 and KA1) had an enriched isotopic character. KA1 was observed to have an isotopic ratio of -8.5 δ^2H, -1.12 δ^{18}O and MH2 was characterised by an isotopic character of -6.4 δ^2H, -1.95 δ^{18}O. Enrichment of the isotopic character may be attributed to the evaporation effect (Gat, et al., 2000). The slight deviation of these upstream sites from the isotopic composition of the local low altitude rainfall sampled during this time may be an indication that the precipitation responsible for water at this site may have undergone slightly different processes before reaching the sampled site.

Downstream in the Verlorenvlei river itself, water was consistently available at site VR1, an in-stream pool along the Verlorenvlei river near Redelinghuys. During dry season sampling instances VR1 had a depleted isotopic signature of approximately -12.2 δ^2H, -3 δ^{18}O. As a result, the isotopic signature of VR1 is closer to the local shallow groundwater. The VR1 site is a standing body of water within the Verlorenvlei riverbed so we would expect it to respond in the same way as the river samples taken at other pools within the tributaries and become more enriched due to the evaporation effect during the dry season when temperatures are higher. However, the isotopic signature of this site, which plots closely to borehole samples and a spring site, indicates that it is possible that the origin of this water source is related to groundwater discharge. While the pool is exposed to evaporation, the inflow and contribution of groundwater which is observed to be more depleted in heavy isotopes may result in the isotopic signature to be less enriched caused by dilution through mixing.

Further downstream within the Verlorenvlei wetland, water remained present at the VV3 wetland site even at the height of the dry season. Site VV3 was recorded to be the most saline point of the river basin (approx. 200 000 µS/cm). As this sampling point is at the end of the Verlorenvlei system, the high salt content within this pool may be due to an increasing accumulation of the salts of the catchment with no apparent opportunity for flushing due to the Verlorenvlei estuary's disconnection from the sea at the estuary mouth. The isotopic signature of this site rivalled the sea water isotopic composition with a far greater isotopic enrichment in comparison indicating that it is unlikely that seawater intrusion influenced the salinity of this site. For site VV3, the isotopic enrichment of this hyper saline pool with heavy isotopes can be expectedly explained by the evaporation effect (Gat, et al., 2000). While it is clear this water body undergoes evaporation, the results obtained provide little evidence of an external water source that may cause this pool to persist into drought conditions. One hypothesis that may explain the persistence of this pooled water may be related to its measured salinity profile. Salinity is known to reduce the evaporation potential of water at high concentrations (Harbeck, 1955). This was demonstrated by the recent study conducted by Mor et al., (2018) which compared freshwater plume evaporation and the evaporation of the dead sea, a hypersaline lake. Stated differently, it is possible that as evaporation acting on the pool increased the pool's salinity through evaporative concentration, the evaporation potential of the water was reduced through increased salinity.

The generation of local runoff by low-altitude precipitation is evident from the stable isotope results for pools along the stream network during the wet season (July 2018). With the rainfall events following an extended dry season, many more pools were able to be sampled along the Verlorenvlei stream network. Pool water isotopic composition were comparative with the isotopic signature of local low altitude rainfall.

6.2.1.2 Groundwater trends

The isotopic signature of sampled groundwater sites showed minimal variation for the duration of the study. Sampled boreholes within the Verlorenvlei basin have a predominantly depleted groundwater character. Spring-fed dams sampled for stable isotopes present an isotopic character which falls between the depleted groundwater isotopic signature and the enriched signature of the surface water sites indicating a mixed isotopic character.

Comparison of the seasonal groundwater (borehole) stable isotope results provide insight into the possible recharge processes of the shallow groundwater. When comparing the isotopic composition of borehole samples from the dry season (March 2018) to the wet season (July 2018), the following trend is observed. During the wet season boreholes PMV1 and PMV2 show very little change in their isotopic signature, boreholes VK1, S1, VK2, GD1 and DS1 show increased isotopic abundance and plot more closely to the signature of local low altitude rainfall. These boreholes are drilled into a known maximum depth of approximately 76m below ground level and are assumed to represent the shallow aquifer. The enrichment of their isotopic signature similarly to the low-altitude rainfall may be indicative of recharge processes with local rainfall following the dry period. The minimal change in the isotopic character of boreholes PMV1 and PMV2 may indicate that they are recharged by a different rainfall source with a more depleted isotopic character than the rainfall received locally along the Verlorenvlei at the coast. Typically, precipitation may become depleted of isotopes as a result of the altitude or continental effect (Gat, 1996; Gat, et al., 2000). This suggests that an inland, high altitude rainfall source may be the source of recharge for the aquifer body these boreholes intersect.

Spring and Groundwater-fed dams have an isotopic character that plots between borehole and instream pool sites along the LMWL. The open-air nature of these dams creates an opportunity for evaporation susceptibility as well as the mixing of groundwater with surface water through precipitation generated runoff.

6.2.2 Groundwater Flow behaviour

The hydrogeological survey and the investigation of physicochemical properties and hydrochemistry of water sources within the area provide information about the groundwater flow behaviour of the Verlorenvlei catchment. The results of the groundwater level survey and physicochemical and hydrochemical tracer survey identify the Verlorenvlei groundwater flow to operate at nested flow system levels which typically are controlled by the topography in the local shallow aquifer.

Groundwater typically flows from areas of recharge to discharge in groundwater flow systems (Tóth, 1999; Younger, 2007). By assessing the hydrochemical facies of the various water sources in the study catchment through hydrochemical analysis, two zones are evident. Although the predominant water type through the catchment is Na – Cl, there are samples that display a Ca – HCO^3 water type in the upper catchment, while the Na – Cl water type was more consistently found in the lower catchment. These results suggest an evolution of the chemical water character from the upper catchment associated with the Krom Antonies river to the lower lying area. The Ca

– HCO^3 dominated chemical signatures of select samples from upper catchment sites KVD and MH1 during the July 2017 and February 2019 field campaigns are typically associated with carbonate dissolution reactions, generally associated with recharge areas (Tóth, 1999).

Water dominated by Na-Cl is predominately present across the water samples taken across all the field-campaigns with most of these water types falling within the lower Verlorenvlei catchment. Na- Cl is typically evident of waters found within the groundwater discharge zones (Tóth, 1999). Water that travels through groundwater systems to discharge zones have undergone slower reactions as a result of their longer groundwater flow paths causing select dissolution of salts to accumulate into the water as it travels through rock pore spaces to the site of measurement. Groundwater with longer residence times may be responsible for the water found in the downstream, lower lying areas of the catchment due to their Na-Cl character and increase in dissolved ions.

The increase in dissolved salts across the catchment profile is evident in the distribution of salinity within the Verlorenvlei. From the physicochemical survey of water samples, an EC profile of low EC values to high EC values from the upper catchment downstream to the Verlorenvlei wetland and river mouth is presented in both groundwater and surface water sources. Few dissolved ions are present in the recharge areas upstream while an increase in dissolved salts further downstream result in increased salinity in discharge areas. EC values were found to be the lowest specifically for site MH1 during the wet season of 2018 with an EC value of 93.3 µS/cm. In groundwater samples, the lowest EC values were found in site KVD during the 2017 wet season. Both of these sites are found in the upstream Moutonshoek valley area.

The groundwater gradient within the catchment can be determined through monitoring of the groundwater levels at boreholes across the study area. The water table levels surveyed in this study were found to be positively correlated with the elevation at a pearson's correlation of $r^2 = 0.7766$ for $n = 51$, evident of a topographically controlled groundwater table or basinal flow. Groundwater in the Verlorenvlei basin is distributed such that higher elevation areas provide recharge and water flows outward away from these areas to lower elevation, discharge areas.

6.3 Interaction Mechanisms

Geophysical surveys create visual representations of the below ground geological features that may contain or compel groundwater flow in a given area (Brodie, et al., 2007). By mapping geological features in this way, an understanding of the subsurface character is developed which provide key information about hydrogeological features that may indicate or influence river-aquifer exchange. In this current study, the geophysical surveys provide a near complete subsurface profile from the origin of the Redelinghuys tributary into the Verlorenvlei river.

Previous geological investigations have described the geological character of the area north of Redelinghuys where the found spring (Figure 25) originates, and the tributary begins to be characterised by TMG sandstones covered by thick sandy material. The porosity of the TMG is governed by fractures to the hard rock formation which form a secondary aquifer. The thick sandy material is characteristic of the Quaternary sands which are known to cover the surface to an unknown depth within the Sandveld area. The reach level geophysical survey of this area provides visual indication of this subsurface geological and stratigraphic features. For Geo-electric Model 2,3,4 and 5 an observed shallow low resistivity layer which extends along the profiles may be indicative of weathered sandy material which has accumulated above the harder sandstones in the valley within which this tributary drains. Zones of low resistivity material which are indicative of highly conductive substratum between the high resistivity areas as indicated in Geo-electric Model 3 and 4 may be due to fracturing of the sandstone which has caused secondary porosity resulting in a greater potential for groundwater occurrence.

The low EC and pH and year-round seepage of the upwelling groundwater at the spring site, suggests a larger fault may be responsible for the origin of the upwelling which is not uncommon in low lying, TMG discharge zones (Rosewarne, 2002; Colvin, et al., 2007; Roets, et al., 2008). From the observed results, it appears that the weathered material which overlies the TMG sandstone geology provides a more conductive subsurface pathway wherein water may flow and be stored more readily than the solid, more resistive TMG material below. Freshwater may seep into this material in this area from below via faults and fractures which characterise the TMG aquifer system, sometimes daylighting at the surface as a spring such as in the case of the upwelling north of Redelinghuys. Unable to infiltrate further into the more resistive rock, the water may flow according to the topographical gradient downstream either overland as the Redelinghuys tributary or via a subsurface flow path towards the Verlorenvlei river. This contrasts a study done by Münch *et al.* (2013) completed in the same area which hypothesised that lateral groundwater flow in the sand is minimal.

Compared to the geophysical surveys of the Redelinghuys tributary area, the Verlorenvlei floodplain displays a more evenly distributed subsurface conductivity without a distinct layer of contrasting resistivity. The geophysical surveys identify a shallow subsurface of more conductive material across the Verlorenvlei floodplain with two areas of greater resistivity evident towards the southwest of the river bed stratum (Geo-electric Model 1). Previous soil investigations of historic studies within the Sandveld area have identified lens-like clay deposits near to the mouth of the Verlorenvlei river and beginning of the Verlorenvlei wetland itself (Meadows, et al., 1993; Baxter & Davies, 1994; Meadows, et al., 1996). As clay is typically more resistive than sand with a lower porosity and greater water retention ability (Schulze, et al., 1985), it is possible that these areas with greater resistivity may be indicative of these clay lens-like deposits.

6.4 Multi-Scale Interaction Model

6.4.1 Regional Interaction

The groundwater flow within the Verlorenvlei is composed of a nested flow system which contributes groundwater to the Verlorenvlei river at varying scales. These flow systems are driven by the three major hydrogeological response units of shared geology and hydrogeological characteristics within the Verlorenvlei river system which can be subdivided into 1) the Secondary Table Mountain Group aquifer unit, 2) the Malmsbury shale unit, and 3) the primary sandy aquifer unit comprised of deposited quaternary to tertiary sands. Conceptual models 1-1 presents the regional groundwater – surface water interaction in the Verlorenvlei. Conceptual model 1-2 visualises the recharge processes and interaction profile of the Krom Antonies catchment. Conceptual model 1-3 presents a cross sectional discharge and interaction model for the Redelinghuys tributary entry to the Verlorenvlei river.

A visualisation of the inflow of deep circulating groundwater into the Verlorenvlei is presented in Conceptual model 1-1. A large contributor to the Verlorenvlei's groundwater balance is the contribution of groundwater inflow through fault-driven, regional flow typically associated with the regional hydrogeological environment of the greater Cape Town area (Rosewarne, 2002; Conrad, et al., 2004). Groundwater inflow enters the Verlorenvlei catchment in a NW direction from TMG faults of the Penninsula formation which may span large distances under the

Quaternary sands, bringing in fresh groundwater from inland. The contribution of groundwater to the Verlorenvlei water balance indicted that overall, the Verlorenvlei basin experiences regional gaining conditions.

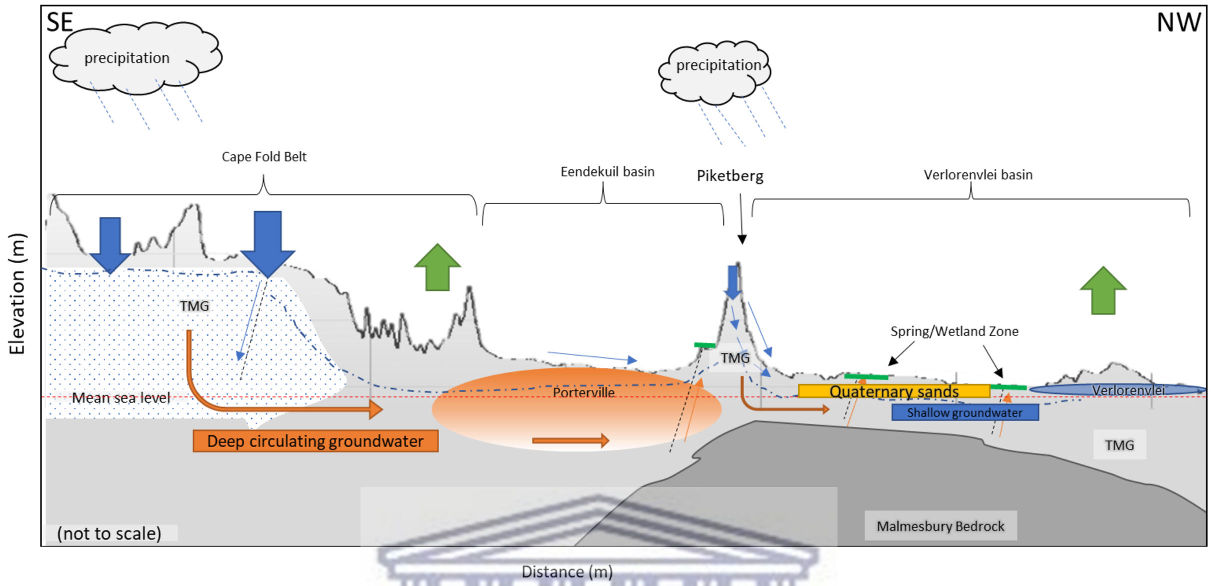


Figure 37: Conceptual Model 1-1 indicating the regional groundwater flow and contribution to the Verlorenvlei catchment.

Conceptual Model 1-2 visualises the interaction processes that occur within the upper Moutonshoek valley. Limited local recharge occurs in the low-lying areas in comparison to the Piketberg mountains (Conrad, et al., 2004). Peninsula recharge occurs in the surrounding high lying area of the Moutonshoek valley which may interact with the primary aquifer of this valley through faults and hydraulic connection. The primary aquifer of the area may receive water from TMG origin through connection of these two aquifers. Water of the TMG is be brought to the surface where contact between geological strata change the hydraulic conductivity of the groundwater flow. Water may daylight at the foot of the Moutonshoek Valley due to contact driven spring flow of layered geological formations. Baseflow may be generated in the Krom Antonies from a sufficient rainfall event, however due to evaporation rates, the baseflow is reduced significantly before generating sustaining runoff that may meet the Verlorenvlei river. Springs at the foothills of the Moutonshoek Valley sustain the baseflow of the Hol river (Watson et al, 2018).

Groundwater movement follows the topography of the area and therefore flows towards the drainage lines and ultimately the Verlorenvlei Wetland. Precipitation which recharges groundwater within the Piketberg mountains follows a short groundwater flow path from recharge to contribution to the Krom Antonies river where groundwater is suggested to contribute to river flow through quick interflow response as proposed in previous study results within the study area

(Watson, et al., 2018). This creates local gaining conditions in the case of these upper catchment in-stream pools. Channel transmission loses of water into the Quaternary alluvium causes low flow attenuation within the Krom Antonies similar to trends highlighted by Costa, et al., (2013). Where sites are not directly contributed to via quickflow or interflow from water filtering through the valley, water may be rapidly lost through the sandy riverbed creating local losing conditions.

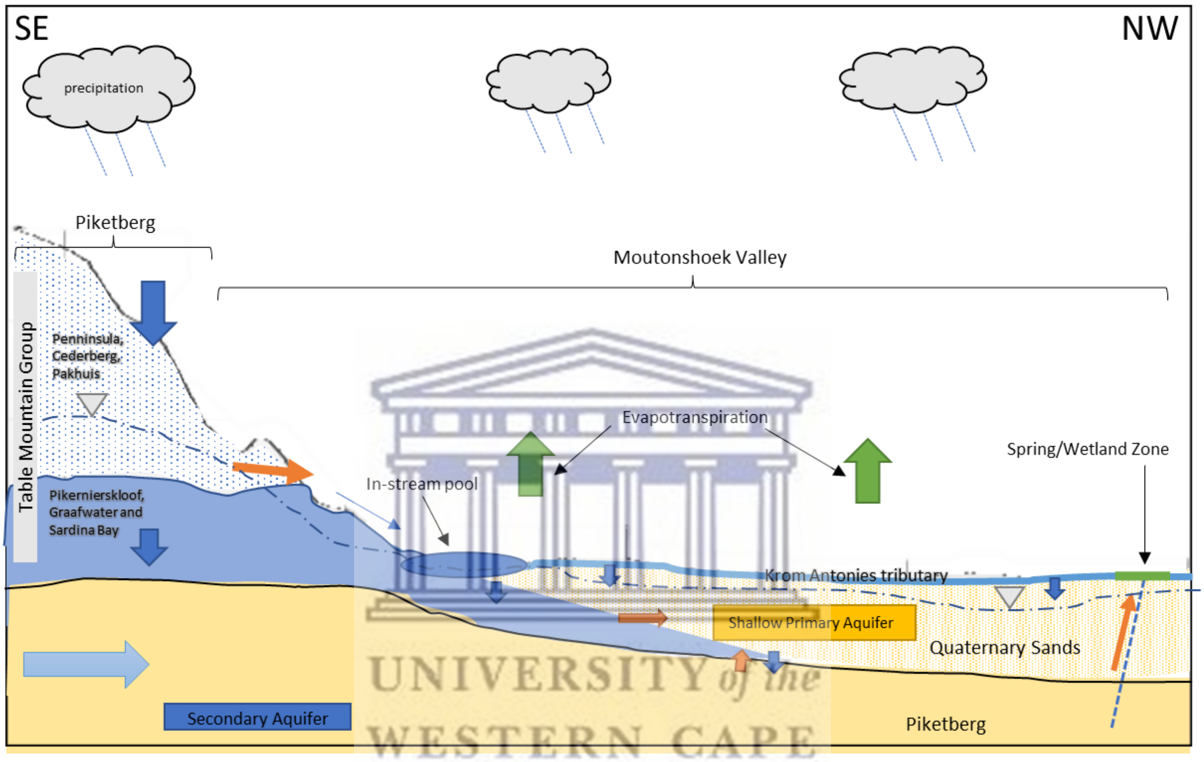


Figure 38: Conceptual model 1-2 of interaction in the Moutonshoek basin.

Conceptual model 1-3 presents the reach level interaction that occurs at the Verlorenvlei - Redelinghuys cross profile. Faults of the TMG occurring within the Pennisula formation may bring spring flow to the surface. The primary sand aquifer offers a local shallow groundwater flow system which may fed through regional or intermediate groundwater flow due to its connection with the secondary aquifer system as established in the Krom Antonies catchment (Watson, et al., 2018). From the transects and auger investigation, an indication of the presence of a shallow sandy conductive layer of sediment was observed which spanned from the source of the Redelinghuys tributary to the Verlorenvlei river channel. This may suggest a shallow subsurface flow path for water to travel laterally from the upstream spring to the Verlorenvlei down gradient of this elevated surface. This subsurface and overland flow of upwelling groundwater creates down gradient gaining conditions where water is continuously supplied to the Verlorenvlei river. At the point where this water enters the Verlorenvlei, it creates a pool which persists throughout the wet and dry period, even during drought (site VR1).

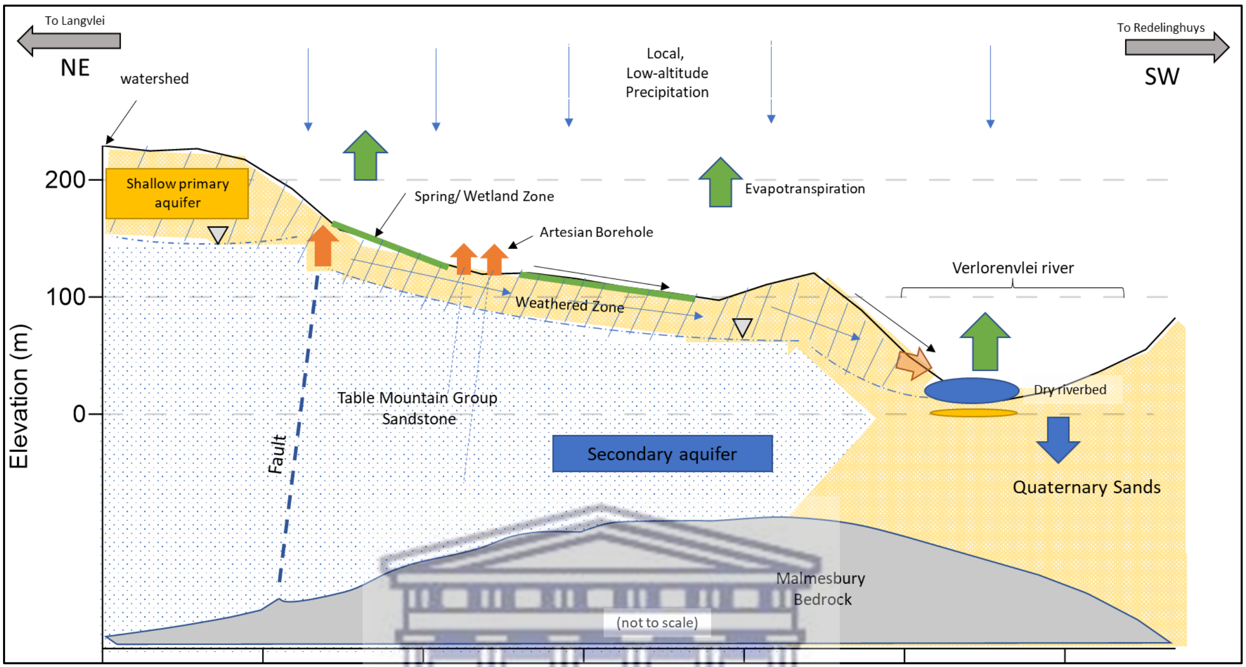


Figure 39: Conceptual model 1-3 of interaction at Verlorenvlei – Redelinghuys cross profile

6.4.2 Local Interaction

In mixed groundwater -surface water interaction types, several properties are identified to influence heterogeneity in riverbed connection at a reach level. Within the Verlorenvlei riverbed, a non-uniformity in the connectivity type is established through auger investigations and geophysical exploration of the below bed resistivity properties as a proximity for subsurface conductivity. Conceptual Model 2 visualises the point scale interaction that may occur within the Verlorenvlei riverbed where pooling water and exposure of dry riverbed occurs simultaneously.

Water within the Verlorenvlei river may be lost to the material below via the thick sand that makes up the riverbed and greater floodplain creating localised losing river conditions. Where pooling water occurs within the Verlorenvlei stream network clay-like lenses such as those potentially identified in Geo-Electric Model 1 may act like a clogging layer and prevent or slow the rate of infiltration in localised areas of the riverbed. During drier periods, these areas may retain their wetness for longer due to their point scale disconnection from the water table and reduced infiltration rate. This is expected according to results by Seaman *et al.*, (2010) where pools remained along a non-perennial river where the evaporation was balanced by spring discharge. Much like lakes and other free-standing bodies of water, non-perennial pools undergo isotopic enrichment through evaporation processes. Where pooling does not occur, infiltration of water into the Quaternary sand may be possible if evaporation does not remove the surface water entirely. Previous investigations in the Sandveld by Nel (2005), noted that runoff rarely occurs in the topographically lower sand-covered areas.

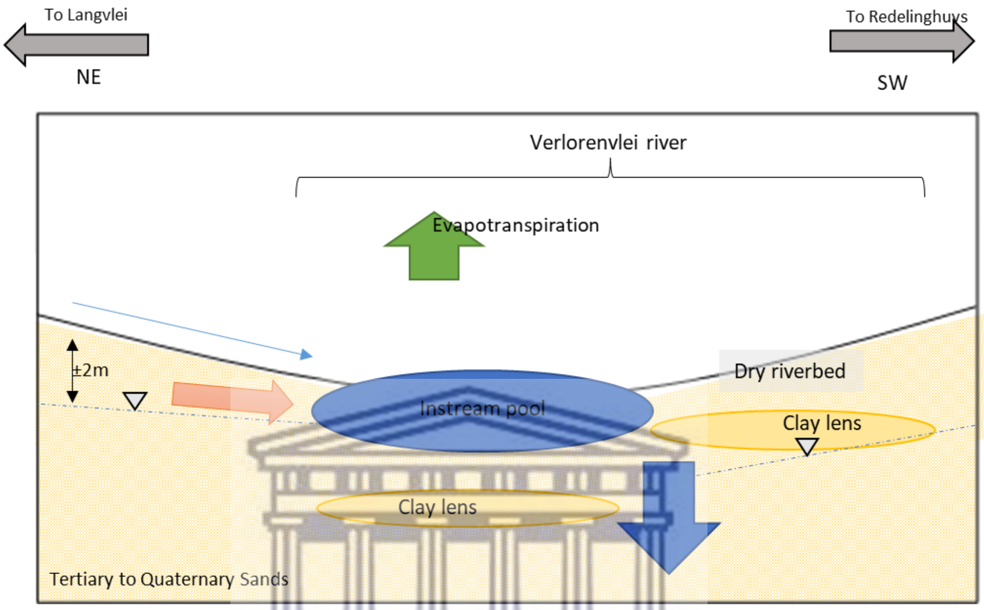


Figure 40: Conceptual model 2 of local instream interaction within the Verlorenvlei river

6.5 Groundwater's role in non-perennial rivers

Groundwater is proposed to have increased importance in non-perennial rivers during periods of low flow (Rossouw, et al., 2005). From the Verlorenvlei case study, we can discern that groundwater may play a distinct role at discrete areas within a costal non-perennial river system. This work confirms the central argument developed in literature that the timing, location and type of interaction between groundwater and surface water sources are a function of the various characteristics that are specific to the river basin in question. Several authors highlight these specific interaction defining controls in their work (Konrad, 2006).

The contribution of groundwater to the water storage of non-perennial pools is site specific and a result of the hydrogeological conditions of the river basin. Within one basin, many types of gaining-losing connection types may occur which are attributed to key characteristics of the riverbed, topography and groundwater hydrometrics and character (Newman, et al., 2006).

6.6 Implications for groundwater resource development in non-perennial rivers

Bunn *et al.* (2006) describes the flow regime of non-perennial river systems to be variable, unpredictable, and characterised by sparsely distributed pools or water holes. Improper water management practices without careful consideration of the nature and functioning of these natural systems may result in altered natural flow regimes by affecting both the hydrologic longitudinal and vertical connectivity within the riverbed, and the frequency of dry (no flow) days between rain events (Bunn *et al.*, 2006). A study conducted by Tian *et al.* (2015) assessed the impacts of agricultural practises on the hydrologic cycle of an interconnected semi-arid to arid basin. In their study, the environmental flows needed to sustain the downstream river and terminal lake of the study area, were of particular importance to ecosystem functioning as increased water use was evident and further degradation due to increased groundwater pumping was to be prevented. The groundwater-surface water interaction within this basin was found to be crucial to the regional water budget and therefore the functioning of the catchment.

Decrease of water inputs or higher salinity in non-perennial systems are associated with a loss in biodiversity as greater competition, predation, and loss of habitat change the biological makeup of the natural system (Skoulikidis *et al.*, 2017). As highlighted by Ivkovic (2009) abstraction from groundwater resources may cause hydraulic gradients to fluctuate thereby potentially reversing flow direction of interaction mechanisms if an aquifer is pumped in close proximity of hydraulically connected rivers. This effect is however absent from disconnected streams as pumping of shallow ground water near the stream does not affect the flow of the stream near the pumped wells (Winter *et al.*1998).

In the case of fractured aquifer conditions similar to the Verlorenvlei, secondary aquifers fed from far off fault driven groundwater may be affected by increased regional groundwater use. Where these faults feed primary aquifers which support rivers and wetlands, an increase in regional groundwater use may reduce the water available for use by the environments that require the water as a reserve for survival.

6.5 Applicability of methods for assessing interaction in non-perennial rivers

The methods used in this study were chosen for their ability to assess interaction between groundwater and surface water within the context of the variable non-perennial river flow regime, characterised by isolated pools and discontinuous flow. By specifically choosing methods according to the information they may provide on interaction, a conceptual understanding of the interaction processes, mechanisms and potential locations was established for the case study.

As scale of interaction between groundwater and surface water was a key focus of this study, methods utilised in this study were chosen to investigate local interaction across the distance covered by the stream network and present results that may be regionally upscaled. Environmental tracers of physiochemistry, hydrochemistry and stable isotopes investigated at local instream pools compared to groundwater sources allowed for an understanding of the across catchment chemical character of water and therefore insight into their water origin, mixing and potential for interaction. Samples were able to be taken consistently from most groundwater sources while surface water samples from in-stream pools were limited to water availability for pooling. The use of stable isotopes as a method of investigating the groundwater-surface water was successful in establishing the origin of water sources within an area and identifying the regional and local processes of replenishment. Specifically, within the study area, the application of environmental tracers created a representative hydrochemical character for Verlorenvlei pools along the river profile. Through application of geophysical survey techniques, movement of water through the subsurface could be further understood. This visual representation of the subsurface built on the conceptual understanding of the hydrogeological environment developed through desktop review of previous work in the same area.

The advantage of using multiple methods to assess the interaction was that the combination of these methods supplemented each of their respective disadvantages. Stated differently, using a multi-method approach allowed us for several aspects of interaction to be investigated concurrently. While this investigation covered a large area across the catchment, a more detailed investigation with a structured river survey for water chemistry may have provided a more accurate understanding of the spatial variability of interaction within the study area due to the nature of the varying geological, lithological and stratigraphic conditions of the subsurface.

7.1 Conclusion

A gap in knowledge in the understanding of the role of groundwater in the hydrological characteristics of non-perennial rivers was identified. This study aimed This study aims to characterise river-aquifer interaction for improved hydrogeological understanding of natural functioning of non-perennial river systems in Verlorenvlei for development of improved water management practices for non-perennial rivers. In doing so, the research would give further insight into how groundwater may contribute to the hydrological characteristics of non-perennial rivers. Three objectives were determined for this study: 1) To determine applicability of methods of assessing groundwater-surface water interaction for use in non-perennial rivers, 2) To explore groundwater-surface water interaction processes at regional and local scales and 3) To conceptualise the natural functioning of the groundwater-surface water processes. For non-perennial rivers, a defining characteristic is the development of isolated pools during periods of flow cessation.

Environmental tracers were sampled from sources of groundwater, in-stream pools and spring fed dams across the case study drainage basin. Stable isotopes revealed that low lying in-stream pools were predominantly of local low altitude rainfall origin with noticeable susceptibility to evaporation as indicated by their enriched isotopic character. Groundwater samples were expectedly depleted of heavier isotopes. Minor local recharge of shallow groundwater is evident in the enrichment of water from representative boreholes that is isotopically similar to local rainfall during the wet season. Dry season sampling of in-stream pools revealed a discrete location of groundwater discharge and gaining conditions within the Verlorenvlei river itself. Spring-fed dams exhibit mixing conditions with an isotopic composition which falls between that of groundwater and surface water samples which is isotopically similar to local rainfall. Chemical character of the Verlorenvlei area was found to be predominately Na-Cl indicative of discharge water. A water evolution path was identified from water in the upstream Krom Antonies tributary which displayed Ca – HCO^3 water characterised as recharge waters. Water movement from the upstream recharge zone of the Krom Antonies towards the Verlorenvlei wetland is corroborated by the increasing salinity gradient which follows the Verlorenvlei profile.

Previous research conducted in the case study area developed the baseline understanding of the driving components of groundwater for the area. Two major inflows to the Verlorenvlei groundwater balance are identified to be groundwater recharge from the Piketberg high relief area and an external groundwater inflow from fault-driven flow associated with the Table Mountain Group Formation. A hydrogeologic survey of boreholes identified that the groundwater flow was topographically controlled and would dissipate from higher elevated recharge areas to lower lying areas of discharge within the shallow aquifer. Cross-sectional survey of a tributary to the Verlorenvlei near Redelinghuys suggested lateral movement of upwelling groundwater from a secondary aquifer through a weathered subsurface flow path down gradient towards the Verlorenvlei, creating localised gaining conditions from lateral inputs. Similarly, geophysical survey of the Verlorenvlei riverbed indicated that areas of lower resistivity within the Quaternary sands may cause localised disconnection within the riverbed reducing the infiltration potential of water into the alluvium at this point. Water presence survey of in-stream pools in the upstream Krom Antonies catchment during the dry season revealed localised gaining conditions at pools which may be attributed to quick response of streamflow runoff due to interflow.

The multimethod approach to assessing groundwater-surface water interaction provided an efficient method to assess the interaction potential and mechanisms across multiple scales. Local scale investigation of geophysical properties, auger investigations and environmental tracers in conjunction with record review of hydrogeological characteristics enabled the mutli-scale interaction processes of the study area to be conceptualised. By combining the main information from these results, findings were able to be upscaled from point and reach measurements to local and regional scale of interaction. While the interpretations presented here are not definitive and processes conceptualised in this study will require further quantitative study for confirmation, the methods used in this study successfully generated explorative information on the interaction processes in the Verlorenvlei case study. The groundwater-surface water interaction within the Verlorenvlei can be described at these levels. Within the riverbed itself, localised gaining conditions are generated from lateral inputs of groundwater at a reach scale. At a regional scale, an overarching gaining condition of the basin itself is evident from the contribution of groundwater from inland sources. By applying this approach, limiting factors that may determine the relative site-specific interaction conditions are identified to include: basin hydrogeology, subsurface stratigraphy and water availability.

Overall, the findings from this study suggest that in areas where basin hydrogeology allows, groundwater sources may provide an important supply of water to non-perennial pools especially during periods of low water availability from precipitation. The mode of input of groundwater sources to these non-perennial rivers may be variable and an extensive study of the basin hydrogeology and groundwater flow conditions will be necessary to confirm the role of groundwater within that area. By determining the role of groundwater in non-perennial rivers, site-specific water resource needs may be determined that can inform water resource development in these areas.

7.2 Reflections

A key limitation to the study of non-perennial rivers is the presence of water along the river profile for the duration of the study. To better inform studies similar to the one undertaken and reflected on here would be to generate more robust information on the presence of water and where water is pooling within a river network through run of the river water presence mapping. These maps would highlight which discrete areas are of particular concern. These areas of concern could then be assessed for their potential vulnerability to depletion in water storage and availability from water use. Where these pools are identified to be fed by groundwater, groundwater capture maps which define the geographical impact of groundwater use and abstraction, could allow for the impact of pumping on these areas of concern to be more thoroughly investigated.

REFERENCES

Archer, E. et al., 2009. Climate change, groundwater and intensive commercial farming in the semi-arid northern Sandveld, South Africa. *Journal of Integrative Environmental Sciences,* 6(2), pp. 139-155.

Arthington, A. H., Bernardo, J. M. & Ilhéu, M., 2014. Temporary Rivers: Linking Ecohydrology, Ecological Quality and Reconciliation Ecology. *RIver Research and Applications,* 30(10).

Banks, E. W., Simmons, C. T., Love, A. J. & Shand, P., 2011. Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: Implications for regional scale water quantity and quality. *Journal of Hydrology,* Volume 404, pp. 30 - 49.

Baxter, A. J. & Davies, B. R., 1994. Palaeoecological insights for the conservation of aquatic ecosystems in dryland environments: A case study of the Verlorenvlei system, South Africa. *Aquatic Conservation: Marine and Freshwater Ecosystems ,* Volume 4, pp. 255-271.

Boulton, A. J. & Hanock, P. J., 2006. Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. *Australian Journal of Botany,* Volume 54, pp. 133-144.

Brassington, F. C., FCIWEM & P. L. Younger, FREng & FCIWIEM, 2010. A proposed framework for hydrogeological conceptual modelling. *Water and Environment,* Volume 24, pp. 261-273.

Brodie, R. et al., 2007. *An Overview of Tools for Assessing Groundwater - Surface water Connectivity,* Canberra: Bureau of Rural Sciences.

Brunner, P., Cook, P. G. & Simmons, C. T., 2011. Disconnected Surface Water and Groundwater: From Theory to Practise. *Ground Water,* 49(4), pp. 460-467.

Brunner, P., Simmons, C. T. & Cook, P. G., 2009. Spatial and temporal aspects of the transition from connection to diconnection between rivers, lakes and groundwater. *Journal of Hydrology,* Volume 376, pp. 159-169.

Bugan, R. D., Jovanovic, N. Z. & De Clercq, W. P., 2012. The water balance of a seasonal stream in the semi-arid Western Cape (South Africa). *Water SA,* 38(2), pp. 201-212.

Buggisch, W., Kleinschmidt, G. & Krumm, S., 2010. Sedimentology, geochemistry and tectonic setting of the Neoproterozoic Malmesbury Group (Tygerberg Terrane) and its relation to neighbouring terranes, Saldania Fold Belt, South Africa. *Neues Jahrbuch für Geologie und Paläontologie - Abhandlungen*, 257(1), pp. 85-114.

Bunn, S. E., Toms, M. C., Hamilton, S. K. & Capon, S., 2006. Flow variability in dryland rivers: Boom, bust and the bits in between. *River Reasearch and Applications,* Volume 22, pp. 179-186.

CGS, 1973. *3218 Clanwilliam 1:250 000 Geological Series.* Pretoria: Geological Survey, Council of Geoscience.

CGS, 2008. *Simplified Geological Map of the Republic of SOuth Africa and the Kingdoms of Lesotho and Swaziland.* Pretoria: Council For Geoscience.

Colvin, C., le Maitre, D., Saayman, I. & Hughes, S., 2007. *Aquifer Dependent Ecosystems in Key Hydrogeological Type Settings in South Africa,* Pretoria: Water Research Commission.

Colvin, C. et al., 2009. *Ecological and Enviromental Impacts of Large-scale Groundwater Development in the Table Mountain Group (TMG) aquifer system,* Cape Town, South Africa: Water Research Commission.

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

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

Costa, A. C., Foerster, S., de Araújo, J. C. & Bronstert, A., 2013. Analysis of channel transmission losses in a dryland river reach in north-eastern Brazil using streamflow series, groundwater level series and multi-temporal satellite data. *Hydrological Processes,* Volume 27, pp. 1046-1060.

Craig, H., 1961. Isotopic Variations in Meteoric Waters. *Science,* 133(3465), pp. 1702-1703.

Crosbie, R. S. et al., 2014. Evaluation of infiltration from losing-disconnected rivers using a geographical characterisation of the riverbed and a simplified infiltration model. *Journal of Hydrology,* Volume 508, pp. 102-113.

CSIR, 2009. *Development of the Verlorenvlei estuarine management plan: Situation assessment. Report prepared for the C.A.P.E. Estuaries Programme.,* Stellenbosch: CSIR.

Dahl, M., Nilsson, B., Langhoff, J. & Refsgaard, J. C., 2007. Review of classification systems and new multi-scale typology of groundwater - surface water interaction. *Journal of Hydrology,* Volume 344, pp. 1-16.

D'Ambrosio, E. et al., 2017. Charcterising the hydrological regime of an unguaged temporary rriver system: a case study. Volume 24, pp. 13950-13966.

Datry, T. et al., 2018. Flow intermittence and ecosystem servies in rivers of the anthropocene. *Journal of Applied Ecology,* Volume 55, pp. 353-364.

de Beer, C., 2002. *The Stratigraphy, Lithology and Structure of the Table Mountain Group,* Bellville, South Africa: Water Research Commission.

Department of Water Affairs and Forestry, South Africa, 2008. *The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models : Groundwater Model Report Volume 3 – Regional Conceptual Model.,* s.l.: Prepared by Umvoto Africa (Pty) Ltd in association with Ninham Shand (Pty) Ltd on behalf of the Directorate : National Water Resource Planning. DWAF Report No. P WMA 19/000/00/0408.

Department of Water and Sanitation, 2015. *GH4178: Groundwater Status Report - Western Cape Region,* s.l.: Department of Water and Sanitation.

Department of Water and Sanitation, 2018. *Water Outlook 2018 Report: Revision 30 – Updated 31 December 2018,* Cape Town: City of Cape Town.

Dollar, E. S. J., 1998. Palaeofluvial geomorphology in southern Africa: a review. *Progress in Physical Geography: Earth and Environment,* 22(3), pp. 325-349.

Dor, N. et al., 2011. Verification of Surface-Grounwater Connectivity in an irrigation Canal Using Geophysical, Water Balance and Stable Isotope Approaches. *Water Resour Manage.*

Drever, J. I. & Smith, C. I., 1978. Cyclic Wetting and Drying of the Soil Zone as an Influence on the Chemistry of Groundwater in arid terrains. *American Journal of Science,* 278(10), pp. 1448-1454.

DWAF, 2003. *Sandveld Preliminary (Rapid) Reserve Determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30. Surface Volume 1: Final Report Reserve Specifications. DWAF Project Number: 2002-227,* s.l.: s.n.

DWAF, 2005. *Groundwater Resource Assessment Phase II (GRAII).,* Pretoria: Department of Water Affairs and Forestry.

DWAF, 2013. *National Water Resource Strategy,* Republic of South Africa: Department of Water Affairs.

Eilers, M., Miller, J., Watson, A. & Sigidi, N., 2017. Groundwater recharge quantification from historial rainfal records and salinity profiling in the RAMSAR listed Verlorenvlei. *Procedia Earth and Planetary Science,* Volume 17, pp. 586-589.

Enemark, T., Peeters, L. J., Mallants, D. & Batelaan, O., 2019. Hydrogeological conceptual model building and testing: A review. *Journal of Hydrology,* Volume 569, pp. 310-329.

Falke, J. A. et al., 2011. The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. *Ecohyrological,* Volume 4, pp. 682-697.

Fleckenstein , J. H., Niswonger, R. G. & Frogg, G. E., 2006. River-Aquifer Interactions, Geologic Heterogeneity, and Low-Flow Management. *Ground Water,* 44(6), pp. 837-852.

Fleckenstein, J. H., Krause, S., Hannah, D. M. & Boano, F., 2010. Groundwater-suface water interactions: New methods and models to improve understanding of processes and dynamics. *Advances in Water Resources,* Volume 33, pp. 1291-1295.

Frimmel, H. E., Basei, M., Correa, V. X. & Mbangula, N., 2013. A new lithostratigraphic subdivision and geodynamic model for the Pan-African western Saldania Belt, South Africa. *Precambrian Research,* Volume 231, pp. 218-235.

Froehlich, K., Gibson, J. J. & Aggarwal, P. K., 2002. Deuterium excess in precipitation and its climatological significance.

Gallart, F. et al., 2008. Invetigating hydrological regimes and processes in set of catchments with temporary waters in Mediterranean Europe. *Hydrological Sciences Journal,* Volume 53, pp. 618-628.

Gallart, F. et al., 2016. Validating alternative methodologies to estimate the regime of temporaqry rivers when flow data are unavailable. *Science of the Total Environment,* Volume 565, pp. 1001-1010.

Gat, J. R., 1996. OXYGEN AND HYDROGEN ISOTOPES IN THE HYDROLOGIC CYCLE. *Annual Review of Earth and Planetary Sciences,* 24(1), pp. 225-262.

Gat, J. R., Mook, W. G. & Meijer, H. A. J., 2000. VOLUME II: Atmospheric Water. In: *Environmental Isotopes in the Hydrological Cycle: Principles and Applications.* Paris/ Vienna: International Atomic Energy Agency and United Nations Educational, Scientific and Cultural Organization, pp. 197 - 206.

Geyh, M., 2000. *Environmental isotopes in the hydrological cycle: principles and applications, v. IV: Groundwater, saturated and unsaturated zone,* Paris: UNESCO.

Gharibi, M. & Bentley, L. R., 2005. Resolution of 3-D Electrical Resistivity Images from Inversions of 2-D Orthogonal Lines. *Journal of Environmental and Engineering Geophysics,* 10(4), pp. 339-349.

Guggenmos, M. R., Daughney, C. J., Jackson, B. M. & Morgenstern, U., 2011. Regional-scale identification of groundwater-surface water interaction using hydrochemistry and multivariate statistical methods, Wairarapa Valley, New Zealand. *Hydrol. Earth Syst. Sci.*, Volume 2011, p. 3383–3398.

Haitjema, H. M. & Mitchell-Bruker, S., 2005. Are Water Tables a Subdued Replica of the Topography?. *Groundwater* , 43(6), pp. 781-786.

Harbeck, J. G. E., 1955. Studies of Evaporation: The effect of salinity on evaporation. *Geological Survey Professional Paper,* Volume 272, pp. 1-6.

Haria, A. H., Shand, P., Soulsby, C. & Noorduijn, S., 2012. Spatial delineation of groundwater–surface water interactions through intensive in-stream profiling. *Hydrologicak Processes,* Volume 27, pp. 628-634.

IAEA/WMO, 1998–2020. *Global Network of Isotopes in Precipitation (GNIP). The GNIP Database..* [Online]
Available at: https://www.iaea.org/services/networks/gnip

Ivkovic, K. M., 2009. A top-down approach to characterise aquifer-river interaction processes. *Journal of Hydrology,* Volume 365, pp. 145-155.

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

Karroum, M. et al., 2017. Geochemical processess controlling groundwater quality under semi arid environment: A case study in central Morocco. *Science of the Total Environment,* Volume 609, pp. 1140-1151.

Katz, G. L., Denslow, M. W. & Stomberg, J. C., 2011. The Goldilocks effect: intermittent streams sustain more plant species than those with perennial or ephemeral flow. *Freshwater Biology.*

Kirsch, R., 2009. *Groundwater Geophysics: A Tool for Hydrogeology.* 1 ed. s.l.:Springer-Verlag Berlin Heidelberg.

Konrad, C. P., 2006. Location and timing of river - aquifer exchanges in six tributaries to the Columbia River in the Pacific Northwest of the United States. *Journal of Hydrology,* Volume 329, pp. 444-470.

Kumar, M., Ramanathan, A. & Keshari, A. K., 2008. Understanding the extent of interactions between groundwater and surface water through major ion chemistry and multivariate statistical techniques. *Hydrological Processes.*

Lamontagne, S. et al., 2014. Field assesment of surface water-groundwater connectivity in a semi-arid river basin (Murray-Darling, Australia). *Hydrological Processes,* Volume 28, pp. 1561-1572.

Larned, S. T., Datry, T., Abscott, D. B. & Tockner, K., 2010. Emerging concepts in temporary-river ecology. *Freshwater Biology,* Volume 55, pp. 717-738.

Levy, J. & Xu, Y., 2011. Review: Groundwater management and groundwater/surface-water interaction in the context of South African water policy. *Hydrogeology Journal,* Volume 20, pp. 205-226.

Loke, M. H. et al., 2013. Recent developments in the diret-current geoelectrical imaging method. *Journal of Applied Geophysics,* Volume 95, pp. 135-156.

Low, A. B. & Rebelo, A. G., 1996. *Vegetation of South Africa, Lesotho and Swaziland,* Pretoria: DEAT.

McLachlan, P. J., Chambers, J. E., Uhlemann, S. S. & Binley, A., 2017. Geophysical characterization of the groundwater-surface water interface. *Advances in Water Resources,* Volume 109, pp. 302-319.

Meadows, M. E., Baxter, A. J. & Adams, T., 1993. The Late Holocene Vegetation History of Lowland Fynbos, Verlorenvlei, SouthWestern Cape Province, South Africa. *Historical Biology,* Volume 9, pp. 47-59.

Meadows, M. E., Baxter, A. J. & Parkington, J., 1996. Late Holocene Environments at Verlorenvlei, Western Cape Province, South Africa. *Quarternary International,* Volume 33, pp. 81-95.

Menció, A., Galán, M., Boix, D. & Mas-Pla, J., 2014. Analysis of stream-aquifer relationships: A comparison between mass balance and Darcy's law approaches. *Journal of Hydrology,* Volume 517, pp. 157-192.

Miller, J. A., Watson, A., Fleischer, M. & van Gend, J., 2018. Groundwater quality, quantity, and recharge estimaton on the West Coast of South Africa. *Biodiversity & Ecology,* pp. 86-97.

Mohamed, A. E., 2014. Comparing Africa's Shared River Basins - The Limpopo, Orange, Juba and Shabelle Basins. *Universal Journal of Geoscience*, 2(7), pp. 200-211.

Mor, Z. et al., 2018. Effect of Water Surface Salinity on Evaporation: The case if a Diluted Bouyant Plume Over the Dead Sea. *Water Resources Research* , 54(3), pp. 1460-1475.

Mosley, L. M. et al., 2012. The Impact of Extreme Low Flows on the Water Quality of the Lower Murray River and Lakes (South Australia). *Water Resource Management,* Volume 26, pp. 3923-3946.

Münch, Z. & Conrad, J., 2007. Remote sensing and GIS based determination of groundwater dependent ecosystems in the Western Cape, South Africa. *Hydrogeology Journal,* Volume 15, pp. 19-28.

Műnch, Z. et al., 2013. Satellite earth observation as a tool to conceptualise hydrogeological fluxes in the Sandveld, South Africa. *Hydrogeology Journal,* Volume 21, pp. 1053-1070.

Negrel, P. & Lachassagne, P., 2000. Geochemistry of the Maroni River (French Guiana) during the low water stage: implications for water±rock interaction and groundwater characteristics. *Journal of Hydrology,* Volume 237, pp. 212-233.

Nel, J. M., 2005. *GH 4000. Assessment of the Geohydrology of the Langvlei catchment,* Pretoria: DWAF.

Newman, B. D., Vivoni, E. R. & Groffman, A. R., 2006. Surface water - groundwater interactions in semiarid drainages of the American south west. *Hydrological Processes,* Volume 20, pp. 3371-3394.

Oxtobee, J. P. & Novakowski, K., 2002. A field investigation of groundwater/surface water interaction in a fractured bedrock environment. *Jounal of Hydrology,* Volume 269, pp. 169-193.

Oyarzún, R. et al., 2016. Chemical and isotopic assessment of surface water–shallow groundwater interaction in the arid Grande river basin, North-Central Chile. *Hydrological Sciences Journal*, 61(12), pp. 2193-2204.

Parsons, R., 2009. Is Groenvlei really fed by groundwater discharged from the Table Mountain Group (TMG) Aquifer?. *Water SA,* 35(5), pp. 657-662.

Parsons, R. & Vermeulen, P., 2017. The hidden hydrology of Groenvlei, a lacustrine wetland on the southern Cape coast of South Africa. *Water SA,* 43(1), pp. 42-47.

Prucha, B. et al., 2016. MIKE-SHE intergrated groundwater and surface water model used to simulate scenario hydrology for input to DRIFT-ARID: the Mokolo River case study. *Water SA,* 42(3), pp. 384-398.

Ramsar, 2020. *The List of Wetlands of International Importance. Ramsar List.* [Online] Available at: http://www.ramsar.org/sites/default/files/documents/library/strategic_framework_rsis_en.pdf

Rau, G. C. et al., 2017. Characterising the dynamics of surface water-groundwater interactions in intermittent and ephemeral streams using streamed thermal. *Advances in Water Resources,* Volume 107, pp. 354-369.

Republic of South Africa (RSA), 1998. *National Water Act (NWA), Act 36 of 1998,* Pretoria, South Africa: Government Printers.

River Health Programme, 2006. *State of RIvers Report: Olifants/Doring and Sandveld Rivers,* Pretoria: Department of Water Affairs and Forestry.

Roets, W. et al., 2008. Determining discharges from the Table Mountain Group (TMG) aquifer to wetlands in the Southern Cape, South Africa. *Hydrobiologia,* Volume 607, pp. 175-186.

Rosewarne, P., 2002. *Hydrogeological Characteristics of the Table Mountain Group Aquifers,* Pretoria: Water Research Commision.

Rossouw, L. et al., 2005. *Environmental Water Requirements in Non-Perennal Systems,* Bloemfontein: The Water Research Commission.

Rozendaal, A., Gresse, P. G., Scheepers, R. & Philippus Le Roux, J., 1999. Neoproterozoic to Early Cambrian Crustal Evolution of the Pan-African Saldania Belt, South Africa. *Precambrian Research,* 97(3), pp. 303-323.

Samouelian, A. et al., 2005. Electrical resistivity survey in soil science: a review. *Soil and Tillage Research,* Volume 83, pp. 173-193.

Schulze, R. E. et al., 2009. *South African Atlas of Climatology and Agrohydrology,* Pretoria: Water Research Commission.

Schulze, R., Hutson, J. & Cass, A., 1985. Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models. *Water SA,* 11(3), pp. 129-136.

Seaman, M. T. et al., 2010. *Developing a method for determining the environmental water requirements for non-perennial systems,* Pretoria: Water Research Commission.

Seaman, M. T. et al., 2013. *Testing a methodology for environmental water requirements in Non-perennial rivers: The Mokolo River Case Study,* Pretoria, South Africa: Water Research Commission.

Seaman, M. et al., 2016. DRIFT-ARID: Application of a method for environmental water requirements (EWRs) in a non-perernnial river (Mokolo River) in South Africa. *Water SA,* 42(3), pp. 368-383.

Shanafield, M. & Cook, P. G., 2014. Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods. *Journal of Hydrology,* Volume 511, pp. 518-529.

Sigidi, N. T. et al., 2017. Geochemical and isotopic tracing of salt loads into the Ramsar listed Verlorenvlei estuarie lake, South Africa. *Procedia Earth and Planetary Science,* Volume 17, pp. 909-912.

Skoulikidis, N., Vardakas, L. & Amaxidis, Y., 2017. Biogeochemical processes controlling aquatic quality during drying and rewetting events in aMediterrean non-perennial river reach. *Science of Total Environment,* pp. 378-389.

Sokolov, A. A. & Chapman, T. G., 1974. *Methods for Water Balane Computations,* Place de Fontenoy, 75700 Paris: The Unesco Press.

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal,* Volume 10, pp. 52-67.

Sundaram, B. et al., 2009. *Groundwater Sampling and Analysis - A field Guide,* s.l.: Geoscience Australia, Record 2009/27 95 pp.

Tanner, J. L. & Hughes, D. A., 2015. *Understanding and Modelling Surface Water-Groundwater Interactions,* Gezina, Pretoria: Water Research Commission.

Tian, Y. et al., 2015. Modeling suface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. *Environmental Modeling & Software,* Volume 63, pp. 170-184.

Tóth, J., 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. *Journal of Geophysical Research,* 68(16).

Tóth, J., 1999. Groundwater as a geologic agent: An overview of the causes, processes and manifestations. *Hydrogeology Journal,* Volume 7, pp. 1-14.

UNEP, 2010. *Africa Water Atlas,* s.l.: s.n.

Uys, M. C. & O'keeffe, J. H., 1997. Simple Words and Fuzzy Zones: Early Directions for Temporary River Research in South Africa. *Environmental Management,* 21(4), pp. 517-531.

Walton, W. C., 1970. *Groundwater resource evaluation. McGraw-Hill series in water resources and environmental engineering (USA) eng.* s.l.:s.n.

Wang, S. et al., 2018. Meteoric water lines in arid Central Asia using event-based and monthly data. *Journal of Hydrology,* Volume 562, pp. 435-445.

Wang, X., Zang, G., Xu, Y. J. & Sun, G., 2015. Identifying the regional-scale groundwater-surface water interaction on the Sanjiang Plain, Northeast China. *Environ Sci Pollut Res ,* Volume 22, pp. 16951-16961.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W., 2018. Estimation of groundwater recharge via precolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South AFrica. *Journal of Hydrology,* Volume 558, pp. 238-254.

Weaver, J. M., Cave, L. & Talma, A. S., 2007. *Groundwater Sampling: A comprehensice guide for sampling methods,* Gezina, Pretoria: Water Research Commission.

Weitz, J. & Demlie, M., 2014. Conceptual modelling of groundwater - surface water interactions in the Lake Sibayi Catchment, Eastern South Africa. *Journal of African Earth Sciences,* Volume 99, pp. 613-624.

Winter, T. C., 1998. Relation of streams, lakes and wetlands to Groundwater Flow Systems. *Hydrogeology Journal,* Volume 7, pp. 28-45.

Woocay, A. & Walton, J. C., 2008. Multivariate Analyses of Water Chemistry: Surface and Ground Water Interactions. *Ground Water.*

WRC, 2000. *Quiality of domestic water supplies. Volume 2: Sampling Guide,* Pretoria: Water Research Commission No: TT 117/99.

WRC, 2017. *Groundwater Sampling Manual,* Pretoria, South Africa: Water Research Commission (WRC).

Xu, Y., Lin, L. & Jia, H., 2009. *Groundwater Flow Conceptualisation and Storage Determination of the Table Mountain Group (TMG) Aquifers,* Bellville, South Africa: Water Research Commission.

Yang, Z. et al., 2015. Simulation of Groundwater-Surface Water Interactions under Different Land Use Scenarios in the Bulang Catchment, Northwest China. *Water,* Volume 7, pp. 5959-5985.

Younger, P. L., 2007. *Groundwater in the Environment: an introduction.* USA, UK, Australia: Blackwell Publishing.

Addendum A: The cation-anion balance (CAB) calculated for all water samples taken during the duration of this current study as calculated using the CAB (%) formula presented by Younger (2007). Suitability is indicated by colour coding of the CAB %: Red is rejected, Yellow and Green are acceptable for use in research.

Site	Jul-17			Oct-17			Mar-18			Jul-18			Feb-19		
	ΣCations (meq/l)	ΣAnions (meq/l)	CAB %	ΣCations (meq/l)	ΣAnions (meq/l)	CAB %	ΣCations (meq/l)	ΣAnions (meq/l)	CAB %	ΣCations (meq/l)	ΣAnions (meq/l)	CAB %	ΣCations (meq/l)	ΣAnions (meq/l)	CAB %
B	12.44	10.87	7										35.83	40.75	-6
DS1	9.80	8.69	6				7.38	7.20	1	9.67	8.31	8	10.30	8.66	9
G33651							8.56	8.43	1	8.21	7.56	4	8.44	7.15	8
GD1	11.26	10.38	4	11.17	11.56	-2	11.91	11.78	1				12.47	10.84	7
GG	2.78	3.38	-10	3.92	4.81	-10	4.25	4.05	2	4.08	4.00	1	5.28	4.14	12
HK1	11.01	2.25	66	8.85	8.61	1	6.86	7.19	-2				8.77	7.33	9
HolD	42.48	41.98	1	48.35	44.34	4	4.47	4.64	-2	63.95	15.04	62	12.72	11.04	7
KVD	2.98	2.91	1	2.75	3.33	-10	2.46	4.08	-25	74.58	5.28	87	4.60	4.79	-2
PMV1	2.19	3.05	-16	4.37	4.99	-7	4.72	4.98	-3	3.77	3.69	1	4.41	3.85	7
PMV2	12.11	19.57	-24	4.54	5.20	-7	4.63	4.88	-3	4.01	3.92	1	13.08	10.66	10
S0	7.79	6.92	6	6.04	5.43	5	4.87	4.21	7	7.24	6.37	6	5.70	4.66	10
HoR				33.66	31.90	3				54.21	12.78	62			
Spr	10.74	10.33	2												
VK1	5.88	5.19	6	5.68	7.21	-12				5.70	5.09	6	5.97	4.91	10
VK2	35.33	34.26	2	27.51	25.42	4	54.51	51.24	3	43.63	43.93	0			
KA1				1.27	3.59	-48				1.16	1.55	-14	4.79	4.57	2
KmR	7.94	7.91	0	3.19	3.27	-1				9.33	57.32	-72			
KR1	39.63	40.42	-1							35.30	35.18	0			
KR2	19.17	20.72	-4												
KR3	1.34	2.10	-22							1.45	1.93	-14	7.64	6.76	6
KR4	44.32	47.41	-3	64.47	83.70	-13									
MH1	0.82	1.18	-18	0.91	1.40	-21				0.89	1.21	-15			
MH2	7.77	7.96	-1							1.32	1.56	-8	6.97	8.03	-7
VR1	11.78	10.81	4	11.28	11.18	0	9.00	9.14	-1	17.30	16.87	1	8.92	8.08	5
VRT1	49.45	49.00	0							20.14	19.89	1			
VV2	55.77	62.97	-6												
PZ5													9.02	10.48	-8