Assessing hydrogeology of springs in Heuningnes Catchment in South Africa

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Declaration

I, Paula Finini, declare that project tittle "*Assessing hydrogeology of springs in Heuningnes Catchment in 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 acknowledge by complete reference.

Full name: Paula Finini

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Date: June 2022

Dedication

I dedicate this work to my beloved mother, Pumza Finini as a gift of appreciation to her hard work and sacrifices she has made to ensure my success and growth. I will forever be grateful for her endless love and support. There is no parenting book in the world that could have prepared me to this young woman that I am growing to be, your strength and efforts will never go unnoticed. “Ahhh!!!! Madeyi, Mshwawu, Xhakaza, Zotsho”.

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Abstract

Springs have been a significant source of water for flora and fauna since the beginning of human history and, in some circumstances, the only source capable of supplying enough water to sustain domestic and agricultural water supplies. Research that expands our understanding of the potential and limitations of these resources has not focused much on springs that are located outside of karst environments. Groundwater discharge is part of the interaction that makes groundwater visible and sustains ecosystems. Groundwater discharges in rivers, springs, and wetlands forms groundwater-dependent ecosystems (GDEs). GDEs are often complex, and poorly understood component of the natural environment. For example, identifying actual spots for spring discharges and validating previously mapped springs remains a challenge; hence, the focus of the current study, which, argues that if spring hydrogeology is not characterized first, then the influence of such springs on the environment and human needs cannot inform their action. This study aimed at providing improved knowledge and understanding of spring hydrogeology. Heuningnes catchment in South Africa was used as a case study. Three specific objectives were set as follows: 1] spring hydrogeology was characterized where new springs were identified, and old springs were validated/crosschecked. A springs map was produced and overlaid on a conceptual model of groundwater flow to describe subsurface conditions for spring occurrence; 2] Flow dynamics of springs were determined where spring flows were measured to estimate discharge rate; 3] the hydrogeochemistry of springs was assessed with hydrogeochemical processes responsible for temporal and spatial changes in the quality of spring waters were established for suitability of water for use by the environment and people. Results showed that the validated springs existed in upland, middle, and lowland within the study catchment. Most springs were associated with Table Mountain Group and Bokkeveld formations with fractures, lithological contacts, and faults that influenced the main flow paths for springs. Three groups of springs were identified namely, shallow circulating springs, lithology-controlled springs, and fault-controlled springs. Results on flow dynamic showed some springs were flowing or discharging groundwater onto the surface throughout the year while others were not. Such seasonal variation in spring flows implied that two systems for springs existed in the study catchment i.e. regional and local fed systems of springs. Such findings are important for protecting, monitoring, and allocating water resources in the water management area. Using EC values of less than 1 000 mg/l, results indicated that water samples from springs were characterized as freshwater. Rock-water interaction analysis was identified to be the dominant geochemical process that influenced spring hydrochemistry. Results of Radon-222 analysis confirmed the presence of groundwater in surface water thereby providing scientific evidence-based results on groundwater-surface water interaction. Although results from the current study are not comprehensive, they have provided reliable, valid, and scientific evidence-based outputs to improve the current practice of assessing groundwater-surface water interaction using springs as groundwater discharge. The current study recommends a long-term monitoring of springs including distinguishing spring source areas and dating for water allocation.

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Chapter 1: General Introduction

1.1 Background to the study

Groundwater (GW) is a valuable natural resource that is critical for the ecosystem's survival and development, particularly in arid and semi-arid environments. In the world, groundwater provides the most important supply of freshwater, making it a critical resource for human consumption and overall regional development (Kumar et al. 2014). On a worldwide scale, groundwater supplies two-thirds of the world's freshwater resources. For many years, groundwater was regarded as a cheap source of water, requiring little or no planning or management (Rossouw et al. 2005). A lack of understanding of the occurrence, movement and discharge of groundwater has however, in many instances led to unsustainable utilization of this resource (Braune 2000), because utilization of groundwater greatly preceded understanding of its origin, occurrence, and movement (Todd & Mays, 2005). The successful exploitation and management of groundwater resources in the future is essentially dependent on the understanding of groundwater processes. For decades, the development of groundwater has supplied the humankind with socioeconomic benefits, and groundwater is now anticipated to supply more than half of the world's consumption water (Adewuyi et al. 2010). Hence, the current study aims at understanding groundwater process with focus on groundwater discharge.

Groundwater discharge is an important component of the hydrological cycle and has been generally defined as the upward movement of groundwater from the subsurface to the surface. Groundwater is induced to discharge from wells (pumping), and discharges naturally from the subsurface to oceans, springs, lakes, rivers (gaining streams), swamps, and other wetlands. The groundwater discharges into the stream provides baseflow during hot summer months (Green 2007). For example, springs as one of groundwater discharge point, support ecosystem linkages in the environment, governing the exchange of water and nutrients, and are source of rivers in some areas. As a result, groundwater discharge can have a considerable impact on ecosystems, as this process is typically critical for preserving or recovering valuable ecosystems in surface water (Jakeman et al. 2016). Natural discharge is governed by topography and geology, with groundwater discharging in topographically low regions (such as valley floors) with higher permeability sandstone layers or gravels (Messene 2017). Discharge (i.e. the volume of water flowing past a given point per unit time) varies substantially from season to season, and discharged water quality is frequently influenced by the flow and geology, which may be a significant contributor to the amount of water and chemical budget of a water resource. Thus, the study focuses on groundwater discharge through springs hence the title of the study, assessment of spring hydrogeology.

More than half of total flows in the global river network are composed of non-perennial rivers (Datry et al. 2014). Such rivers are by far the most dominant river type in South Africa and neighbouring countries such as Namibia, Zimbabwe, Botswana, and Angola, due to the semi-arid and arid conditions (Rossouw et al. 2005). The potential for perennial rivers to transition into non-perennial rivers is projected to increase because of climate variability and water resource development (Costigan et al., 2016). Groundwater has been confirmed to be one of the variables that regulate the flow regimes and categorization (perennial, seasonal or ephemeral) of a river system (Robinson et al., 2015). Groundwater flowing into rivers during dry periods is important because it provides river discharge and to sustain aquatic biodiversity (Uys and O'Keffe, 1997). Therefore, in order to understand the contribution of groundwater in non-perennial river environment, it is also important to assess the component of the groundwater discharge surrounding such river systems. Hence, there is a need to understand the mechanism that leads to groundwater reaching the rivers as it affects flow dynamics and quality of such waters.

The discharge of groundwater from an aquifer through springs and seeps results in the discharge of groundwater to rivers, which is limited to a small area of the aquifer. The rate and volume of water discharged from aquifers through springs further flowing to rivers are determined by the aquifer type and features (Mulligan and Charette 2009). Aquifer properties may also influence the rate and timing of groundwater discharge. These properties include hydraulic conductivity, porosity, and transmissivity (Alley et al. 2002). The classification of these is based on the location of the water table on the subsurface, aquifer structure and hydraulic conductivities, which are governed by confined or unconfined aquifers. Aquifers vary depending on the permeability and porosity of the rock type and include sandstones, conglomerates, fractured limestone and unconsolidated sand, gravels and fractured volcanic rocks (Christelis and Struckmeier 2011). Some aquifers are characterized by high porosity and low permeability including granites and schist whilst those with high porosity and high permeability include rocks like fractured volcanic rocks (Javaid and Khan 2018). Thus, understanding the subsurface condition that influences the occurrence and distribution of springs remains vital in the assessment of the component of groundwater discharge as they affect flow dynamics [rate and volume] of springs.

Several rivers are heavily reliant on spring discharge as springs form sources of rivers. A spring is a visible flow of groundwater that flows to the earth surface. Springs with clear-water ecosystems are common in headwater regions (Kresic and Stevanovic 2010). Springs can have continuous or intermittent flows and can vary widely in size. During seasons of low flow and elevated temperatures, spring fed rivers provide a safe harbour for fish and invertebrates from neighboring rivers due to consistent flows and temperatures. Furthermore, because the flows are controlled by groundwater recharge, most spring-fed rivers have little seasonal variation in discharge (Hayes et al. 2018). As a result, most spring-fed rivers are deeply incised, have a generally consistent rectangular channel morphology with few bars, and rely on surface flows that drain into the same river (Allen and Hay 2011). Water abstraction, on the other hand, can significantly reduce the flow, disturbing the predictable flow of rivers dominated by spring discharges. Therefore, this study seeks to investigate discharge from springs to understand the hydrogeology of springs by determining flow dynamics of the springs.

A spring is one of the forms of natural outflow of groundwater at the surface of the Earth. Springs connect the underground and the surface parts of the water circulation system. The existence of a spring requires that the subsurface is unable to transmit water as fast as it is supplied, so that the potentiometric surface intersects the land surface and a range of geological structures, properties and topography can thus bring water to the surface (Manga 2001). Groundwater rises to the surface through faults, fractures or depressions, and its occurrence is controlled by many factors such as lithology, slope, structures, and landforms. Hence, spring diversity is representative of wide variety of geological and hydrological conditions that contribute to their occurrence. Spring water offers a reliable source of potable water in many parts of the world and are an indirect source of information (Kresic and Stevanovic 2010). For example, in some regions, groundwater emerging at springs provides the only available means for obtaining information about the regional scale subsurface hydrology over large spatial areas and extended period of time. The composition, temperature, and discharge variations of the spring water reflect these processes that occurred over the entire sub-surface and history of transport. Thus, by using springs to understand the subsurface and the way groundwater moves until it reaches discharge zones such as springs remains essential for understanding the concept of spring hydrogeology.

The concept of groundwater flow systems has been found useful in hydrogeology to describe the patterns of flow and chemistry in the subsurface (e.g., Freeze and Cherry, 1979). A basic assumption of the flow system is that the spring water is meteoric in origin, having infiltrated from the ground surface. This has been found to be the case virtually for all normal springs, although some of the water may have been in the subsurface for a very long time and have infiltrated under very different conditions than those which currently exist in the area (Manga 2001). Thus, the flow rate, hydrogeochemistry, and temperature of a spring at any time represents a combination of flows from distributed recharge points. As the contributions from different recharge points change, the output (discharge) of the spring will vary. Hence the current study aimed at determining the dynamics of flow in springs to characterize groundwater discharge through springs.

Springs are found in the headwaters of rivers and, as a result, usually exhibit pristine water quality. This is because headwater zones are typically found in areas with little or no development, as well as few or no point sources of pollution that could impair water quality and ecosystem. Furthermore, water originating from groundwater is thought to be pure, though this may be modified by the geological properties of the formation that holds the water (Wu, 2009). The water quality of the discharging spring water is an important determinant for the ecosystem of the spring. Freeze and Cherry (1979) for instance suggest that the total dissolved solids content of the water should be one of the features by which water quality is described. Other aspects of the water quality such as oxygen content, nutrient content and organic detritus are also important. The quality of the groundwater flowing towards the spring is determined by hydrogeological conditions along the flow systems that feed the spring. Hence, the current study assessed the water chemistry of spring water [groundwater discharge] contributing to river flows in the catchment.

Thermal springs are the most researched of all natural resources worldwide including South Africa (Derso et al., 2015; Perry, 2018). The chemical content of the water in hot springs changes according to the chemical composition of rocks situated on path of the hot water flow (Rajapaksha et al., 2014). Olivier et al. (2011) indicated that assumptions that all spring water is pure should not be made, since many naturally occurring minerals are harmful or even dangerous to human and animal health. There have been different studies in South

Africa focusing on assessing the hydrogeology of springs. However, most of such studies have focused on thermal spring characterization mostly in the Limpopo province (Olivier 2008; Durowoju et al. 2019). While studies on springs (cold) focussed more on hydrogeology of springs in relation to the biodiversity of spring fauna, water chemistry and quality (Manga 2001; Gao et al. 2020; Gleason et al. 2020). Therefore, this study attempts to narrow that knowledge gap by characterizing spring hydrogeology, determining spring flow dynamics and assess the chemistry of spring water.

1.2 Problem statement

1.2.1 Research problem

GDEs are often complex, and poorly understood component of the natural environment. Spring discharge to rivers has been recognised to be important in contributing to environmental flows. Despite groundwater discharge through springs being important for sustaining river flows and water supply, they often do not feature in catchment management plans. For example, identifying actual spots for spring discharges and validating previously mapped springs remains a challenge. This is a problem because there is uncertainty about factors and conditions that are explaining the existence of springs at specific locations. The main driver to the problem is poor understanding of the relationship between springs and hydrogeology that leads to poor characterization of groundwater discharge through springs. Therefore, this study attempts to close the gap by improving the knowledge and understanding on spring hydrogeology in terms of subsurface characteristics/conditions that lead to the occurrence and distribution of springs on the surface

1.2.2 Unit of analysis

This section of the thesis describes unit of analysis upon which the study is framed and elaborates on what variables formed the unit of analysis that were investigated. The present study is about spring hydrogeology assessment. For the first objective of this study, which focuses on describing the subsurface conditions for spring occurrence, the unit of analysis was the spatial distribution of springs (spring coordinates) and geological units such as lithology. The information from the borehole logs and geological maps, existing models were compiled to construct the geological cross sections. While the hydrological framework was developed from the aquifer hydraulic parameters, groundwater level data. This means that research of the studies from Mazvimavi et al. (2017), Manyama (2017), Banda (2019), Xaza (2020) were used for the model development. For determining the flow dynamics of spring water, the unit of analysis were the flows. The focus was on measuring the flow of spring. In addition, on assessing the chemistry of spring water for establishing groundwater discharge contribution to the surface using hydrogeochemical data, the unit of analysis were the springs major cations and anions, general chemistry parameters, and radon (^{222}Rn) stable isotope obtained from spring.

1.2.3 Research question and hypothesis

The background to the problem is poor understanding of the relationship between springs and hydrogeology that leads to poor characterization of groundwater discharge through springs. To provide improved knowledge and understanding on spring hydrogeology, the current study puts forth the main research question as follows: ‘What are the subsurface conditions responsible for spring occurrences?’

The present study hypothesized that if spring hydrogeology is not characterized, then the influence of such springs on meeting the requirements to protect the environment and supply human needs cannot be met. The study aspired to answer this question and prove the hypothesis. In other words, we assume that if there is no proper understanding of the subsurface conditions that results on spring occurrences on the surface, characterisation of spring hydrogeology will remain poorly understood in terms of geological condition for their occurrences, distribution, flows and quality. The improved knowledge on spring hydrogeology enhances the water allocation process including the monitoring and protection of ecosystem environment.

1.3 Study aim and objectives

The aim of this study is to improved knowledge and understanding on spring hydrogeology. Subsurface conditions or characteristics that lead to presence of spring waters on the surface remain critical. This would provide improved knowledge and understanding of groundwater discharge for nature-based solution that enhance the water allocation process including the monitoring and protection of ecosystem environment. In addition, the improved information generated will inform the basis for better utilization and protection of spring waters in the study area. The Heuningnes Catchment in Cape Agulhas, Western Cape was used as a case study.

To ensure the study aim is achieved, the following objectives were formulated:

1. Describe subsurface conditions for spring occurrences (Characterization of spring hydrogeology)
2. Determine the flow dynamics of springs
3. Assess the hydrogeochemistry of springs for supporting socioeconomic progress and ecological integrity

1.4 Significance of the study

The study generates information on characterization of springs, flow rates and hydrochemistry of springs of the Heuningnes catchment and groundwater discharge through springs. The study will publish papers for each of the research study objectives to disseminate the research, including scientific and practical contributions, to other scholars and researchers in groundwater and hydrogeology field. The novelty of the study is seen through the knowledge advancement in spring hydrogeology and the gap in characterizing groundwater discharge through springs. In addition, three papers prepared for publications which contribute to scientific knowledge or the scholarship in the field of spring hydrogeology, water resource protection and management as follows: Paper 1 based on the first objective on the characterization of spring hydrogeology in coastal environment. The produced conceptual model of springs in coastal area showing the spatial distribution and subsurface geological make up from the observed springs on the surface. Paper 2 on flow characteristics of the springs and third paper on hydrochemistry of springs to suggest the suitability of spring water usage either for drinking or irrigation including environmental water requirements. Through the publications, scientific researchers, and practitioners with similar interests aware of new knowledge generated in the case study area and helps to advance knowledge on springs in the study area and its application in other environmental settings.

In practice, the results can be used as learning material for teaching purposes providing reference point in groundwater discharge, springs, hydrogeology, and groundwater quality topics. This information can be used as a reference for future hydrogeological studies carried out within the area. For example, the videos captured in the field that showed groundwater discharge to the surface through spring can be used for practical demonstrations. Furthermore, the calculation used to estimate the flow rate could be used to generate a clear understanding of the applicability of speed formula in groundwater hydraulics.

In addition, the study could add to the literature for researchers. Researchers can use the findings and recommendations from the current study as a database since studies on spring hydrogeology are limited and as a source for literature review. This study is part of a bigger project of spring hydrogeology however the generated findings inform policy modification and protection of water resource assessment around springs, such as the quality and quantity, which provides an insight on allocation process including the monitoring and protection of ecosystem environment. This research study aims to inform and advice on modifications around water policies in protection or assessment of resources, to better manage groundwater systems in and around springs, as it provides insight into the possible implications of using springs water quality and usage. As water regulations, water policies, and water strategies are silent on how spring water can augment the water allocation reform process in South Africa.

1.5 Scope and Nature of the study

1.5.1 Scope of the study

Hydrogeology highlights the interrelation of geological processes and materials with water. The study of springs captures both cold springs and hot springs usually referred to as thermal springs. However, the current research study is not about thermal springs but focuses on cold springs generally referred to as springs in literature. Within the cold spring topics, studies can focus on spring hydrochemistry, biodiversity of springs, flows of the spring, spring economics, public health interventions from springs, bottling spring water, springs for tourism (ecotourism), cultural activities, utilization and regulation of springs, modelling springs and other studies can focus on recharge zones of springs among others. With the diversity of studies around springs the current research study is about the hydrogeology of springs. In other words, the study focuses on establishing the subsurface in which groundwater discharges on the surface, through the investigation of springs occurring in the coastal environment of Heuningnes. The concept of hydrogeology is very broad and covers aspects like physical, chemical and environmental hydrogeology. The current research is primarily concerned with physical and chemical hydrogeology, in terms of geological condition for spring occurrences, distribution (spatial and temporal), flows (rate) and quality (chemistry and hydrogeochemical processes). The aim of this research is to provide improved knowledge and understanding on spring hydrogeology in the Heuningnes Catchment systems (Western Cape).

1.5.2 Nature of the study

The current study adopts quantitative experimental and desktops design to achieve the three objectives. The quantitative experimental design, in this case, involves field trials for the collection of spring coordinates, flow measurement, physicochemical parameter and water samples for major ions and radon isotope to achieve the objectives of the study. The desktop design, in this case, involves the collection of secondary, locations, groundwater discharge, groundwater dependent ecosystems, and springs, as well as geological and hydrogeological data sets to achieve the objective focusing on characterisation of spring hydrogeology through conceptualization for the Heuningnes Catchment. The experimental design, in this case involves physical investigation for verification and identification of the eye for actual spring locations which were used for collection and analysing water samples for major- and minor-ions chemistry, radon isotope and determining flows through measuring the speed of water to estimate flow rate. To conceptualize the effect of local hydrogeological characteristics on groundwater flow and discharge, the desktop design was utilized which involved collecting secondary data on geophysical subsurface data, discharge, geology, hydrogeology, chemistry, and isotopic data for both groundwater and surface water in study area. Geographical Information System (GIS) and software's (Surfer, Geochemist Workbench) were used as analysis tools for mapping as well as plots generation in conjunction with accumulated field data to characterize and identify preferential groundwater flow paths in respective geologic settings. The study was concerned with understanding the various subsurface hydrogeological processes and flow paths taken by groundwater before emerging on the surface as springs as well as the water quality. As a way forward into deepening understanding and knowledge on spring hydrogeology in Heuningnes Catchment.

1.6 Conceptualisation of the study

In general, the idea of assessing spring hydrogeology was conceived by the existing studies on springs and studies in the selected case study area. The idea of the research study is selected on the basis that there have been studies on surface water and Groundwater (Banda 2019, Mokoena 2019, Xaza 2020) in the study area but there is no intense research done on springs around Heuningnes catchment. Previous WRC funded studies in the Nuwejaars Catchment in the Cape Agulhas have shown that river flows are sustained by surface runoff originating from upland areas with high gradients, diffuse seepage of subsurface water along slopes towards rivers, and spring discharges. Yet stream flows during dry period with minimal rainfall occurring are reported to be sustained by groundwater discharge in the form of springs and diffuse discharge in middle and lowland areas of the catchment (Mazvimavi et al. 2021). Furthermore, the idea of spring hydrogeology was conceived from the gap identified in literature (Drew 2001, Pearson et al. 2003, Kresic and Stevanovic 2010) with more research studies in South Africa focusing on thermal springs than cold springs and those focusing on cold springs only focused on quality and utilization of springs. However, in order to better understand the catchment system, a study on groundwater discharge through springs was much needed to provide improved understanding and knowledge on spring hydrogeology. That is how the idea for the current study was conceived as it looks at the system holistically in terms of geology, flow, hydrogeochemistry, and quality.

1.7 Outline of thesis

The current study is contained within six chapters. Chapter 1 is the general introduction which provides an overview of the current research and outlines the main aim to be achieved. The study aim, the research problem, unit of analysis, research question and thesis statement, study objectives, significance of the study, scope and nature of study, study conceptualisation are outlined. Chapter 2 provides a review of numerous studies on groundwater discharge, springs, groundwater dependent ecosystem, characterization of spring hydrogeology. The chapter also outlines frameworks for the study i.e., conceptual, theoretical, research and interpretational framework guiding the current study. Chapter 3 presents physiographic description of the regional setting of the study area along with those of study sites. The research design and methodology, data collection and analysis methods, quality assurance and control, statement of ethical consideration and limitations of the study are presented and outlined in Chapter 4. Chapter 5 presents and discusses the findings objective by objective, starting with results on subsurface characteristics (flow-path identification) that leads to the presence of the springs on the surface, through a conceptual model of spring hydrogeology characterisation. In addition, demonstrating results from the determination of flow dynamics of springs. Chapter 5 also presents and discusses finding from the assessment of hydrochemistry of springs using hydrogeochemical data and radon isotope for various interpretations about the groundwater discharge system through springs. Ultimately, Chapter 6 provides a summary of the current study with highlights of major findings from each objective and recommendations for future studies on spring hydrogeology systems.

Chapter 2: Literature review

2.1 Introduction

Chapter one has provided the general introduction of the current study in terms of scientific research problem, research question, hypothesis, objectives, and the significance of the study. In this chapter two, a review of previous studies was provided such a review is presented in terms of what is known and what is not known about spring hydrogeology/groundwater discharge in different settings around the world, and within the study area in order to understand how springs sustains water resources. Three objectives were set as follows: 1) Describing sub-surface conditions for springs occurrence 2) Determine the flow dynamics of springs 3) Assess the hydrogeochemistry of spring. The reviewed literature has been presented systematically (objective by objective) and analytically (showing the gap in knowledge) to show how the current study narrowed such gap. The general overview on groundwater discharge with focus on characterizing spring systems in coastal environment has been presented. Principles and concepts that guide spring hydrogeology are explained. In this chapter, the argument is that groundwater discharge through springs needs to be evaluated first before establishing their influence on the environment and for human needs. The previous studies were reviewed from global, regional, and national level perspective to contextualise the current study at such levels. The chapter ends with a review on frameworks that guide the current study such as theoretical, conceptual, interpretation and research frameworks for the study.

2.2 Groundwater occurrence: Spring hydrogeology

One of the most important resources on the planet is groundwater, which is water that exists in the pore spaces and fractures in rocks and sediments beneath the Earth's surface. According to Freeze and Cherry (1979) groundwater is characterized as water that occurs below the subsurface in soils, fractures, and permeable geological formations. In general, it accounts for the majority of the world's available freshwater. It begins as meteoric vapour from precipitation in the form of rain or snow. Some of the water is lost due to evaporation, transpiration, and stream flow; only the excess water infiltrates the subsurface, where it is stored as groundwater in saturated or unsaturated zone separated by the water table. The hydrological cycle is the most fundamental principle of groundwater hydrology, which is a conceptual model that describes the uninterrupted flow of water above, on, and beneath the subsurface (Figure 2.1). Groundwater is a valuable water resource that can be used to supplement water needs for current and future generations. Understanding groundwater occurrence is critical for future groundwater exploitation and management. Therefore, the current study aims at understanding the mechanism of groundwater discharge as fundamental to elucidate groundwater occurrence on the earth's surface.

Groundwater occurrence can be explained through water cycle which includes groundwater processes involved in water entering and leaving the groundwater system are known as recharge and discharge (Amend 2012). The balance between the amount of water that infiltrates into the ground and evaporation/transpiration losses is known as recharge and to maintain a groundwater resource, enough recharge to an aquifer system is required (Mazor, 2004). Recharge occurs when precipitation falls on the ground surface, generally in mountainous areas, at a pace that is sufficient to compensate for and exceed the soil moisture deficit (Figure 2.1). The ability of the rock to store and transmit water make up the hydraulic properties of that rock (Weight, 2008). The dominant factors controlling groundwater flow (movement) are topography and geology. With the two key controlling factors, they determine where the water moves/flow in the subsurface, depending on porosity (the amount of open space in the material) and permeability (how easy or difficult it is for water to move) (Freeze and Cherry 1979). The drainage of groundwater from subsurface aquifers is known as discharge, can occur through vegetation, surface water bodies, and natural springs among others. In all of its manifestations, groundwater discharge is controlled by the interplay between subsurface geological structure and landscape. Although groundwater processes have been highlighted, the current study focuses on groundwater discharge. However, discharge cannot investigated without understanding other mechanisms.

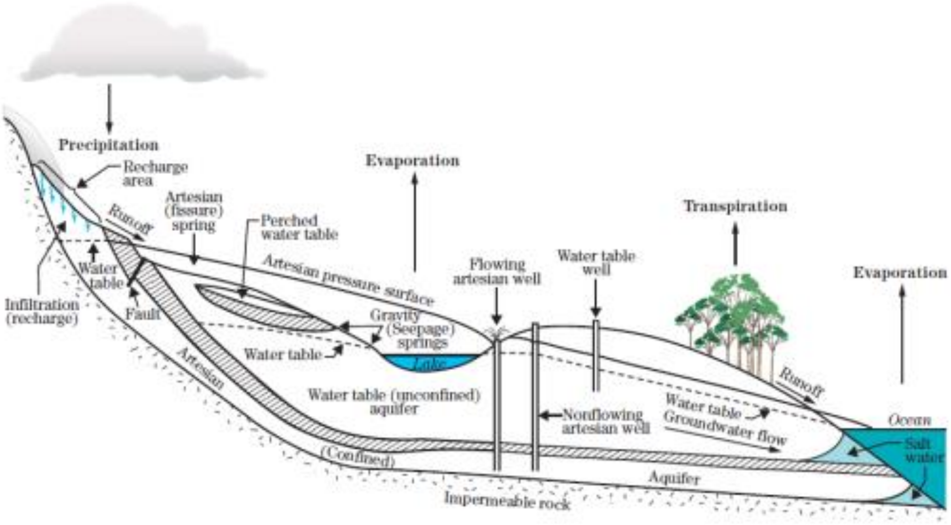

Figure 2.1 : The hydrological cycle showing the subsurface and surface flows of water in the environment (Amend 2012).

Groundwater discharge can happen all over the place, such as when vegetation is dependent on groundwater. Discharge can also occur in places with a single point of origin, such as natural springs. Groundwater can also discharge onto surface water bodies like rivers and lakes in some instances. Amend (2012) defined a spring as a natural outflow of water from an underground supply to the ground surface Therefore, it is necessary to understand how groundwater occurs in the region and the various characteristics of these features, as they have decisive influence over groundwater movement and localization.

2.3 Previous studies on groundwater discharge

Groundwater discharge had been studied extensively from different angles and in different parts of the world. Most of these studies had been focusing more on aspects such as groundwater surface water interactions, groundwater flow modelling and groundwater quality, and governance issues in relation to groundwater use activities for particular areas. The current study focuses on three aspects of hydrogeology which are chemistry, groundwater flow system, conceptualization for the Cape Agulhas in relation to spring hydrogeology and is using Heuningnes Catchment as the case study.

Groundwater discharge is one of the more complicated aspects of the hydrological cycle to predict, but it is becoming increasingly important for future economic growth. Groundwater is occurring in different geologic formations and topographic features; those factors mostly control the distribution and development of groundwater. Messene (2017) investigated groundwater potential of the Lower Gidabo Catchment, Rift Valley Basin, Ethiopia catchment by exploring groundwater flow direction, recharge and discharge zones. The data secondary data sources used included land use, geologic, and soil data, completion reports of pump test boreholes data, geologic well log data, and features of boreholes and hand drilled wells, for the analysis. Surfer 8 and Arc GIS 9.3 programs were used for the study to realize groundwater flow direction, recharge, and discharge zones. The results from groundwater flow lines and contour maps showed that groundwater was flowing in a western direction from the eastern highlands of the catchment to the plain regions. With the largest recharge of groundwater occurring in the highlands of the catchment, which was referred to as a recharging region and other sections of the area were concluded to be discharge zones (Messene 2017). This study adopted methods and software's used by Messene, (2017) on discharge zones to characterize spring flow system.

Groundwater discharge is geographically, spatially, and temporally variable from the reach to the basin scale in terms of water quantity. Groundwater delivery to surface water bodies is aided by reach scale preferred flow pathways in the subsurface. Hiscock and Bense (2014) suggested that in unconsolidated strata, the lithology and stratigraphy become the most important controls of groundwater flows. Fleickstein et al. (2006) stated that the hydrologic connections among groundwater and surface water bodies is through the subsurface horizontal passage, through the unsaturated soil and by penetration into or ex-filtration from the immersed zones. Pandy and Kazama (2011) analysed the spatial variations in hydrogeologic characteristics of shallow and deep groundwater aquifers in Kathmandu Valley to estimate transmissivity. To map spatial distribution in hydrogeologic characteristics Geographic Information System (GIS) technique were used and such maps were useful in delineating potential areas for groundwater development and simulating groundwater flow in the aquifer system. Therefore, characterizing aquifer system that support spring flows in non-perennial river systems remains critical aspect that requires data to support its ecological value. Although the current study was not on aquifer parameters but some of the techniques used by Pandy and Kazama (2011) were used to map geographical and spatial distribution of springs.

From the South African context, Roets et al. (2008) developed an integrated conceptual understanding on groundwater interaction with aquatic ecosystems in the Table Mountain Group (TMG). The aim of the study was to characterize the groundwater dependence of the aquatic ecosystems (streams, rivers, springs, seeps and wetlands) associated with the TMG aquifer. The purpose was to determine whether coastal wetlands in lowland environments are dependent on deep circulation limited TMG aquifer groundwater. Both lowland wetlands are in the coastal zone of the southern Cape. The analysis of the model revealed a definite and intimate link between the TMG aquifer and aquatic ecosystems, especially those located in the mountain and foothill areas of the TMG and those located at the discharge end of the aquifer. The observed results suggested that the properties of the TMG aquifer system of having huge fracture systems inside the TMG arenites had the potential to be key water resources due to their ability to contain large amounts of water along fracture system flow routes as supported by De Beer (2002). Roets study addresses objective 1 of the current study, however, the current study aimed at characterising the springs as groundwater dependent ecosystem whereas Roets et al. (2008) focused more on wetland dependency on groundwater. The current study, however, expects geological group which corroborate with those of Roets et al. (2008).

Different methods have been used to assess the interaction between aquifers and rivers. Brodie et al. (2007) documented a wide range of methods including seepage measurements, field observations, ecological indicators, hydrogeological mapping, geophysics and remote sensing, hydrographic analysis, hydrometric analysis, hydrochemistry and environmental tracers, artificial tracers, temperature studies, water budgets and the use of modelling. They argued that some methods, such as field observations or chemistry, are also employed to provide critical information on catchment scale connections as well as targeted locations for further inquiry. Meanwhile, simple equipment like seepage meters or mini-piezometers can be used to gain a thorough understanding and quantification of key processes. Brodie et al. (2007) pointed out that it is critical to employ a variety of methodologies in order to validate the interpretation and extrapolate findings across place and time. This study focuses on identifying the methods used in various groundwater discharge studies which can provide an understanding on groundwater discharge within the bigger aspect of interaction at local scale.

Radon is a radioactive noble gas that occurs naturally. Radon fulfils all the requirements for usage as an environmental tracer due to its extensive occurrence in nature, chemical and physical properties, and easy detection (Briganti et al. 2018, Schubert 2015, Strydom 2021). Radon concentration in groundwater is mainly due to alpha recoil processes from aquifer rock and, to a lesser extent, to dissolution and decay of radium-in-water (Briganti et al. 2018). The radon concentration in the pore space of an aquifer or soil is determined by the emanation coefficient, porosity of the aquifer, radium activity concentration, and bulk density of the mineral matrix (Schubert 2015). Rn222 concentrations, tend to increase along faults and fractures, particularly when aquifers have been exposed to tectonic activities (Strydom 2021). Therefore, the lithology of the aquifer material influences the concentration of Rn222 found in the aquifer. Rn222 is produced in various lithological structures and subsequently transported with groundwater through fractures and pore spaces in an aquifer towards surface water discharge points in rivers and springs.

Environmental isotopes have been used for decades as natural tracers in studies aimed at understanding complex hydrogeological processes such as groundwater and surface water interactions. Strydom et al. (2021) used radon isotopes to detect groundwater discharge in streams draining TMG aquifers, South Africa with the aim of determining the concentration of Rn222 within both surface water and groundwater in TMG aquifer systems, and the feasibility of using Rn222 isotopes as a natural tracer in groundwater-surface water interaction studies. The study found that Rn222 concentrations in the surface water samples exceeded 100 Bq\L. These abnormally high Rn222 concentrations were attributed to the influx of groundwater with extremely high Rn222 concentrations. Under ambient (no pumping) conditions, Rn222 concentrations in groundwater ranged between 391 and 593 Bq\L. These extremely high Rn222 concentrations in groundwater were attributed to the underlying granitic geology and the prevalence of faults. The study concluded that the use of Rn222 isotopes as an environmental tracer in groundwater–surface water interaction studies is therefore regarded as a feasible option in similar highly fractured aquifer systems. Therefore, the study by Strydom et al. (2021) informs objective 3 of the current study on the use of radon as an environmental tracer.

2.4 Groundwater Dependent Ecosystem: Spring hydrogeology

Groundwater dependent ecosystems are ecosystems which depend on groundwater in, or discharging from, an aquifer (Hiscock 2005, Klove et al. 2011). They are distinctive because of their connection to the aquifer and would be fundamentally altered in terms of their structure and functions if groundwater was no longer available (Hiscock 2005). Groundwater discharge is controlled by climate variability and the rock type of the aquifer that provides water, nutrients, and a relatively constant temperature (Colvin et al. 2007). Ecosystems are divided into aquatic (e.g., wetlands, springs, and lakes) and terrestrial (e.g., forests and grass-lands) types. Both types comprise partly or entirely groundwater-supported species, seasonally or all-year round. In arid and semi-arid regions with non-perennial rivers, many GDEs (e.g., seepage wetlands) are seasonally supported (Majola et al. 2022). In many cases within the variety of aquatic and terrestrial ecosystem, groundwater makes an important contribution to sustain health of groundwater dependent ecosystem, yet they are poorly documented (Kløve et al. 2011). Groundwater is often the main source of water for vegetation in dry climates. International agreements emphasize the protection of groundwater dependent systems and the services they provide as some systems, such as springs, are completely fed by groundwater and would not otherwise exist. This is reflected in the fauna and flora, with many species adapted to these unique conditions in and around springs. Thus, the study aims at understanding the degree of dependency of aquatic ecosystem with focus on springs within different seasons.

Groundwater dependent ecosystems occur at a variety of scales within the landscape and occur throughout the South African landscape in areas where groundwater flows and discharge influences ecological patterns and processes. The presence of diverse GDEs across a landscape is driven by temporal and spatial groundwater flow variability that is related to geology, climate, and land use. These ecosystems require groundwater from aquifers for all or part of their life cycle, to maintain a habitat with a water budget, or water quality that contrasts with the surrounding ecosystems. South African study by Colvin et al. (2007) mapped national potential GDEs whereby broadly similar habitat types (e.g., riparian) and hydrogeological characteristics that control aquifer discharge regimes linked to ecosystems were grouped into categories and mapped. For example, Colvin et al. (2007) highlighted the key variety of types and scales of GDEs which can be simplified into type-settings based on principal aquifer types (based on lithology) and habitat types within hydrogeological settings in South Africa. Although, the current study is not focusing on all the GDEs but rather focuses on the influence of spring characterization on meeting the environmental requirements and supply human needs.

In investigating the hydrogeological characteristics of groundwater discharge in terms of understanding their underlying conditions that control discharge, it is important to be clear on the terminology. Many researchers and scholars have used different ways to define springs for various fields (Amend 2012, Kresic and Stevanovic 2010, Colvin et al. 2007). Although most dictionaries of geologic and hydrogeologic terms would have similar definitions, it is surprising how many interpretations of the word exist in everyday practice, depending on the circumstances. For example, Amend (2012) defined a spring as a natural outflow of water from an underground supply to the ground surface. Kresic and Stevanovic (2010) defined a spring as a location at the land surface where groundwater discharges from the aquifer, creating a visible flow. Meinzer (1923) defined springs based on the consistency in flow and grouped the spring classes as continuous, seasonal, or occasional. Furthermore Colvin et al. (2007) defined it as a place, usually a distinct point or small area, where groundwater emerges generally because of topographical, lithological or structural controls on groundwater movements.

Gleason (2020) described a spring as a concentrated discharge of groundwater that emerges on the surface as a stream of water that flows spontaneously from a rock sediment or soil. While Durojowu (2019) provided a broader definition suggesting springs as natural geological phenomena that originate either from geologic platonic activity or from rainwater that percolates into the ground through permeable rocks or via conduits such as joints, faults and fracture zones in less permeable rocks (meteoric origin). The current study adopted the definition of Amend (2012) who defined springs as water naturally flowing from bedrock or soil onto the land surface.

Springs can be visualised as points of focused groundwater discharge from groundwater flow systems. Flow systems transport groundwater from recharge areas to discharge areas under the influence of pressure as well as gravity. The concept of groundwater flow systems has been found useful in hydrogeology to describe the patterns of flow and chemistry in the subsurface (Freeze and Cherry 1979). Changes in spring flow are believed to have influenced river base flow and water stress in associated riparian species. The basic assumption of the spring flow system is that the spring water is meteoric in origin, having infiltrated from the ground surface. This has been found to be the case for virtually all normal springs, although some of the water may have been in the subsurface for a very long time and have infiltrated under very different conditions than those which currently exist in the area. The current study wants to confirm these using springs in coastal environment.

The combined use of various geochemical and hydrologic tools can considerably enhance the understanding of complex groundwater flow patterns as well as the mixing of groundwater and surface water in a particular spring. For instance, Manga (2001) used springs to study groundwater flow and active geologic processes. The study collected and interpreted measurements of isotopic tracers, water chemistry, discharge, and temperature to determine the mean-residence time of water, infer the spatial pattern and extent of groundwater flow. It was concluded that springs provided access to water that has recharged in distant regions, springs provided discharge water from distant periods in time and preserve information about paleoclimate. Thus, the current study adopted methods from Manga (2001) to infer spatial chemical patterns of spring waters to address objective 3 of the research.

Groundwater flow paths vary greatly in length, depth, and travel time from the recharge areas to discharge areas such as springs. These flow paths are informative parameters as they provide information about type of springs. Springs can be classified using a number of criteria. In the literature reviewed, spring classifications are usually based on either physical characteristics or occurrence parameters such as geology, magnitude, variation, permanence of flow, quality, mineralization, and temperature of spring water. Kotze (2001) developed a spring classification with three types of groundwater discharge pathways. Shallow seasonal springs and seeps emanating from perched water tables; represents localised discharge of interflow, not connected to the groundwater flow system, and are not impacted by groundwater abstraction were classified as type 1. While Type 2 grouped lithologically controlled springs, often discharges at lithological contacts with flow being more permanent and plays an important role in sustaining baseflows and such springs are susceptible to the impacts of localised groundwater abstraction. Furthermore, type 3 grouped fault-controlled springs that are permanent in character, they may discharge either hot or cold water and are only potentially impacted by large scale regional abstraction. Using the spring classification system proposed by Kotze (2001), springs in low-lying areas have a higher probability of being groundwater fed springs (Type 2) than those on the slopes of mountains. Those in topographically elevated areas are probably perched springs (Type 1 springs above the water table), but cognisance must be taken of structurally and piezometrically controlled springs (Type 3) such as hot springs and artesian springs. The study adopted the spring classification of Kotze (2001) that addresses objective 1 of the current study on the characterisation of spring hydrogeology.

The survival of GDEs depends on the presence of suitable groundwater characteristics. Identifying these characteristics is critical because it helps in the development of groundwater monitoring strategies (Kreamer et al. 2015). One of the most significant groundwater attributes for GDEs springs is the depth-to-groundwater (from the land surface) as it maintains the hydraulic gradient for groundwater discharge, therefore providing wetness

(Eamus et al. 2016). This is especially true for terrestrial ecosystems that depend on subsurface groundwater supply. The groundwater pressure is essential to hydraulic head and its expression sustains groundwater discharge to springs, while the fluxes influences the flow rate and volume of groundwater supply as well as flow direction. The groundwater quality is also an important attribute as it maintains suitable chemical composition in water supply and living environments. Hence the current study desires to understand these groundwater attributes to better elucidate the spring system in the coastal study environment. Therefore, the discharged groundwater through springs to support ecosystem health in non-perennial river system were evaluated.

2.5 Groundwater discharges: A synthesis of cold and hot springs

Groundwater discharge is frequently critical for maintaining or restoring significant ecosystems in surface water or at the groundwater-surface-water ecotone. Groundwater discharge is difficult to detect and quantify because flow rates can be very low, exchange is often highly heterogeneous both in space and time, and surface-water hydrodynamics can both impact the exchange and hinder measurements (Pandy and Kazama 2011). The source of every major river in the country is represented by a system of springs that is often religiously revered. Springs have been a significant source of water since the beginning of human history and the only source capable of supplying enough water to sustain domestic and agricultural water supplies, however, spring related information continues to lack. Springs are natural point sources of groundwater discharge and are indicated by locations or points on the ground surface, where water from beneath the ground emerges on to the surface. They are often a clean, reliable water source that can support the establishment of an entire community (Van Sickle, 2016). Springs occur in geomorphic settings that are far more complex than those of most wetlands, emerging from hill slopes, cliff faces, and beneath other bodies of water (Klove et al. 2011). Adding to their complex emergence environment, springs often support a wide array of microhabitats not observed in wetlands. Although springs emerge onto the surface and may be treated as surface water after they discharge, they are part of a sub-surface system of aquifers that follows hydrogeological principles that needs to be understood. Hence, the focus of present study was to characterize the spring hydrogeology in the coastal environment.

Groundwater discharge through springs may vary in terms of temperature, flows, water quality and origin. Temperature of spring waters may vary from mean atmospheric temperature lower or higher, even to boiling temperatures. These springs may be divided according to temperature into thermal and non-thermal springs. Most non-thermal springs have temperatures that are approximately the same as the mean annual temperature of the air of the region in which they are found. Whereas thermal springs are those whose water has a temperature that is much higher than the mean annual temperature of the atmosphere in the region of the spring. For instance, Kresic and Stevanovic (2010) specified that the temperature of non-thermal springs generally reflects groundwater residence time and flow paths. As depth below the Earth's surface increases, temperature increases due to deep circulating groundwater being warmed up. If groundwater velocities are low and the springs are small, most of the heat will be conducted through the rocks and the water will remain cold (Niggate et al. 2020). However, when the springs are large, the spring water also will be cold because the volume of water is greater to be adequately warmed. Yet, another spring may be present with its temperature varying depending on the precipitation pattern, seasonal influences, and the mixing mechanism of waters with different temperatures. Hence, the current study assessed the quality of the springs to answer the research question; What are the subsurface conditions responsible for spring occurrences?

Springs occur in geomorphic settings that are far more complex than those of most wetlands, emerging from hill slopes, cliff faces, and beneath other bodies of water. Adding to their complex emergence environment, springs often support a wide array of microhabitats not observed in wetlands. There are many monographs on thermal springs. To date over 90 thermal springs have been identified in South Africa, of which the Limpopo Province has more than any of the other provinces. A number of hot springs in Limpopo have been developed for recreational and tourism purposes, and at some water is bottled and sold for therapeutic purposes (Durowoju 2019). The majority of hot springs discharge groundwater heated by magma (molten rock) intrusions in volcanic areas. However, some thermal springs are unrelated to volcanic activity. Due to no proof of recent volcanic activity, it is generally assumed that all thermal springs in the country are of meteoric origin and are associated with faults and impermeable (Rajapaksha et al., 2014). In such cases, groundwater percolating downward approaches depths of a kilometre or more, where the temperature of rocks is elevated due to the natural temperature gradient of the Earth's crust, and the water is heated by convective circulation. However, the current study is not about hot springs but on non-thermal springs as it has characterized cold springs in coastal environment.

In South Africa, about half of the documented 74+ thermal springs have been developed for family leisure and recreational resorts alone, while the rest remain undeveloped. In comparison with global trends, South African geothermal resources appear to be under-utilized. Groundwater moving through the TMG aquifer system transports substantial quantities of heat and thereby alters the subsurface temperature field, so that the measured heat flow in overlying stratigraphic units, such as in the Bokkeveld Group is locally lowered (and may locally be raised elsewhere around discharge points). Olivier et al. 2011 assessed thermal and chemical characteristics of hot water springs in the northern part of the Limpopo Province, South Africa. The objective of the study was to determine the optimal use of a thermal spring as they are largely dependent upon their physical and chemical characteristics. Field data and water samples were collected for analysis of physical and chemical parameters. The classification used for South Africa, as proposed by Kent (1949), was as follows: 25-37°C = warm; 38-50°C = hot or hyperthermic; >50°C = scalding. Results showed that the temperatures at source vary from 30°C to 67.5°C ranging from warm to scalding in temperature. The mineral composition of the thermal waters reflected the geological formations that occurs at the depth of origin of the thermal spring water rather than surface geology, since adjacent springs have disparate chemical properties. The springs were discovered to be associated with faults and impermeable dykes and are assumed to be of meteoric origin. The above study served as reference/guide in terms of physical and chemical composition to be monitored on a regular basis for understanding spring water quality, informing objective 3 of the study.

South African thermal springs generally have low flow rates in comparison with volcanic countries where fumaroles and geyser type thermal springs occur. Brandvlei, in the Western Cape had the highest flow rate of 126 l/s and was found in an area with an annual rainfall exceeding 600 mm. The flow rate at Brandvlei has remained constant over the last 50 to 60 years but this is not the case with a low-flowing spring such as Siloam (Kent 1969). The Siloam spring had a flow rate of 0.15 l/s measured in 2004, decreasing to a mere trickle in 2008, and increasing to just over 1 l/s in 2012. Other springs such as Winburg (Free State), Icon, Constantia and Masequa (Limpopo) have dried up completely. The reason for this is not known but may be due to decreased rainfall in catchment regions or increased groundwater extraction for domestic and agricultural purposes (Olivier et al. 2008). Where rock permeability is low, groundwater flow velocities are low. In rocks with high permeability, flow velocities are high because high permeability also results in large volumes of circulating water (Hartnady and Jones, 2007). Hence, the focus of present study was to determine the flow dynamics of cold springs however not in Limpopo and Free State but in Heuningnes catchment, Western Cape.

Minerals are generally more soluble in hot water and thus thermal springs are often enriched with trace elements. Certain minerals dissolve more readily than others and some rocks are richer in minerals than others. Durowoju (2019) assessed isotopic signatures and trace metals in geothermal springs and their environmental media within Soutpansberg. The study was aimed at elucidating on the isotopic signatures and trace metals concentrations from the geothermal springs to their environmental media in Soutpansberg region. The data collected was analysed for physicochemical, geochemical and isotopic compositions of the geothermal springs and boreholes. The results from this study by Durowoju (2019) showed that the studied geothermal springs and boreholes were classified according to their temperature as hot and scalding. The δD and $\delta^{18}O$ values of the geothermal spring water confirmed that the waters was of meteoric origin, which implied that rainfall was the fundamental component of these groundwaters. The dominant water types were Na-Cl and Na-HCO_3 which were typical of marine and deep groundwaters that are influenced by the ion exchange process. The geochemical processes controlling the geothermal spring chemistry were demonstrated through Gibbs diagram and all the geothermal springs were grouped in rock-water interaction zone. Although the current study is not focussing on thermal spring rather cold springs, however knowing the origin of springs especially for spring-fed rivers remains critical to sustain the flows in non-perennial river systems. Therefore, the current study would want to assess the hydrogeology of springs in the selected study sites to evaluate geological characteristics of this natural phenomenon to conclusively understand the origin of each individual spring in the study area and associated geological structures determining their quality.

Graphical data analysis provides visual summaries of data which more quickly and completely describe essential information than do tables of numbers. Graphs are essential to provide insight for the analyst into the data under scrutiny, and to illustrate important concepts when presenting the results to others. Olivier et al. (2008, 2011) and Saeze and Rikhotso (2013) studied the chemical composition of thermal springs in Limpopo. Piper diagrams were used to assess the influence of geology on thermal waters (developed by Piper 1944). These, trilinear diagram with Gibbs plot (Gibbs 1970) were used by Saeze & Rikhotos

(2013) to determine geochemical processes affecting groundwater chemistry in Limpopo. They found that thermal springs in Limpopo can be subdivided into groups according to the chemistry composition, i.e., springs emanating from gneissic rocks depict sea water type NaCl. The other group of springs originated from basalt rocks and their typical composition is $NaClHCO_3$, while the other grouped between fresh water ($CaHCO_3$) and sea water type NaCl. Weathering of aquifer material was the dominant process controlling the chemistry of groundwater apart from three springs that seemed to be controlled by crystallization. Although the current study is not investigating thermal springs, the parameter and methods used for analysis were taken into consideration when assessing the spring water quality and some expectation from the quality of fractured environment.

Research that expands our understanding of the potential and limitations of spring resources has not focused much on springs that are located outside of karst environments. Most research work on springs focused on thermal spring resources, and biodiversity around springs (Olivier 2008; Rajapaksha et al. 2014; Derso et al. 2015; Perry 2018; Durowoju 2019). However, based on this dominance of research on thermal spring, this study has seen that there is inadequate information on cold springs. More information was generated and published on hot springs but there was little on cold springs other than biodiversity, hence the current study investigated cold spring for their occurrences, distribution, flows and quality. Groundwater is often misinterpreted because of the lack of knowledge of time and space scales associated with the response of groundwater flow to natural and anthropogenic stresses. These groundwater flow systems occur at different scales both in time and space.

Flows from cold springs have not been measured over time and space, hence there is little information regarding their reliability and yields during different periods of the year. For cold springs, the study hypothesised that groundwater velocities are low in the subsurface and most of the heat was absorbed in the rocks and the water remained cold. It was anticipated that the occurrence of cold springs in the area were geologically controlled, and the source of cold springs could be due to local and regional recharge with short and long residence time respectively. Hence, the current study investigated the occurrence of cold spring in the coastal area and their linkage to ecosystem in terms of their yield and quality in sustaining river flows.

2.6 Characterization of spring hydrogeology

Spring catchments are frequently dominated by hard rocks comprising intact rock bodies separated by discontinuities termed fractures. Rehrl and Brick (2010) described spring catchments as often composed of fractured or karstified hard rocks, with large parts of these areas tending to focus flow via solutions conduits toward prominent points of outflow, the karst springs. Depending on the type of rock, the porosity of intact rock bodies ranges from nearly zero to values much higher than the porosity created by fractures. The permeability of intact rock bodies is often relatively low though. Thus, discontinuities provide the major flow paths in fractured rocks. Dissolution of soluble rocks, such as limestone and dolomite, causes widening of fractures, thus creating karst aquifers with a third type of porosity, the highly permeable solution conduits. Since the karst conduit system is often regionally well connected, karst springs may drain large catchment areas and thus frequently provide a high discharge. This makes them an obvious choice for water supply purposes. In fractured rocks, discontinuities provide the main flow paths. Given the ecosystem's reliance on groundwater, one of the most important topics for managers of water resources is how discharge changed over time. Hence the current research study investigated spatiotemporal analysis of springs in the coastal environment.

Identifying long-term trends and understanding general seasonal water availability on a basic level, a record of discharge is important. The defined classes of spring’s perenniality are based on the consistency in flow and Meinzer (1923) grouped the spring classes as continuous, seasonal, or occasional. Springs are viewed as perennial if they discharge water continuously and generally, they are large, thus even in low flow periods they continue to discharge, or intermittent if their discharge is normally delayed or inconsistent. In addition, discontinuous springs may flow consistently at hourly or every day (e.g., a few fountains), occasionally, yearly, or inter-annually, or just on inconsistent basis. Springs are widely recognized for their physical diversity and are abundant point sources of biodiversity and productivity that often have substantial ecological, socio-cultural, and economic function and value (Stevens et al. 2020). However, the contribution of these groundwater dependent ecosystem in maintaining river flows in which they flow in remains poorly investigated. Therefore, the current study determined the temporal consistency of groundwater discharge through springs and the impact of spring flows due to discharge fluctuating for water resource protection.

Understanding the temporal and spatial variability of water sources within a basin is vital to interpret hydrologic controls on biogeochemical processes and to manage water resources. Gao et al. (2020) used water quality data of the four major spring groups situated in the karst area of Jinan in the Northern China. The aim of the study was to determine the temporal variations of spring water quality and characterize the flows as well as identifying the major influence factors, causing spring water changes. The study analysed the temporal variation characteristics of spring water, through the long-term data of water quality (four spring groups), spring discharge, precipitation, groundwater exploitation, and urban land area in the study area. Graphical data analysis method such as piper and durov diagram, were the effective tools utilized for determining water types. Descriptive statistics and correlation analysis were utilized. To evaluate the quality of spring water, hydrochemical characteristics of the water were analysed. The study showed that the hydrochemistry was mainly controlled by the dissolution of calcite, dolomite, and gypsum, as well as the occurrence of de-dolomitization in the study area (Gao et al. 2020). The hydrochemical type evolved from Ca-HCO_3 to Ca-HCO_3-SO_4 or Ca-Mg-HCO_3 as the spring water flow experienced stages, from decline to recovery. The study concluded that the exploitation of karst groundwater, change in land use, and decrease of atmospheric precipitation were among the most important factors affecting spring discharge dynamics. The study recommended that the protection of spring water should be carried out simultaneously from two aspects: spring water quality and spring water flow. Although the setting of the above study is different to that of the current study; however, the current study applied similar methods as the above study to determine factors influencing dynamics of spring discharge.

It is essential to understand the underlying geology and related aquifer and flow systems, spatial and temporal variability in the GDE–groundwater connection, and ecosystem composition (e.g., vegetation types) when investigating and monitoring GDEs. Gleason et al. (2020) assessed the hydrogeology of desert springs to determine the geologic controls on, flow paths, and mean residence times of springs in the Panamint Mountains, California, USA. The aim was to identify rock units that supports groundwater flow to springs and the residence times of these springs. The study used environmental isotopes and evaluation of the dissolved major ion concentration which were used to infer groundwater flow path and mixing processes. Results showed that the major geologic controls on spring occurrences was discovered to be the fault system as most sampled springs groundwater flow path emerged at faults and four springs were not flowing during 2017 sampling campaign, yet they were flowing in the 1990s and 2000s. All springs were at least partly supported by recharge in and flow through dolomitic units with dominant water types as Ca-HCO_3 and $CaSO_4$, thus the geochemical composition of springs was largely explained by the dissolution of dolomite and gypsum with concurrent precipitation of calcite (dedolomization). Therefore, Gleason et al. (2020) informs objective 2 of the study and some of the methods were used to characterize spring and their flow dynamics.

The temporal and spatial aspects of groundwater flow and water supply issues in hydrologic systems are addressed through the understanding of the origin of groundwater. The composition and temperature of groundwater as it passes through an aquifer will change depending on the aquifer. As a result, hydrologic investigations revealed details about a region's subsurface geology. For example, Baioumy et al. (2014) discussed the potential sources and the origin of hot springs by considering their geological settings in the tropical rain forest of Malaysia. It was discovered that the common feature of the spring in the area was they were located either in or close to granitic masses or along the major fault or shear zones. Other thermal springs occurred at the granitic-sedimentary contacts or within sedimentary rocks near the granite contacts based on their geological setting. The source of water was derived either from the surface water which entered the underground passages (fractures and faults) and circulated to greater depths and attained the high temperature or it originated from the old water in the aquifers. While the chemical composition of the hot springs water was characterized by relatively high SO_4 concentrations. Thus, spring water aids in understanding the processes that occur over the entire subsurface and history of transport. Hence the current research assessed the hydrogeology of springs in terms of geological condition for their occurrences, distribution, flows and quality both in time and in space.

Subsurface characterization requires the spring-river interface, which is located near river bodies and actively controls the transfer of nutrients, pollutants, and water between spring systems and the river environments. The spring-river interface is difficult to characterize with direct observations due to geological, hydrological, and biogeochemical heterogeneity. Characterizing properties and processes need to consider the geophysical applications in subsurface structure, mapping zones of spring-river connectivity, and monitoring hydrological processes. For example, Parlov et al. (2016) made the hydrogeological and hydrogeochemical investigations from the faulted and fractured structural setting of Ivanščica

Mountain located in Republic of Croatia. Hydrogeological mapping was undertaken on approximately 20 km^2 (at a scale of 1:25000), with 41 springs recorded and water samples were taken from 10 springs. The main characteristics of the southern slopes was the occurrence of periodic springs at high altitude and the occurrence of permanent springs (and permanent surface flows) at lower altitudes. The hydrogeological map was constructed using ArcMap 10.1 software. The results for the basic chemical composition of water plotted on the piper diagram revealed the chemical composition of water from springs were $Ca\text{-}HCO_3$, $Ca\text{-}Mg\text{-}HCO_3$ and $Mg\text{-}Ca\text{-}HCO_3$ types. These hydrochemical facies were assumed to be a result of dissolution of carbonates, limestone, and dolomite. Therefore, understanding on the hydrogeology of springs in terms of geological condition for their occurrences, distribution, flows and quality requires the subsurface to be characterized to improve knowledge on spring hydrogeology which enhances the monitoring and protection of ecosystem environment.

Chemical characteristics of groundwater play an important role in assessing and classifying the quality of water. Hydrochemistry is of prime importance in deciding about the quality of groundwater supply. Al-Khashman et al. (2017) monitored and assessed spring water quality in Southwestern Basin of Jordan. The goals were to study the chemical, physical and biological characteristics of spring water and characterize the suitability of the springs water for drinking and agricultural purposes. Temperature, conductivity, dissolved oxygen, pH, major cations, major anions, and trace metals were all measured in the water samples. The in-situ measured temperature for the water samples ranged between 16.31˚C and 24.30˚C. The results revealed strong positive correlation between Na^+ and Cl^- indicates the dominance of Na-Cl rich recharge water from coastal origin. The high conductivity of the water samples corresponded to the high concentrations of dominant ions, which was concluded to be from ion exchange and solubility of rocks in aquifer. The findings demonstrated that the assessed water samples indicated that groundwater, in general, was chemically suitable for drinking and agricultural uses. Therefore, the parameters assessed in the study by Al-Khashman et al. (2017) inform objective 3 of the current study on the hydrochemistry of spring waters.

The spatial and temporal differences in spring-river interaction are important in scientific monitoring of water supplies and aquatic ecosystems. Their properties and processes are therefore spatially and temporally heterogeneous. Heterogeneity in coastal deposits can influence permeability, subsurface residence times, and zones of exchange. In addition, the classification of springs is based on the rock structure and the force that results in groundwater discharge. Temporal variability is thus influenced by hydrostatic forces that determine locations and timings of spring- river interactions, the interaction of GW discharge and consequently biogeochemical reactions. Ordinary springs are divided into gravity and artesian springs, and springs are classified according to the character of their openings (Bryan 1919). Therefore, field methods that provide spatially and temporally complete data sets about geological and hydrological information at site were used to understanding the spatial and temporal variability of springs to interpret hydrologic controls on biogeochemical processes and to monitor spring water resources. Therefore, field methods that provide spatially and temporally complete data sets about geology, hydrology, and biogeochemistry at site-specific catchment scales are necessary.

2.7 Frameworks for the study

2.7.1 Conceptual framework

The current study is based on the science of interaction. Interaction is a broad term and it happens in one or two ways. The interaction considered in this study was one way interaction. In this study, interaction refers to the exchange of water in an environment, from the subsurface to the surface. The current study is based on the concept of groundwater discharge. Jakeman et al. (2016) states that groundwater discharge is the loss of water from an aquifer to a surface-water body, the atmosphere, or abstraction for human uses. Mazor (2004) says discharge relates to the emergence of groundwater at the surface as springs, water feeding swamps and lakes, and water pumped from wells. Discharge in natural from groundwater system is from the flow of water into Rivers, wetlands and springs and evaporation from upper parts of capillary fringes where groundwater is close to the surface (Messene 2017). Whereas Nigate (2020) says groundwater discharge is the removal of groundwater from the saturated zone across the water table surface. The operational definition for the study is adopted from Mazor (2004) who defined groundwater discharge as the surface appearance of groundwater as springs, water feeding swamps and lakes, and water pumped from wells. The groundwater discharge concept in the study focuses on the discharge through springs. This study used the concept of groundwater discharge in spring hydrogeology to answer the research question “What are the subsurface conditions responsible for spring occurrences?”

2.7.2 Theoretical framework

Groundwater flow is driven by gradients in potential energy (hydraulic head) when water flows from high elevation to low elevation (Freeze and Cherry 1979). In groundwater discharge, water is lost from groundwater (aquifer) to the surface. The theory of discharge is based on pressure system and upthrust force. The pressure pushes water from where there is high pressure(subsurface) to low pressure(surface). While upthrust force causes water to be pushed upwards. This theory is based on the principle that water will move from high pressure to low pressure regardless of gradient and slope (Hiscock 2005). Alternatively, the push force acts on the direction opposite to that of gravity. It is not because the water will flow in mountainous locations, however it will help with local discharge in that regard. However, when it comes to regional discharge, it's all about the pressure system. Upthrust is a force and is directly proportional to the pressure.

The assumption is that spring discharge are based on upthrust force and pressure system in the subsurface, not on gradient or slope. The water comes emerging from spring comes out through facture openings as pathway within the geological media. The constant flow of water is due to the constant engine/pressure that keeps pushing water to the surface. As a result, springs would be continuously flowing due to the continual pressure. The slope and mountains can be there but if there is no pressure, the local springs would dry out because there is nothing (pressure) pushing water to the surface. Thus, understanding the geology assists in understanding the opening or pathway where water is passing in various geological media.

2.7.3 Interpretational framework

The interpretation framework aims to provide a plan that was followed to interpret the analysed data for various objectives. Tables, graphs, and diagrams were used as outputs for the research study as basis of interpretation on the study findings. Diagrams in form of models were used to discern the subsurface make-up that results on the emergence of spring on the surface, in the study area to meet the first objective. For the interpretation of collected data to address objective two on flows of the identified springs, images were captured at various spring points together with tables to compare obtained flow consistency and measurements for the research study. The diagrammatic structure presented in Figure 2.2 containing variables and showing relationship between variable, therefore providing a guide in terms of how the variables influence the flows from springs to help in providing an interpretation/analysis of the observed flows in the study area.

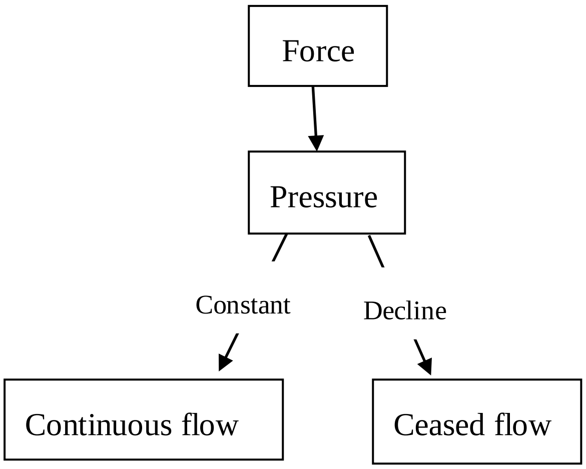

Figure 2.2: Analytical framework of the study on spring flow dynamics

Tables, graphs and diagrams were used as outputs for the last objective about spring chemistry as basis of interpretation on the study findings. These tools aided for straightforward analyses of water chemistry as understanding of groundwater flow mechanisms. Based on the knowledge that hydrochemical patterns are influenced by groundwater flow and that high and low mineralisation of groundwater are usually correlated to long and short resident time respectively. For instance, theory of discharge can be used in samples with high mineralization from indicative subsurface of more minerals from geology due to rock-water interaction and long residence time. Therefore, the current study used geochemical processes in chemistry as interpretational framework that the longer the water had been on the subsurface, the higher mineralized the water due to water-rock interaction. In the fields of hydrogeology and groundwater analysis, piper plots (moreover known as trilinear diagrams) remain remarkably effective tools for visualizing the relative abundance of common ions in water samples. Piper diagrams were used to determine water sample types, allowing for grouping water samples by groundwater facies and other criteria. In addition, tables and graphs were useful tools for organising present data, making it easy to highlight the relationships between variables. Therefore, these graphical plots helped in the interpretation of the collected data.

2.7.4 Research framework

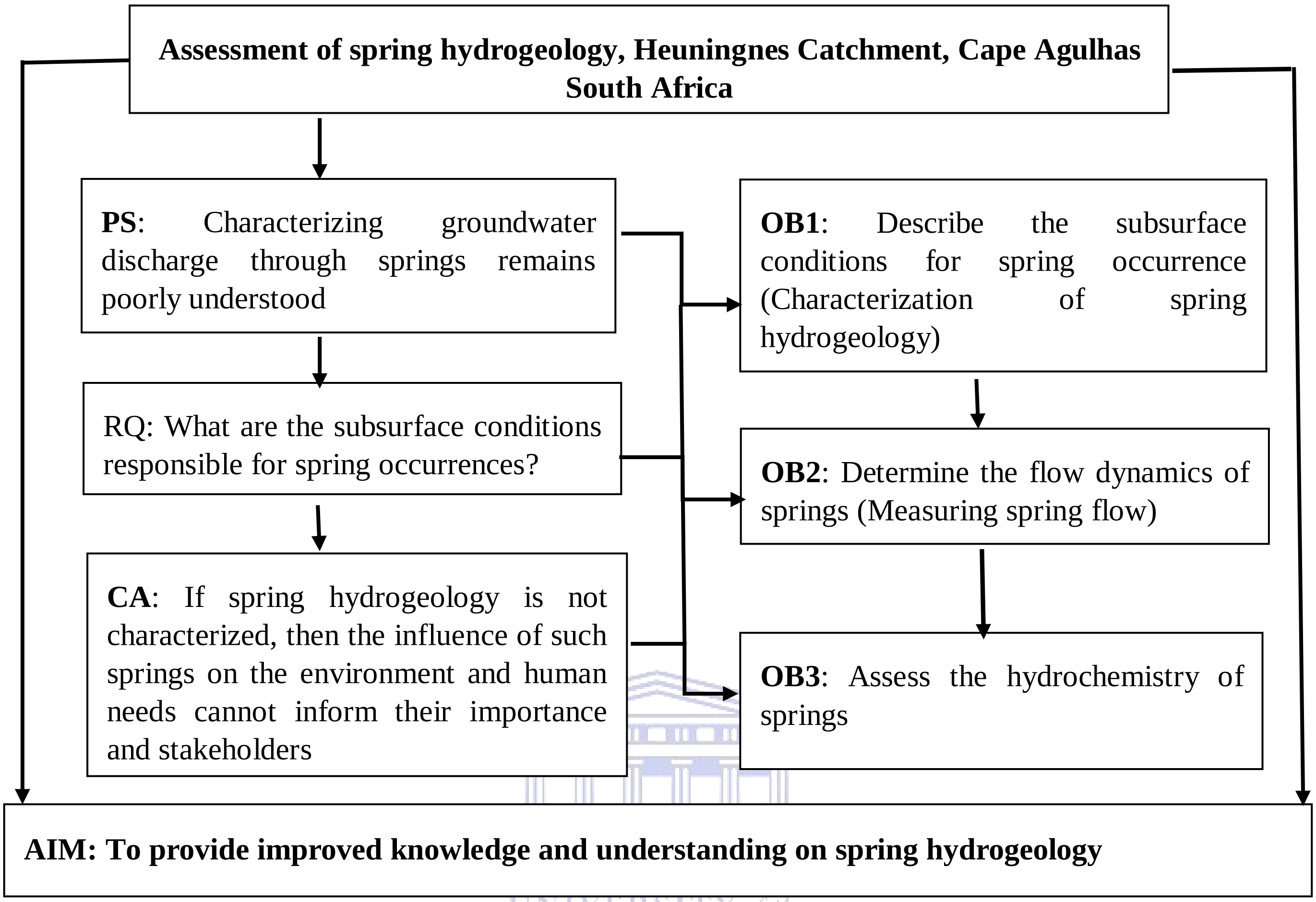

Figure 2.3: Overview of the research framework

Chapter 3: Description of the study catchment: The Heuningnes

3.1 Introduction

The current chapter provides a description of the study area where the study was conducted. The physiographic characteristics at regional and local scales are described to understand their influence on the interaction between springs and rivers of the study area. The chapter focuses on describing features such as geology, surface topography and climate. Such features have potential to facilitate or slow down the recharge, flow and discharge rate of groundwater and surface water in the study area. Attention is given to rainfall as the source of groundwater discharge in the area, geology as a host media of the groundwater, hydrology (surface water bodies) as a potential source of focused discharge. A detailed description of the study area is essential, as it informs basis in site selection, applicable methods to collect and analyse the data, and helps in interpretation of the results.

3.2 Description of Heuningnes catchment

The Heuningnes catchment is situated in the southernmost tip of Africa spreading out to the Agulhas Plains. It is within the Western Cape Province of South Africa, under the Cape Agulhas Municipality in the Overberg district. The area of study is located between the coordinates of 34° 20’ and 34° 50’ S latitude and 19° 33’ and 20° 17’ E longitude of the geographic coordinate system. The study area falls under the tertiary catchment G50, with five quaternary catchments namely G50B, G50C, G50D, G50E and G50F, with three inland towns Bredasdorp, Napier, Elim and three coastal towns of Cape Agulhas, Struisbaai and Molshoop (Figure 3.1). Various sources (Kinoti 2018, Banda 2019) estimated the Heuningnes catchment area to be about 1400 km^2 and 1938 km^2 respectively. Recent studies (Xaza 2020; Mokoena 2019; Manyama 2019) indicates the overall catchment area to be 1400 km^2. The town of Elim, which falls within the study area (Figure 3.1), has a population of 1412 people, whose livelihood depends on the water resources (springs) within the catchment (Mazvimavi et al. 2017).

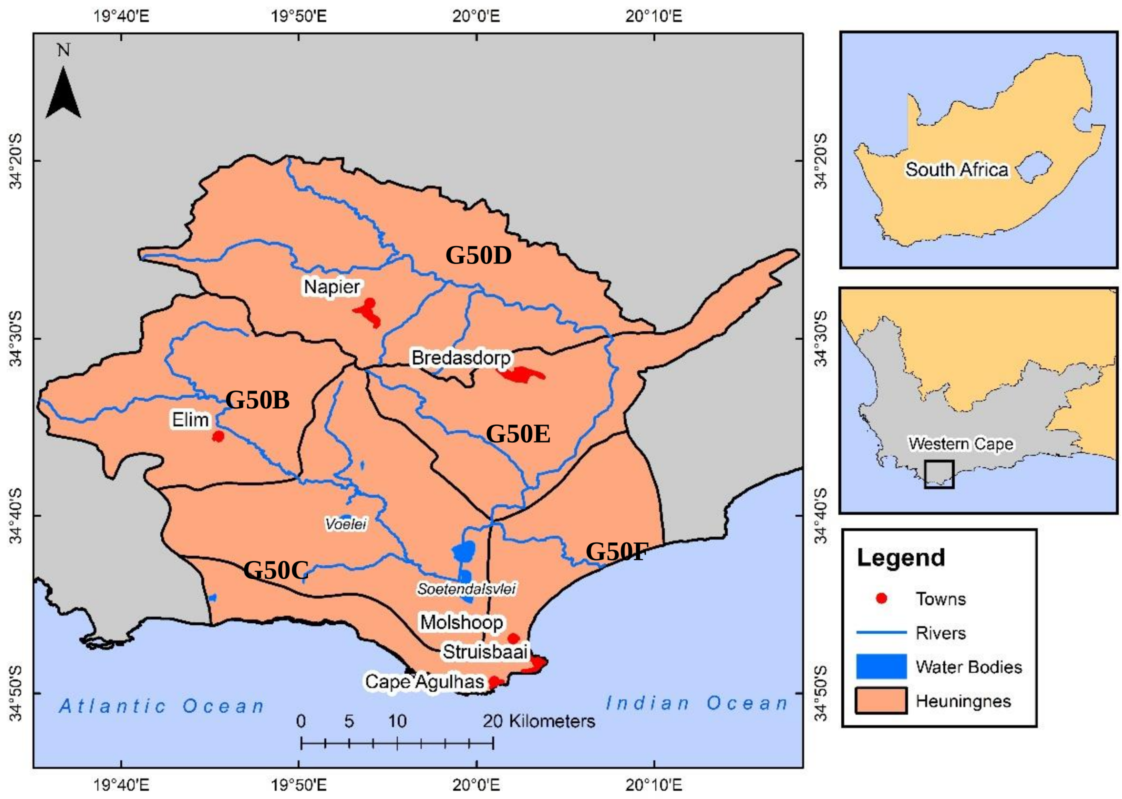

Figure 3.1: Quaternary catchment map of Heuningnes Catchment in South Africa

3.3 Justification for using Heuningnes as the study area

To capture the full extent of Heuningnes, the study selected spring sites located in all (lowland, middle and upland regions) parts of the catchment. The catchment area is 1400 km^2 with altitude varying from 100 – 654 m above sea level in the headwaters or uplands, 41 – 100 m in midslopes, and 7 – 40 m in lowlands. The study used boreholes, rivers and springs within the upper, middle and lower part of the catchment as the study population. These sites include Sandfontein, Spanjaardskloof, Wolvegat, Rhenosterkop, Elim and Tiersfontein. All springs used in this study are situated in Heuningnes catchment only. The reason for choosing springs in Heuningnes only is that the study used Heuningnes catchment as a case study to demonstrate how the concept of spring hydrogeology can facilitate decision-making regarding using springs for water allocation.

The sites were selected partly because the area is strategically important for research as most studies have been carried out around water quality, hydraulics, water use etc but not on springs. Thus, the area provides an opportunity to meet the objective of this study. The justification behind the site selection for study area was that it is well instrumented and data (secondary data) availability as well as accessibility. Spring discharge to rivers has been found to be important in contributing to river flows (previous studies) but there is inadequate knowledge regarding spring hydrogeology in the catchment. Furthermore, there is very little understanding on the subsurface conditions resulting in spring occurrence, rates of discharge and the hydrochemistry of these springs. Thus, the main motivation behind the study sites selected was that the catchment has been a living laboratory for the University of the Western Cape and many assessments on various water systems have been conducted, however there is a gap in understanding groundwater discharge through springs within the bigger concept of interaction.

3.4 Influence of topography and landform on spring hydrogeology

The Heuningnes catchment topography varies significantly between the upper and lower parts of the area of study (Figure 3.2). The elevations as described by Kinoti (2018) ranges from 7 to 654 m beyond sea-level. Higher elevation zones are marked by the Bredasdorpberge, Kouberge which forms sources of the streams adding to the Nuwejaars River. Recharge localities for these zones are local groundwater in the region. Most parts of this study are focused on G50B and G50C quaternary catchment with a total area of 760 km^2 (Mazvimavi et al. 2017) popularly known as the Nuwejaars Catchment, and has identifiable upland, mid-slope, and lowland regions. The Nuwejaars Catchment has headwaters in the Koue and Bredasdorp Mountains with altitudes ranging from 400 to 650 m above sea level. The quaternary catchment G50C makes up majority of the catchment which is low-lying with an altitude ranging between 5-60 m above sea level, with several ponds of water. The catchment is characterized by a rapid decrease in altitude from the headwaters to the main tributaries in the low-lying sections of the catchment (Mazvimavi et al. 2017). The northern part of the landform is distinguished by a rippling terrain, while the southern and south-eastern part has a relatively flat terrain sloping gently towards the seashore. As such, surface water runoff is towards the south coast, and the regional groundwater flow from the high elevation areas is expected to be close to the sea. Understanding the effects of the hydrogeologic environment on groundwater flow systems – that is, the effects of topography, geology, and climate is necessary to understand GW–SW interactions (Fleckstein et al. 2006). Thus, these differences in elevation are expected to facilitate groundwater flow direction, which is important to consider when dealing with groundwater discharge points such as springs due to the topography influencing flow patterns of local groundwater. Based on this, the study assumes that topography drives local groundwater flow that emerge on spring.

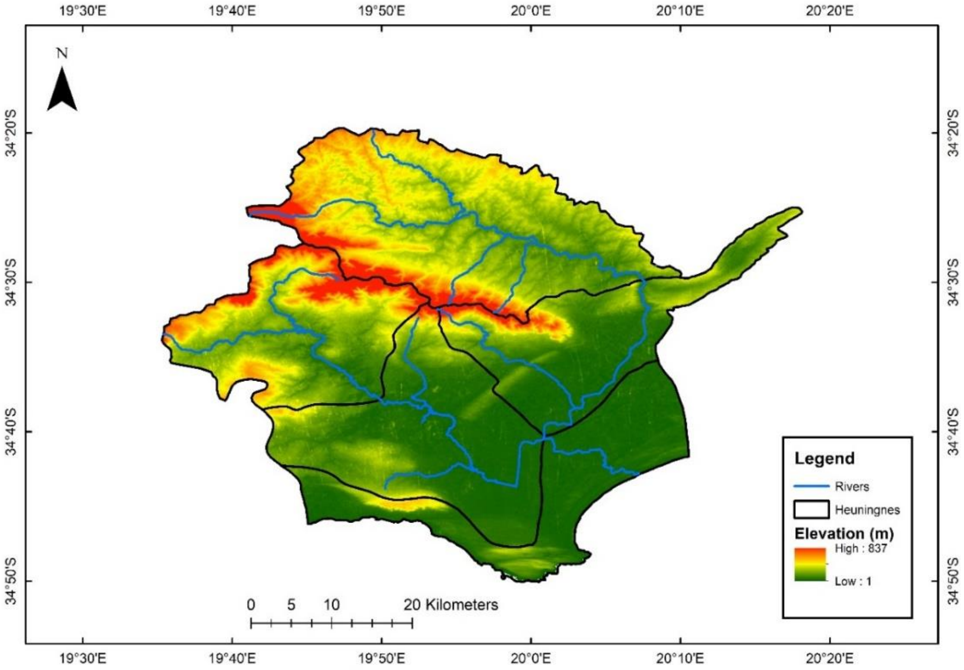

Figure 3.2: Elevation distribution in Heuningnes Catchment

3.5 Influence of climate variability on spring-river interaction

Climate is the time-varying uncertain summarizing description of multiple properties of a representation of a system for a specified spatial and temporal domain dependent on external factors varying in time and space (Bothe 2018). Although the concept of climate is easy to understand, there is not any uncontroversial definition of it. In the context of the study, climate refers to a region's long-term changes in weather conditions, being described through rainfall, temperature, and evaporation features. The Heuningnes Catchment is within a semi-arid region and experiences a Mediterranean climate characterised by cold, wet winters and hot, dry summers and falls within the Winter Rainfall Zone (WRZ) of South Africa. This is largely due to the position of the subcontinent relative to low pressure systems between 40° to 50° south (Midgley et al. 2005). These low-pressure systems bring winter rainfall to the south-western part of the country by means of a procession of cold fronts when the westerly waves shift northward. Dry conditions are attributed to variations in the westerly wave and high-pressure cells positions annually. Therefore, the rainfall pattern differs between lower and higher elevated areas with the influence of frontal rainfall dominating in most parts of the catchment while in the upper hilly reaches, orographic rainfall partly dominates. Based on this, the current study assessed effect of climate variability on spring occurrence (groundwater discharge).

The mean annual rainfall varies between 400 and 600 mm per year (Mazwimavi 2017). The Nuwejaars Catchment typically receives rainfall throughout the year, although the highest rainfall is received during the winter months (June to August), while the least is received during summer (December to March) evident in Figure 3.3. The average annual reference evapotranspiration for the catchment is 1140 mm/year, with high evaporation rates experienced in summer, and subsequently reducing water availability (Figure 3.3). Temperature variation in the area is controlled by its locality being near to the ocean. The observed increase in evaporation could be attributed to the temperature increase with respective months thereafter resulting in decreased water balance. The maximum temperature ranges from 20 to 30°C and minimum temperature from 12°C to 18°C in summer and winter respectively (Banda 2019). The catchment experiences maximum temperature during summer months and minimum temperature in winter months. High temperatures have an implication of decreasing the catchment water balance which may influence stream generation from groundwater discharge. Based on this, the study assumes that after a dry period (summer) the landscape has storage capacity for water and when rainfall event occurs, groundwater levels and groundwater discharge are expected to increase as the landscape would be saturated with water. Therefore, the study expects spring discharges to be influenced by rainfall patterns and evaporation.

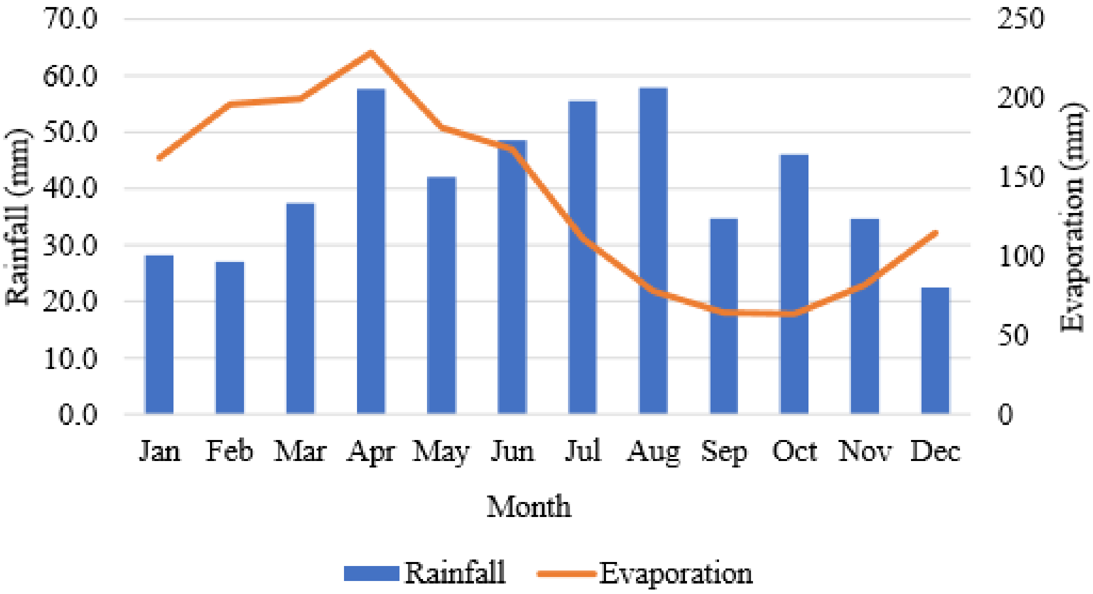

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Figure 3.3: Bredasdorp (G5E001) average monthly rainfall and evaporation (from Class A pan) from 1980-2015 (Data source: DWS, 2017. Adapted from Banda 2019)

3.6 Influence of rivers and drainage patterns on springs

The Heuningnes catchment is characterized by numerous surface water bodies, including rivers, wetlands, and seasonal pans. Heuningnes River as the major river in the catchment has two tributaries: the Kars River and the Nuwejaars River (Figure 3.4). The main tributaries of Nuwejaars River include Koue, Wolwegatskloof, Jan Swartskraal, Boskloof and Uintjieskuil (Bickerton, 1984). Before flowing southwards and entering the Heuningnus River, the Kars River arises from the northern slopes of the Soetmuisberg and Bredasdorp mountains. Bickerton (1984) reported the Kars River of having six tributaries namely Twee, Leeu, Klein Sout, Klipdrif, Groot Sanddrif and the Grashoeks. The river flows in the NW - SE direction and runs ~55 km from its primary source and drains into one of the South Africa's largest freshwater lake called Soetendalsvlei. When Soetendalsvlei overflows confluencing with Kars River, the excess water flows into Heuningnes river which forms an estuary discharging into Indian ocean (Russell and Impson 2006, Kinoti 2018). Based on the presence of more rivers in the area, which provides an indication of the subsurface being saturated and groundwater discharge contributing to such rivers. The research study would want to highlight the role of groundwater discharge on forming these rivers.

In the study area, several wetlands, and pans both seasonal and perennial exist (Figure 3.4). These considerable wetlands and pans include Voelvlei, Soutpan, Melkbospan and

Soetendalsvlei, are present over a small area within the low-lying sections of the catchment (Kinoti 2018). The wetlands are habitat to many rare bird and aquatic species, some unique to this area (Kraaij et al. 2009; River Health Programme 2011). Soetendalsvlei and Voelvlei, which are usually inundated all year round, are connected to the Nuwejaars River, while the surrounding temporary and hypersaline pans (Soutpan, Melkbospan) are not (River Health Programme 2011). These wetland and pans may be connected to groundwater as at the end of the wet season, drainage of water stored in this wetland sustained downstream flows from October to December 2016 after which the river dried up, with the seasonal ones having water even in dry seasons where there is no rainfall, while with reduced rainfall the availability of water may be reduced even on the perennial ones (Malijani 2019). Based on the above-mentioned groundwater dependent ecosystems that have been researched in the catchment, thus the study wants to assess the hydrogeology of springs as groundwater dependent ecosystem.

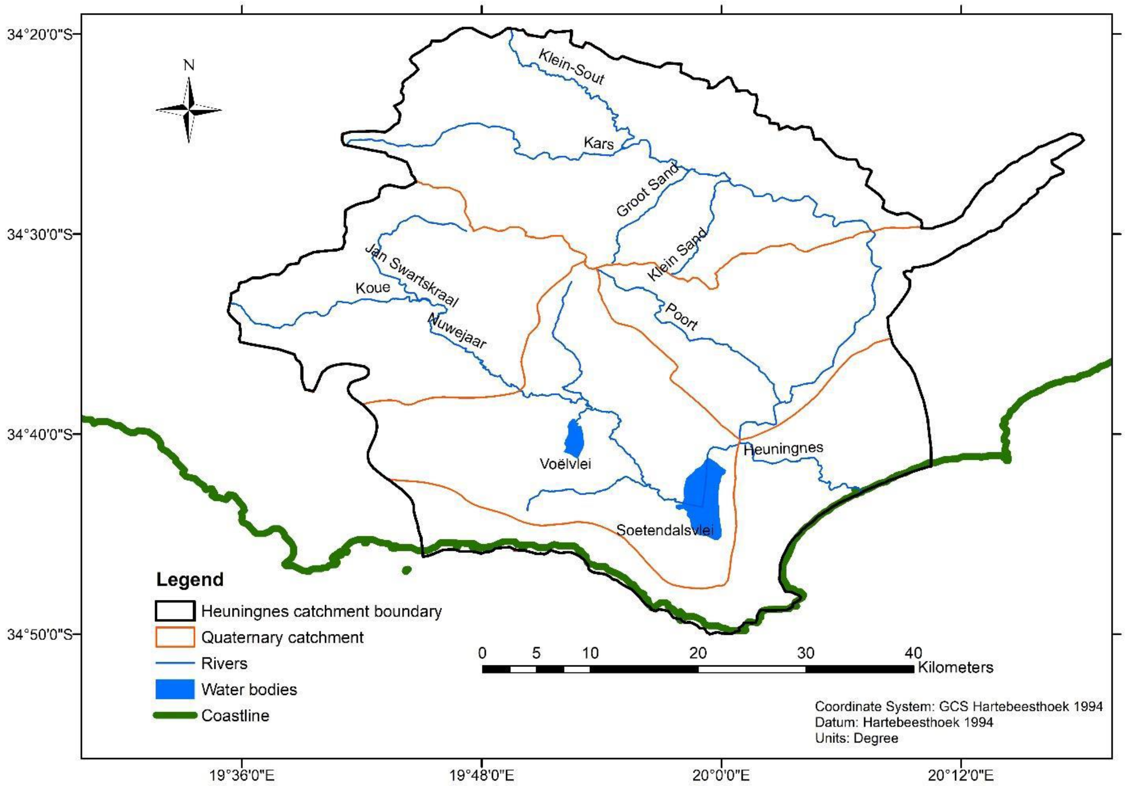


Figure 3.4: Rivers and other water bodies in Heuningnes catchment

The upper segments of the Nuwejaars and Kars Rivers have been identified as priority rivers for conservation initiatives due to their relatively unimpacted nature and high numbers of indigenous fish species (Herdien et al. 2005). According to the complexity of Mediterranean climate observed in the study area, these rivers are predicted to be subjected to naturally high flow variability, with seasonal weather patterns expected to occur in these areas, in terms of flooding and droughts. Streams draining uplands areas that form headwaters on the north-western and northern parts are perennial. With minimal rainfall occurring during the dry period, December to April, flows during this period are due to groundwater discharge in the form of springs and diffuse discharge (Mazvimavi et al. 2017). As such, the channel may have reaches during dry periods that can have permanent flows, isolated pools or even completely dry (Malijani 2019). A connection between groundwater and surface water allows for pools to develop because of groundwater discharging to the surface. Groundwater is therefore likely to influence the water quality of pools, as well as their persistence especially during the dry season (Seaman et al. 2013). Malijani (2019) confirmed that some of the pools are dependent on groundwater hence even during dry season there is water observed from groundwater discharge contributions. It is important to understand these surface water bodies as they sustain ecological systems and provide habitat for many plant and animal species. They also support numerous human uses, including drinking water, irrigation, livestock, industrial uses, hydropower, and recreation. These rivers and wetlands are points of groundwater discharge and are expected to be highly sustained by groundwater especially in dry seasons.

3.7 Influence of geology on spring hydrogeology

The main geological formation composing the Heuningnes Catchment are Table Mountain Group (TMG), Bokkeveld Group and Bredasdorp Group (Figure 3.5). Outcrops of the Malmesbury Group and Cape Granite Suite also occur and are the oldest basement rocks overlain by the Table Mountain Group and the Bokkeveld Group (Kinoti 2018). The outcrops of the intrusive Cape Granite Suite and Malmesbury Group are exposed mainly by faulting. The Bokkeveld Group and TMG belong to the Cape Supergroup rock formations are intruded by the basement lithologies in the Heuningnes Catchment (Manyama 2017). The quartzitic sandstones of the TMG formation dominates the upper sections of the Nuwejaars Catchment. In understanding the nature of groundwater resource, availability/potential and flow directions, knowledge of the hydrogeological setting is essential for such needs. The physical properties of interest include among others geological units, groundwater zones, stratigraphy, rock type, dykes, faults, and fractures (Thamm and Johnson 2006). These subsurface properties are useful when explaining the occurrence, movement, and discharge of groundwater. Understanding the geology of the region is very imperative for the current study especially when dealing with groundwater discharge and its chemistry. Often groundwater flow within an aquifer system is dependant on the presence of geological structures such as faults, folds, and fractures. Therefore, geological structures are expected to provide flow-paths for groundwater migration especially for deeper groundwater that are under pressure.

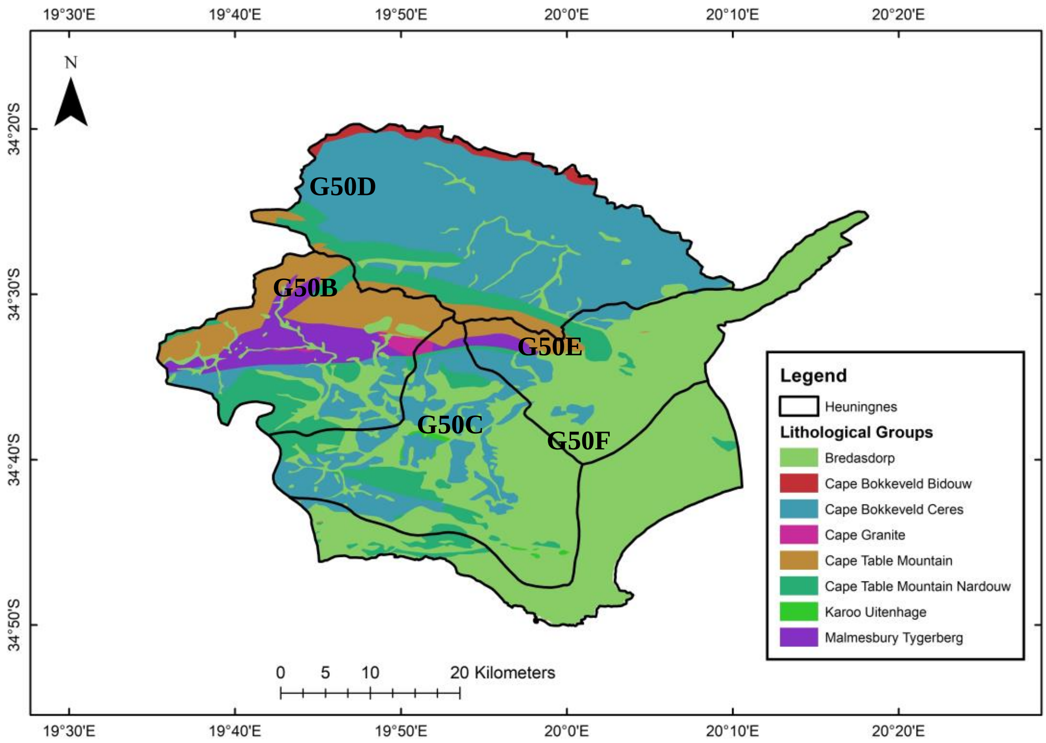


Figure 3.5: Quaternary catchment overlaid with lithological groups of Heuningnes Catchment

The upper sections of the catchment are dominated by formations of the TMG, which consist of quartzitic sandstones (Roets et al. 2008; Kinoti 2018). The TMG formation is highly resistant to weathering processes that resulted to TMG sandstone being the most noticeable feature in the landscape producing high ground and mountain ranges. The quartzitic sandstones of the TMG were affected by deformation that resulted in the occurrence of faults, folds, and joints in the area hence the presence of a fractured aquifer. The TMG geology, is not extremely reactive, thus providing an indication that chemistry in the upper part may not necessarily be influenced by geology (Xu et al. 2009). Therefore, springs occurring in the upper part of catchment are expected to be occurring in TMG formation with high discharge and water occurring in this type of geological group is expected to be less turbid.

In the Heuningnes Catchment, the Bokkeveld Group, covers the largest area and lies between the Table Mountain and Bredasdorp Group. This formation is susceptible to weathering and is intruded by the basement lithologies. In addition, the Bokkveld formation is a poor aquifer, and the little groundwater produced from it tends to be brackish to salty (Mokoena 2019; Xaza 2020). Within the catchment, this group dominates the mid-sections of the catchment, between Elim and Soetendalsvlei Lake, and consists primarily of shales and fine-grained sandstones in an alternating sequence (Manyama 2017). Because of this, the study assumes that groundwater discharge through springs in this type of lithological group will be low and has great influence on the chemistry of groundwater in middle section of the catchment.

The Bredasdorp Group is dominant from Soetendalsvlei to the mouth of the Heuningnes River. This formation primarily consists of calcified dune sands and limestone and overlies the Bokkeveld Group and the TMG rocks. The calcareous sands are rich in calcium bicarbonate, because of this, it explains the water type associated with this geological group (Kinoti, 2018). Its low yielding primary porosity forms key component of the southern part of the catchment which may have an effect on groundwater availability and water balance in the area. Hence, the study would want to assess the spring water chemistry to provide improved knowledge and understanding on groundwater discharge.

These different geological formations would influence groundwater discharge affecting both quantity and quality of exchanged water. In the study area, faulting is prevalent, with fault lines running almost east-west direction. Identifying these faults with the associated geological groups in the catchment is essential for the assessment of spring hydrogeology, as they can act as groundwater boundaries that restrict or facilitate the movement of groundwater. In the catchment, faulting occurs mostly on the Bokkeveld and Table Mountain groups giving rise to secondary porosity in these formations (Xu et al. 2009). The characterisation of geological structures within these geologies is essential in gaining knowledge on spring characterization by classifying the type of spring and expected yield. The type of geology determines the extent to which the reaction with the host rock proceeds (water-rock interaction), which then affects water quality depending on the chemical composition of the rock and the rate at which water passes through the rock. Therefore, the study is important as it provided improved understanding on the nature of groundwater discharge through characterizing springs using the underlying formations.

3.8 Hydrogeological influence on springs

Directly linked to the catchment geology, the upper part of the catchment is dominated by fractured aquifers meanwhile the intergranular primary shales with low yield occur at the lower part of the catchment. The TMG units form the most significant fractured aquifers in the area, because of the intricate network of fractures, faults, joints, and fissures on the TMG making it the most productive aquifer in the area. While rocks of the Malmesbury (basement) can yield water where fractured, a number of perennial-springs feeding into the wetland located south of Bredasdorp are hosted by the faulted and fractured quartzites of the TMG (Lasher 2011). These geological structures are one of the most important features that control the occurrence of groundwater due to their unique properties that facilitate in the formation of springs. As a result, strata and rocks might be reconstructed by various phases of crustal movement which created different types of discontinuities in the form of joints, faults and unconformities. Groundwater flow in the regional fractured sandstone rock aquifer is primarily controlled by the fractures and fault systems. Due to the faulting and fractures, in most areas the TMG formation has high yields, and the fracturing is prevalent because of the brittle and competent nature of the TMG arenaceous deposits (Xu et al. 2009). Therefore, groundwater discharge rates are expected to be higher in the TMG especially where it outcrops in the higher mountains. Thus, groundwater flow system would be influenced primarily by the underlying geology and geological features.

In the upper reaches of the catchment, a connection between groundwater and surface water exists (Mazvimavi et al. 2017). Due to much fracturing and faulting of the TMG, water quality is generally good and of low Total Dissolved Solids (TDS). For instance, upstream springs within the TMG region of the catchment are connected to fault systems. These springs situated upstream provide water from deep aquifer systems that are a source of constant base flow for the Koue, Pietersielieskloof and Jan Swartskraal tributaries. Springs upstream that occur within the TMG region of the catchment and are expected to be closely linked to fault systems thus providing guidance on the characterization of such springs. These springs are a valuable source of fresh water, as they supply the town of Elim with water for domestic use all year round and feed rivers during the dry season (Mazvimavi et al. 2017). In addition, irrigation water is also available through springs in the upper catchment (Mazvimavi et al. 2017). On the other hand, the Bokkeveld aquifers are low yielding due to lesser degree of faulting, and water quality is expected to be generally poor, and of high TDS, usually inherent from the rock formation through which groundwater flows (Xaza 2020). Meanwhile, the Cape Granite, which outcrops in fewer areas across the catchment has a low groundwater potential whose flow is through fractures and some weathered profiles. This offers an opportunity to characterize the subsurface structures leading to the presence of the springs on selected study area sites. With fractures and faults being the common geological structures in the area, these structures provide a flow path for groundwater to emerge on the surface. Therefore, this provides an idea to the type of springs likely to occur in the area as geological structures assist the study in characterizing the springs.

3.9 Influence of land cover on the hydrogeology of springs

Most of the land in the catchment is maintained in its natural state and includes grassland, bushland, wetlands, and shrub land fynbos (limestone and sandplain) covering up to 41% of the catchment (Kinoti, 2018). Some areas are dominated by agriculture and livestock farming (Kraaij et al. 2009). Wheat, barley, and canola are among the crops grown in the catchment, which also includes vineyards (Russell & Impson 2006). Dryland agriculture is the most common method of farming in the cultivated areas (River Health Programme 2011), indicating that the region receives little to no rainfall. Several cattle and sheep-breeding farms are located near the Nuwejaars River. Meanwhile, urban growth is limited to the towns of Bredasdorp, Elim, Napier, L'Agulhas, and Struisbaai, which make up a small percentage of the catchment (Mazvimavi et al. 2017). Anthropogenic activities in these areas may influence the quantity and quality of various water bodies, requiring an assessment of such potential influence before suggesting definitive conclusions for water resource protection such as springs. Therefore, the land-use effects dominantly alter the long-term temporal dynamics of the spring discharge over time, the change in the seasonality of the discharge can be attributable to the combined effect of the land-use and climate variability. Thus, this provides an idea of the type of springs in the area. As to deduce the drying up of springs in dry season and not in wet season then such springs are fed by shallow, local flow system.

3.10 Relationship between ecosystems and spring hydrogeology

The exposure of groundwater at the Earth's surface and its frequent flow have an impact on springs. They are abundant and have played important, highly interactive ecological, cultural, and socio-economic roles in various environments throughout human evolution and history (Durowoju 2019). Spring flows may be seen too small to be even measured compared to lakes and rivers, yet they play a leading role in the greater hydrologic cycle. Ecosystem in this context refers to the vegetation and animals. Ecological variables such as vegetation have been used to differentiate spring types and where they are occurring. Some terrestrial vegetation in arid and semi-arid regions may be maintained by the direct and indirect access to groundwater. There is a relationship between the presence of certain vegetation in certain season and where they are occurring. The occurrence of unique vegetation such pine trees, result in no visible signs of release, such as springs, while such vegetation is using groundwater and dependency by plants may go undetected (Zhang et al., 2019). Many species depend on habitats maintained by groundwater discharge adding to the ecological diversity of a region and can be indicators of the overall biological health of a system. Some plants and animals that depend on groundwater are rare, unique, or threatened. Hence, over the course of human history springs are important as they support ecosystem in the environment as they form the source of rivers in some areas. In addition to their utility as a resource, springs integrate the signal of geological and hydrological processes over large spatial areas and long periods of time, they are indirect source of information which provides a unique opportunity to study a range of subsurface processes. They serve as window into the earth by studying their temperature and ionic content of the water which then reflects the flow path and geologic setting of the aquifer feeding the spring.

Some spring sites are of archaeological and social value, as they have cultural significance and can have social and economic values. The values range from many benefits of springs from religious and traditional, medical, agricultural as well as tourism and recreation benefits. The use of springs has been an ancient practise across the world even before the modern civilisation. For instance, in the medical field the different minerals and gases within spring waters have proven to have different healing abilities such as circulatory and heart disorders (Durowoju 2019). Some have been used for irrigation purpose from time immemorial, for instance, in Heuningnes Catchment some spring waters are used for tomato irrigation. For these springs to attain such roles, there is a need for development of a more comprehensive water-management, land-use and energy-development strategies that fully recognize groundwater's important role in the hydrologic cycle. This requires better characterization of spring basins, their interconnection with surface water and ecosystems, and a better understanding of the response of the spring discharge system to natural and human-induced stresses. Hence the present study aims at improving the knowledge and understanding on subsurface conditions or characteristics that lead to presence of spring waters on the surface.

Chapter 4: Research design and methodology

4.1 Introduction

This chapter presents research design, sampling techniques and methods followed to achieve the three objectives of the research study outlined in chapter 1. Methods that were used to collect and analyse data are explained, as well as type of research that was followed is described to answer the study question set forth in Chapter 1. In addition, the data quality assurance and research integrity measures that were followed are outlined. The limitations experienced during the research and how they were overcome in order to achieve the study's objectives are highlighted. This chapter explains what was done, how it was done, and why it was done in that way. This chapter elucidates that in order for results to be reliable and valid, the processes that contributed to them must be logically defined and described using standard methods and procedures.

4.2 Research design

A research design is a plan of the basis for the methods and techniques to be used for conducting the research (MacMillan and Schumacher 2001). The author further stipulated that the purpose of a good research design is to produce reliable results, hence the choice to assess the hydrogeology of springs. Together with the appropriate methods for the study, to ensure that the research's established question is addressed, and the identified problem is resolved. The research design employed in this study is described in detail below.

4.2.1 Research design approach

An integrated approach was followed for assessing the various factors influencing spring occurrences and distribution, groundwater flow dynamics (springs), and hydrochemistry. The current research followed an experimental study type through the use of field visits, where measurements were conducted at different sites within the study area, then a general conclusion was drawn from interpretation of the data. This approach was used as it allows for the quantitative and qualitative assessment carried out.

A research design is a methodical approach to investigating a scientific issue. A study's design determines the study type which include descriptive, correlational, semi-experimental, experimental, review, meta-analytic (Creswell 2014). The review (literature review, systematic review), meta-analytics, and experimental design were included in the study. Through record review approach which formed the basics for the interpretation of results and to source literature from global, regional, and national peer-reviewed journals, the literature reviewed assisted in identifying what has been done and what can be done on springs in coastal areas, which included performing a comprehensive reading on current studies. Secondly, meta-analysis was followed which was used to systematically synthesise or merge the findings on studies on the study site to know the available numeric data for secondary data of current and existing conceptual models that better explain the spring occurrence in coastal areas, to determine the conceptual model that best explains the discharge process through springs. Lastly, the experimental design was used to understand groundwater discharge process through field chemistry and sampling. The methods used in this study provided a systematic characterization of the spring resource, consisting of stages that included understanding their spatial distribution in coastal region, mapping of the subsurface and details on physical resources such as groundwater units and rock type; spring resource classification; determining groundwater flow dynamics with a focus on flow directions and constructing a conceptual model to describe the groundwater flow mechanism.

4.2.2 Sampling design

There are different sampling design and approaches that could be used in research. These include purposive, reliance, cluster, and random sampling design amongst others. The current study used a purposive sampling design in which the units to be observed were selected on the basis of researcher’s judgement. Purposive sampling design was used based on the study objectives to collect water information directly from springs other than the surrounding environment. The 14 samples were therefore collected directly from the eye of the springs and secondary information collected in river and boreholes close to the springs.

4.2.3 Unit of analysis

For the first objective of this study, which focused on describing the subsurface conditions for spring occurrence, the unit of analysis was the spatial distribution of springs (spring coordinates) and geological units such as lithology. Coordinates of the spring locations were obtained and used in the generation of the spatial distribution map. The information from the borehole logs and geological maps, as well as existing models were compiled to construct the geological cross sections which provided an understanding of the subsurface system. While the hydrological framework was developed from the aquifer hydraulic parameters, groundwater level data. This means that components of the studies from Manyama (2017), Xaza (2020), Banda (2019), Mazvimavi et al. (2017) were used for the model development.

For determining the flow dynamics of spring water, the unit of analysis were the flows. The focus was on measurement of the flows from spring. In addition, for the hydrochemistry assessment of springs which uses hydrochemical and environmental isotope analysis, the unit of analysis were the springs general chemistry, major cations and anions, and radon (^{222}Rn) stable isotope obtained from springs, borehole and surface water.

4.3 Research methodology

A research methodology is a technique or architectural design by which a researcher establishes a way for identifying and solving problems. Within qualitative, quantitative, and mixed methods approaches, research techniques are types of inquiry that provide precise direction for procedures in a research design (Creswell 2014).

Qualitative methodology is a type of research that relies on open-ended and conversational communication to gather information. Berrios and Lucca (2006) stated that narrative research, phenomenologies, ethnographic technique, grounded theory, and case studies are examples of data necessary for this type of research approach, and data sources include interviews, postcards, secondary data, and observations. In contrast, quantitative method has its origin based in the scientific method through evaluating the relationship between variables to test objective theories. These variables can then be measured using instruments, resulting in numbered data that relies on statistical procedures for data analysis. The mixed methodology refers to an approach that collects and uses quantitative and qualitative data in the same study, as these methods complement each other. Both quantitative and qualitative data were collected, analyzed, blended in various formats, and one or both types of data are given priority. The central premise of this type of inquiry is that combining both methods yield a more comprehensive understanding of a research issue than either approach alone, as qualitative findings need to be supplemented with quantitative results. Creswell (2014) stated that mixed methodology can be applied to a single study or numerous phases of a study. Therefore, quantitative research method was employed in this study, for quantifying variables and analysing relationships between variables to test objective hypotheses.

In this empirical research study, numerical (existing) data was collected and analysed, from conceptual models, hydrochemical and radon data. The secondary data was utilised to identify long term trend in the data together with data collected by current study. In addition, geology maps were analysed to identify rock types responsible/promoting flow path of springs for proper subsurface characterization. Primary data was obtained from the field by measuring variables using various instruments with values recorded. The primary data and the generated results from laboratory analysis were incorporated with the secondary data, with the primary data validating the secondary data.

4.4 Data collection and analysis methods

4.4.1 Describe subsurface conditions for spring occurrence

Field indicator method was used for initial reconnaissance which highlighted hotspots where groundwater is discharging to the surface and interacting with surface water features. This method was used in the research study as it was easily incorporated into field work. Even though its effectiveness varies with observer’s knowledge of field indicators such as plant or aquatic biota. The advantage of using field indicator method, was for the quick identification of seepage hotspots and with return visits can provide information on seasonal changes in seepage flux. In addition, it enabled the researcher to observe locations and situations which indicated groundwater discharging to the surface, then forming a river. This was achieved by using ecological indicators that allowed for identification of specific vegetation communities that indicated groundwater discharge.

For verification and validation aspect of spring locations which were previously mapped by other scholars, the study used rivers to locate springs. The data was collected through identifying where rivers were and walking from the bottom following the river channel to the top(headwaters), to where the river starts. The aim was to identify places where water was seeping from the subsurface to the surface and observed for unique information indicating discharge. The ecological indicator method was employed to highlight connectivity as some areas were wet in the dry season (summer April month) but in other areas within the environment it was not (Figure 4.1). With utilization of the method, the study managed to observe the saturated floors and dry areas in dry season which indicated groundwater discharge variability.

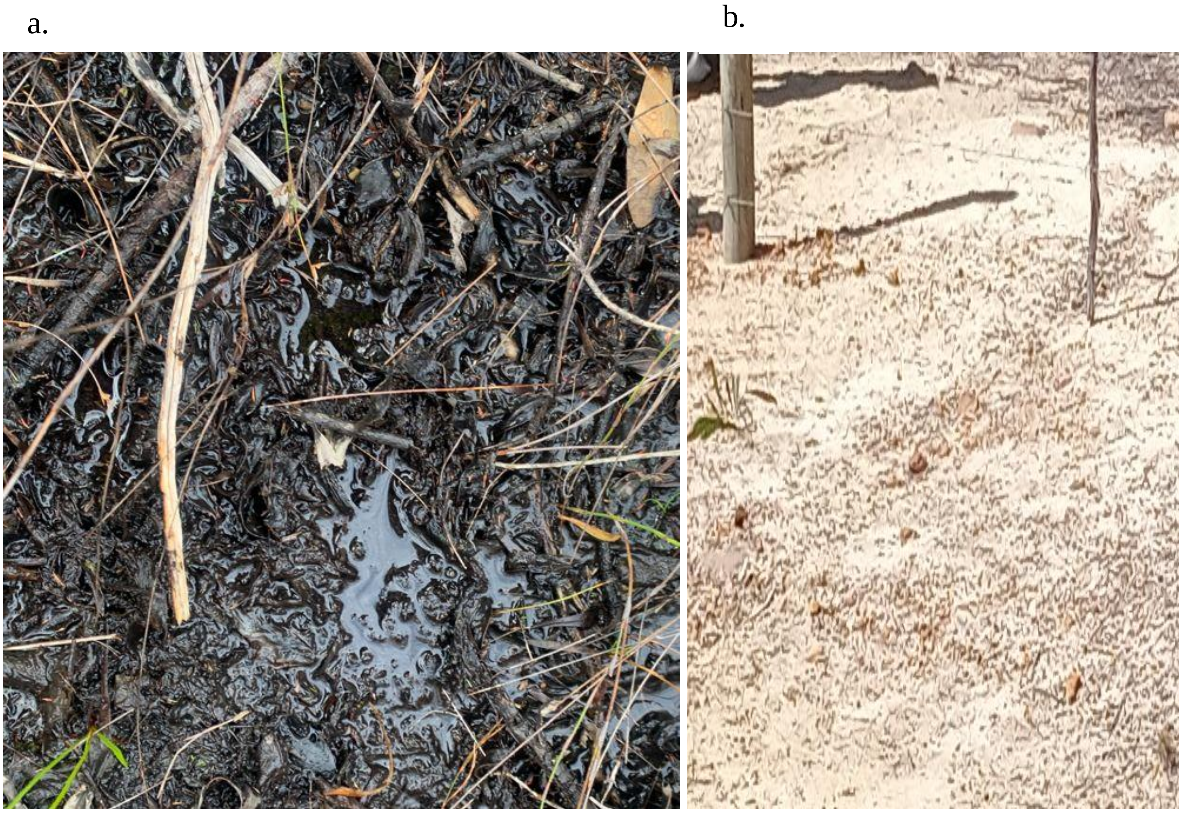


Figure 4.1: Observed wetness (a) and dryness (b) in April 2021 near Elim

The distinctive change in vegetation was observed as it was indicative of seeps and springs close by, with the green vegetation being dominant along the wet depressions and channels (Figure 4.1). The popal and pine trees were quite distinctive, as they grew tall and very green in colour, indicative of productivity and water availability in their location, though it was in dry season. In addition, from every spring eye and along the spring run, buttonbush and fern plants were common which provided evidence that water was seepage from the subsurface as they grow in consistent moisture. Field observations provided unique information in understanding how the system functions due to its advantage of direct observation of water flow from springs at the margins or within the stream bed, or changes in water colour or odour. While ecological indicators assisted in identifying certain dense vegetation, such as pine trees, growing in a dry environment around the point of discharge. With successful field observation, I had many new ideas and a valuable knowledge base for the project. Field indicators included direct observation of water flow from springs at the margins or within the stream bed and changes in water colour around water sources, as well as dense vegetation growth in dry areas. Thereafter successfully identifying the spring eye, a Garmin eTrex 30x Global Positioning System (GPS) was used to locate 14 sampling points and where necessary markers were used such as floor marking on such points to ensure that same points are sampled throughout the study period.

Figure 4.2: Green vegetation observed in Sandfontein(a) during dry season (April 2021) and GPS(b) used to collect the spring coordinates

Record review was used to analyse both primary and secondary dataset, that were used to develop the groundwater discharge conceptual model to assess the subsurface conditions for spring occurrence (Figure 4.3). To collect existing dataset such as geological, hydrological and geographical datasets, record review was used. These were collected because they were required when setting up a model. Geological dataset collected included borehole logs, geological map and geological cross-sections of the study area. Hydrological data included water levels from monitoring wells and previous investigations on the aquifer in the vicinity. Geographical dataset included soil maps, land use maps, aerial photographs and topographical maps. Once all the necessary data was collected, a hydrogeological conceptual model that explains groundwater discharge was developed. This model explaining subsurface conditions for spring occurrence of the study area was produced using Surfer 11 software. The model showed lithological groups distribution, flow direction and geological structures.

Figure 4.3: Diagrammatic representation of desktop (record review)

4.4.2 Determination of flow dynamics of springs

Discharge was estimated through the indirect discharge method of surface velocity distribution. To measure the spring flow rate, the float method (F- method) was employed which is simple/easy, efficient, and inexpensive method to use for measuring flow rate through an open channel. The float method was likely to be most accessible, though its accuracy was limited. Where there was significant wind, large ripples, or back currents on the spring run, the method was less accurate. This method allows measuring small to large water flow with medium accuracy. Although not as accurate as a measuring device such as a flume or a flow probe, the float method provided an estimate. The method measured the time it took for a floating object to travel across a specified/know distance. This method was best used in channels with calm water and during periods of clear weather. It was not used in conditions where there was too much wind, and the surface of the water was rough resulting in the float not travelling at the normal speed.

Dropping the floater object(leaf) on the water surface helped for determining if flow was present or not through observing its movement. In the spring run, 1 metre was measured using a measuring tape, a stick was used to mark the start and the end of where the float travelled. Then, we threw the floating object (leaf) into the spring channel upstream of the marker A (Figure 4.4). The timer was on standby and started when the object crossed the upstream marker (A) and stopped the timer when it reached the downstream marker (B) as presented in Figure 4.4. The time it took for the float (leaf) to travel over the 1 metre distance was recorded. The measurement of spring flow procedure was repeated at least 3 times on the same travel distance. The average time was used to determine the flow measurement. To determine the speed, the velocity formula was used (Equation 1) as it allowed to measure the change in position (Δs) over the change in time (Δ t).

$$\text{Velocity (m/s)} = \Delta s/\Delta t = \text{Distance travelled(m)/ Average time(sec)} \qquad \textbf{Equation 1}$$

Figure 4.4: Method applied in measuring spring flows with equipment used

4.4.3 Assessment of the chemistry of springs

Various methods are used to assess groundwater discharge within the bigger aspect of interaction (Brodie et al. 2007). These can be grouped into field-based measurements and desktop methods. Field based methods include hydrometric analysis, hydrochemical analysis, environmental tracers, stable isotope analysis, remote sensing, geophysical and field indicators. Hydrogeological mapping, modelling and hydrographical analysis are some of the desktop methods. All these methods differ in terms of their application, procedure, spatial and temporal scale. This study used the hydrochemistry and environmental tracer methods since they can provide information on connectivity at catchment scale as well as providing spatial and temporal dynamics of spring hydrogeology.

During the field visit, water samples were collected from the validated springs in the catchment during both wet (rainy) and dry periods. Sampling period took place in September 2021 that was representative of the wet period due to more rainfall, high river flows, and low evapotranspiration while April 2021 data was representative of the dry period with high temperature, evapotranspiration, and low flows. Secondary datasets were also collected from the review of records. Water samples were collected in polyethylene water bottles of 1l capacity using purposive sampling method (Figure 4.5). The water to be sampled, was first used to rinse the bottle to avoid any dilution before collecting the sample. At each sampling point, the bottles were physically submerged into spring water from the eye and were filled to the brim of the water bottle to get a representative water sample. For spring runs that had little water, a well rinsed beaker of 250 ml was used to collect the water from the spring from which it was transferred to the sampling bottle. The beaker was rinsed at least 3 times to avoid cross contamination of the sample with particles in the beaker. Care was taken to ensure the correct labelling, packaging, and transportation of collected water samples to prevent hydrochemical changes, spillages and/or misinterpretation of laboratory results due to incorrect labelling. The samples were preserved in the cooler box containing ice to keep the temperature standard (4°C) until analysis was performed.

Figure 4.5: Sampling of some springs in the catchment

Temperature, pH, dissolved oxygen, and Electrical Conductivity (EC) were measured in-situ with a YSI portable multi-parameter sensor tool (Figure 4.6). These parameters were measured in the field because they do change once the water samples are exposed to ambient conditions, as well as during storage and laboratory analysis (Hiscock, 2005). The measured value for each parameter was recorded only when meter had stabilized. Before each field trip, the probes were calibrated using standardized solutions within the research area's EC and pH ranges.

Electrical conductivity along the river is unlikely to change significantly, unless the river receives inputs of groundwater with different chemical characteristics, or the river water becomes contaminated due to anthropogenic activity. It was one of the most frequently measured water-quality parameters that was used to assess the salinity, ionic strength, major solute concentrations, and total dissolved solids of natural waters and soil solutions. As a result, to define hydrochemical characteristics, EC was employed as a proxy for salinity and degree of mineralization. The extent of salinization was indicated using the classification by Freeze and Cherry (1979) as provided in Table 4.1; Hiscock and Bense (2014) where total dissolved solids (TDS) was calculated from EC values using the relationship.

$$\text{TDS (mg/l)} = 0.64 * \text{EC } (\mu\text{S/cm}) \qquad \textbf{Equation 2}$$

Figure 4.6: General chemical parameter measurement *in-situ* using YSI handheld multiparameter meter

Table 4.1: Simplified classification of groundwater salinization (Freeze and Cherry, 1979)

Type of water	TDS range(mg/L)
Fresh water type	<1000

Brackish water type	1 000 -10 000
Saline water type	10 000 -100 000
Brine water type	>100 000

All water samples were analysed for major ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}) and chloride (Cl^{-}). This was due to these ions comprising over 90% of all dissolved solids in groundwater regardless of whether the water was fresh or saline (Freeze and Cherry, 1979). These major ions were analysed at the BIOGRIP Node for Soil and Water Analysis in the University of Stellenbosch using Metrohm IC930 Ion Chromatography system (Figure 4.7). Standard methods were used according to the Stellenbosch University laboratory for water analysis. The results of the analysis were verified using the Cation-Anion balance (CAB) to evaluate the reliability of the dataset and was subjected to descriptive statistics to summarise the data and to trilinear piper plots to identify dominant water types. The similarities and differences between separate water analyses were spotted through piper diagram, therefore, it was suitable for analysing spatial and temporal variations in spring hydrogeology. Water type on these plots is determined by the position of the water sample. Samples that plot within the same region are of the same water type and are therefore likely to originate from the same source. While Gibbs plots were used to determine the chemical reactions involved in the evolution of groundwater chemistry as they dependent on the aquifer material or the country rock mineralogy with which the groundwater was associated with. The diagrams were generated using the Geochemist's Workbench student edition 12.0 software (Xaza 2020).

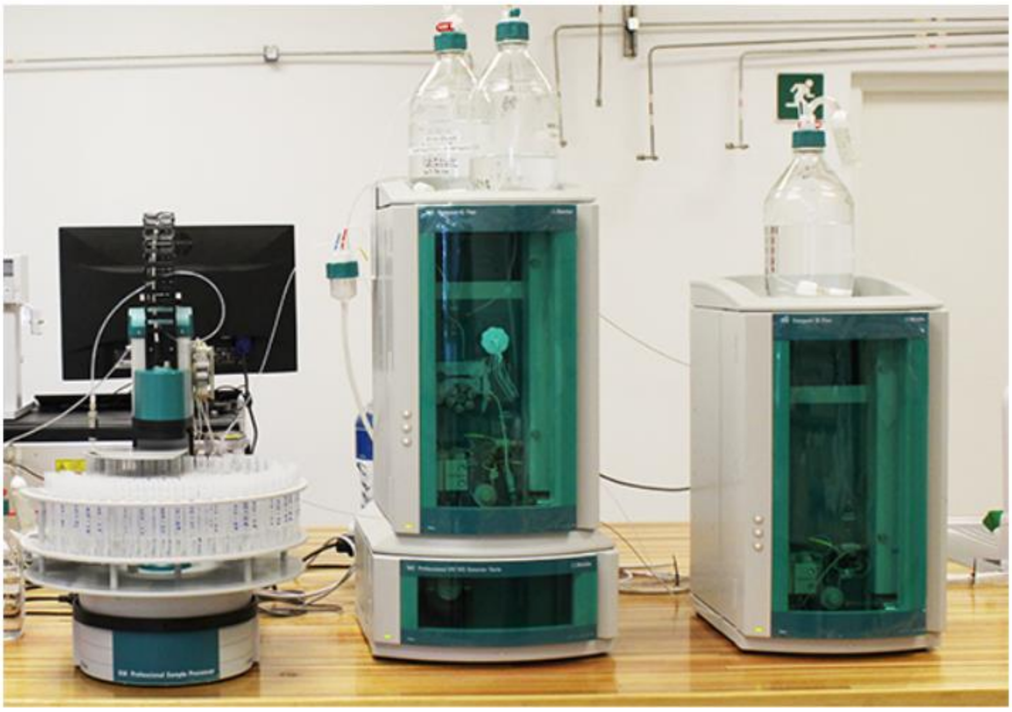


Figure 4.7: Ion chromatography instrument at the BIOGRIP Node for Soil and Water Analysis.

The mostly used statistical method among the families of multivariate statistics is the Principal Component Analysis (PCA). This method can identify patterns in the data and presents them based on the similarities or dissimilarities within the dataset. Indicating patterns in extensive datasets with complex relations is a challenging task to undertake. Thus, using PCA can provide reliable results on the dominant components. The advantage of PCA is that it can summarize the multivariate dataset by reducing the statistical noise in the data, exposing the outliers, and then arranging components in descending order. Specifically, a Pearson correlation matrix was used to determine the relationship between variables. Classification of the correlation matrix are based on Guilford's rule of thumb (see Table 4.2) for the Pearson product-moment correlation.

Table 4.2: Guilford's rule of thumb for interpreting correlation coefficients r-value (Xaza, 2020)

r-value	Interpretation
0.0 - 0.29	Negligible or little correlation
0.3 - 0.49	Low correlation
0.5 - 0.69	Moderate or marked
0.7 - 0.89	High correlation
0.9 - 1.0	Very high correlation

Amber glass bottles were used to collect water samples from different springs at various locations of Heuningnes catchment (as shown in Figure 4.8), which are mainly used for drinking, irrigation and also other everyday purposes. These bottles kept the water samples safe and unchanged. Following radon sampling procedure according to RAD7 manual, each sample was collected into 250ml glass bottle (Figure 4.8) and the vial was closed immediately after collection to avoid contact with the open air (Durridge 2012). After collecting each sample (within 48 hours) was taken to Physics Laboratory, University of the Western Cape for measuring radon concentration.

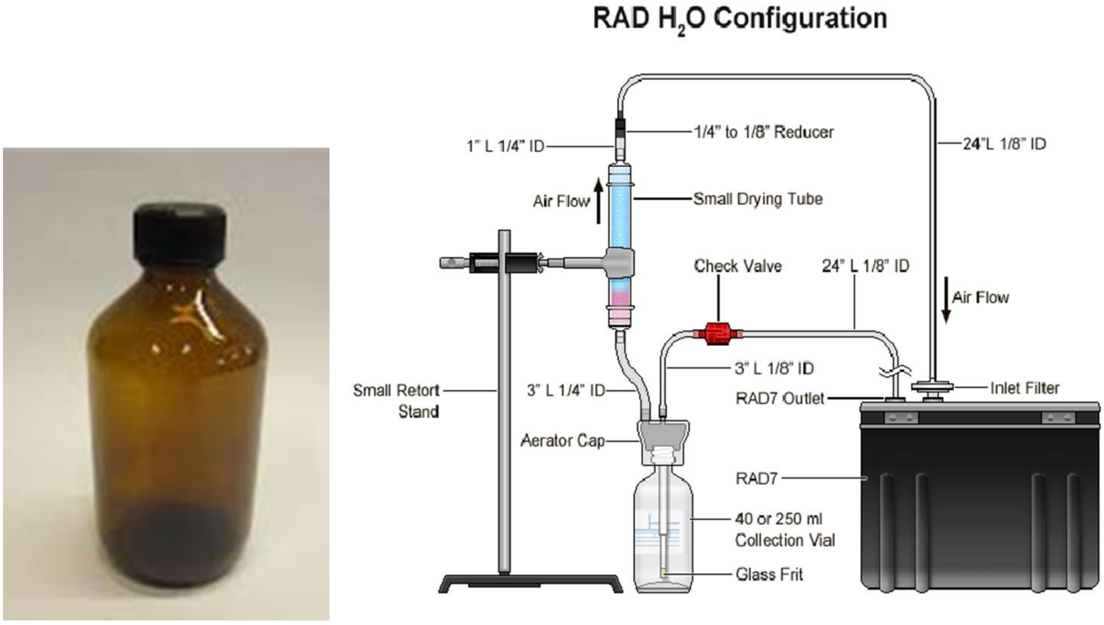


Figure 4.8: Radon water sampling bottle (left) and schematic representation of the RAD-7 experimental set-up (right) for radon analysis (Durridge 2012).

The radon activity concentration in the groundwater, surface water and spring water was measured using a RAD7 monitor, which is an electronic radon detector manufactured by Durridge Company, USA with RAD H2O technique (shown in Figure 4.8). This equipment was used for monitoring radon concentration in water which had specific protocols for water tests. The equipment RAD7 detected alpha particles only and it used a solid-state semiconductor detector that converted alpha radiation directly to an electrical signal with the advantage of electronically determining the energy of each alpha particle (Durridge 2012). Figure 4.9 below shows graphical representation of the steps undertaken to analyse water samples for radon concentration using RAD H2O technique in the Physic department at the University of the Western Cape.

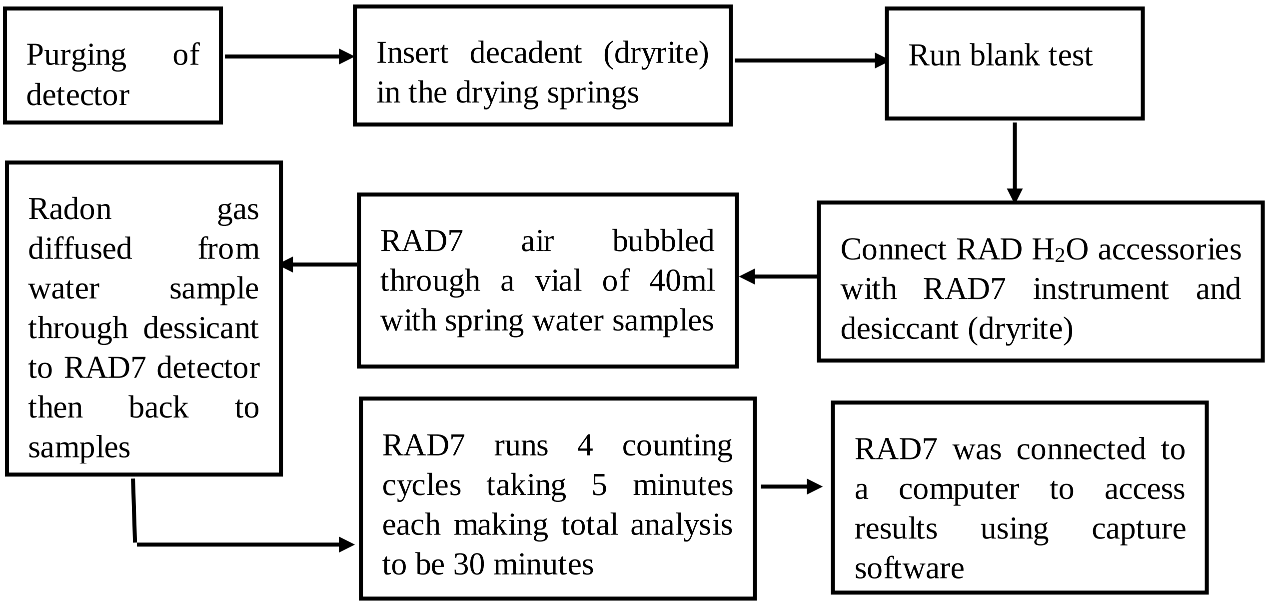


Figure 4.9: Steps undertaken to analyse water samples for radon concentration using RAD H_2O technique

4.5 Quality assurance and quality control/Research Integrity

Quality assurance (QA) is a set of operating principles that, when consistently applied during sample collection and analysis, will result in data of known and defensible quality. That is, the analytical result's accuracy can be reported with a high degree of certainty. Quality control was carried out in a number of ways. The following protocols were followed to ensure the reliability and validity of the data collection and analysis method for evaluating the hydrogeology of spring processes.

4.5.1 Adequacy of results

All the sampling, storage and transportation procedures of water samples were adhered to so that all samples were not contaminated in anyway. Water samples from springs were acquired from the eye of each spring. The field water quality parameters, for instance temperature, EC and pH that change during transportation and storage were measured on site immediately during sampling. The multi-parameter probe was calibrated on each field day when measuring water quality field parameters. In addition, before collecting the samples for analysis, the sample bottles (polyethylene) were washed at least three times with sample water. All the water samples were tested/analysed in an approved laboratory that followed international guidelines. A GPS was used to validate the location of springs distribution spatially, and a permanent mark was placed on site for easy identification. Duplicate samples were sent to the laboratory from the same spring and were decanted into two different bottles and marked differently. The results from this study were compared to those that are conducted in the same setting as the study area. Therefore, the primary data was used to validate the secondary data

4.5.2 Reliability of results

To ensure the reliability of the spring parameter estimation results, the estimates obtained were compared with those estimates by previous authors such as Manyama (2017), Xaza (2020), Banda (2019), and Mazvimavi et al. (2017) who also estimated the hydrochemistry parameters in Heuningnes Catchment using similar methods and same sampling points as the current study. To ensure the reliability of the results on spring hydrogeology, data for water chemistry parameters was subjected to charge balance error (CBE) using Equation (2). Following the principle of electroneutrality, stating that water cannot carry the net electrical charge, but must always be electrical neutral (Younger 2007). Some authors (Weight 2004, Younger 2007, Hiscock and Bense 2014) claimed that an acceptable water analysis have CBE less than 5% is suitable for scientific research, while errors of 5–10% should be used with caution. Samples with cation anion balance above 15% should be discarded.

CBE (%) = [∑ (cation concentration) - ∑ (anion concentration)/ ∑ (cation + anion concentration)] X 10 **Equation 2**

The CBE can be positive or negative. A positive CBE means there are more cations in the water sample than anions. A negative CBE, on the other hand, denotes the presence of more anions.

Table 4.3: Charge balance results

Site Name	Sample ID	CBE (%)
Sandfontein	Spring 1	-0.188
Elim Right	SP4R	-3.064
Rhenostekop	Spring 2	2.339
Elim Home	Spring 3	-6.198
Elim Right	Spring 4	-3.009
Youth Spring	SP4R	-3.064
Spanjaardskloof	SPJKF	-6.011
Youth Spring	E. HOME	-7.506

Wolvegat	WVGT	3.169
Sandfontein	SDFTN	0.322
Tiersfontein	CCP	6.918
Elim Right	E.RGT	-2.887
Elim Left	E.LFT	-1.628

Most samples had a negative CBE and fell within the <10% (Table 4.3). Nine samples had a charge balance error (CBE) less than 5% and 4 samples had an error between 5% and 10% with no samples above the 15% CBE.

4.5.3 Validity of results

In this study, measurements were done to conceptualize the subsurface and flow system, assessment of spring-river interaction. The information generated on these aspects was used to provide an explanation of how the subsurface facilitates water flow to springs. Even though the study did not measure directly spring flow rate, but information generated from the aspects of flow dynamics measured in this study allowed for flow estimations.

4.6 Statement of ethical consideration

The integrity of any research should be based on four principles, according to the Singapore statement on research integrity: honesty in all aspects of research, accountability in the conduct of research, professional courtesy, and fairness in working with others, and good stewardship of research on behalf of others (Resnik and Shamoo 2011). Prior to field experimental research, legal considerations were adhered to by ensuring permission to access privately owned sites was gained through a verbal agreement with the owners (Figure 4.10). These includes all the sites where springs were protected by community and those that had spring eye in private boundaries such as within the yard of farmers. In addition, access to the secondary data that was used for this research was granted, the principle of honesty was applied because the data and findings were shared openly to the research team. The permission to request data was gained through a verbal agreement between students and supervisors, then the response to grant usage of data was in written form such as email. All research papers and secondary data that made material contribution to the research were appropriately referenced/ to acknowledge their efforts and contributions.

Figure 4.10: Farmer providing oral right of way agreement to enter private owned land in Heuningnes.

In order to avoid denial of access to areas with springs, during the verbal agreement, the benefits and exposures associated with the research were fully conveyed to the private landowners. Relevant authorities (farmers and community stakeholders) were informed verbally about dates/days the involved students and staff from the University of the Western Cape were going to be on the catchment to access certain sites. The study did not use anything that could harm the environment and the people, to avoid causing harm to the environment or people. During the assessment of spring water chemistry, no tracers were introduced into the environment, which might potentially modify groundwater quality and harm the environment. When measuring the spring flows, the channels were not modified to avoid changing the original environment of the springs and after accessing each site, the gates were closed to avoid vandalism and to maintain a standard relationship with owners. As data interpretations were completed to address the specified objectives, the principle of integrity was also implemented. Everyone involved in the research was handled with dignity and respect, and everyone was fully informed about the research processes.

4.6 Limitations of the study

The first limitation of the study was accessing the spring eyes and locating the springs, as the locations documented by previous researchers in the catchment were not the actual spots of discharge. Performing this activity was time consuming and challenging to collect data. From the acquired coordinates of the springs from secondary, some were incorrect while some were referring to ponds. In addition, some areas were not accessible due to the area being overgrown by vegetation. To overcome this limitation, we then traced the sources of the observed waters in the ponds and rivers recorded in secondary data, where we walked between bushes investigating/tracing the points on the ground where water was coming to the surface. The study solved the limitation in overgrowth in vegetation and fallen trees that delayed/limited data collection. The study found the right equipment such as panga machete/knives to clear pathway to get to the actual spring eye.

The second limitation of the study was related to admin procedures of organizing field trips. Because it caused delays as I had to organize vehicles for transportation of equipment and accessing the sites, accommodation as the catchment is far. To overcome this limitation, I communicated with my supervisors and departmental administrators that assisted in booking vehicles and organizing funds for the trip. In addition, my colleagues working in the catchment provided guidance on appropriate accommodation with rates to contact for reservations. Thereafter, I made the necessary calls for booking and payments.

The last limitation of the study were the regulations of COVID-19, which resulted in country lockdown restricting movement that delayed the planned field trips for primary data collection. The project area is 185 km from the University of the Western Cape, and under normal operating conditions, research team members would put up for some nights in Struisbaai. During 2020 all facilities providing accommodation were closed. This limitation caused a delay in time for collection of large data sets for long-term monitoring. To overcome this limitation, the study resumed with planned sampling field trips right after the regulations were eased down. In addition, the research overcame this limitation through the use of a research design that enabled the generation of key important aspects about spring hydrogeology. Even though the data was not long term, however the study manged to capture seasonality with data for both wet and dry season.

Chapter 5: Results and Discussions

5.1 Introduction

This chapter presents and discusses results obtained for the three objectives of the study. The first objective was to describe subsurface conditions for spring occurrence, the second one was to determine the flow dynamics of spring water. Lastly, assessing the quality of spring water was the third objective of the research study. The chapter argues that groundwater discharges through springs need to be evaluated first before establishing their influence on the environment and for human needs. Therefore, the question posed was "What are the subsurface conditions responsible for spring occurrences?"

To achieve objective 1 on subsurface conditions for spring occurrence, the study collected quantitative primary datasets from field measurements taken during research period. Data collected in the field included spatial coordinates and elevation of the springs that were collected using GPS (Global Positioning System). Secondary data sets were also collected from review of records from various sources such as Water Research Commission (WRC) reports and previous scholars in catchment. The secondary data included geological cross-section and groundwater flow direction models. A conceptual model was developed using Surfer 11 that merged primary and secondary data. The spring locations and geological cross sections were merged for clear representation on the subsurface with respect to each spring point.

To achieve objective 3 which assessed the chemistry of spring water, the study gathered quantitative primary data from samples collected in springs and from measurements of in-situ physicochemical parameters within the area. Quantitative secondary data was also collected from previous projects within the study area. Water samples from springs were sent to the laboratory at the University of Stellenbosch for analysis of major ions using Metrohm IC930 Ion Chromatography system. This equipment was specifically used for the analysis of major dissolved components of spring waters, which included the anions bicarbonate, chloride and sulphate, and the cations sodium, calcium, magnesium and potassium.

5.2 Description of results

5.2.1 Description of subsurface conditions for spring occurrence

This section integrates different hydrogeological data to develop a groundwater discharge conceptual model for the study area. Geology, hydrogeology, recharge/discharge, groundwater flow and hydrology data were used to construct the conceptual model while chemistry data was used to verify the conceptual understanding of the model. Developing an accurate conceptual model is an essential step in the process of a groundwater modelling. The conceptual model provides information on how groundwater flows in the various geological layers. A discussion of how the different hydrogeologic settings influences spring occurrence in the study area is presented.

5.2.1.1 Spatial distribution of springs

Table 5.1 shows the spring’s coordinates and elevations that were validated within the Heuningnes Catchment during April and September 2021. The catchment area is 784 km^2 with altitude varying from 100 – 654 m above sea level in the headwaters or uplands, 41–100m in midslopes, and 7 – 40 m in lowlands. The validated springs were located within all three elevation groups within the catchment, with 4 springs in upland, 3 springs located in the middle section and 3 in the lowland of the catchment.

Table 5.1: The validated springs coordinates and altitudes

		Coordinates		
No.	**Site Name**	**Degrees Lat.**	**Degrees Lon.**	**Elevation(m)**
1	Sandfontein	34º 29.255'	019º 41.677'	219
2	Rhenostekop	34º 45.789'	019º 55.850'	16
3	Youth Spring	34º 35.941'	019º 45.271'	74
4	Elim Right	34º 35.530'	019º 44.850'	87
5	Elim left	34º 35.576'	019º 44.835'	95
6	Rater River Spring	34º 43.737'	019º 40.895'	37
7	Spanjaardskloof	34º 29.254'	019º 41.673'	20
8	Wolvegat	34º 40.133'	019º 38.240'	157
9	Sandfontein	34º 29.256'	019º 41.672'	222

10	Tiersfontein	34º 34.075'	019º 35.7852'	214

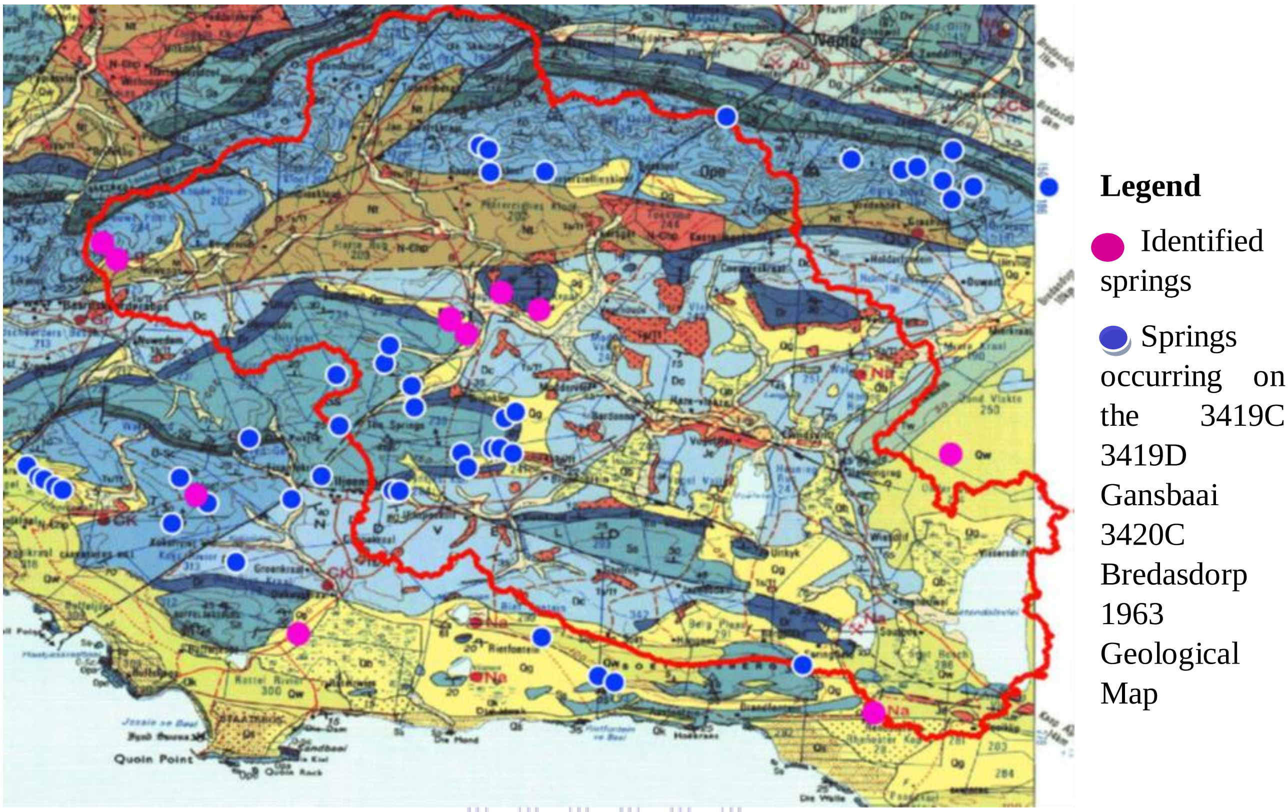


Figure 5.1: Locations of springs in the Heuningnes Catchment.

Figure 5.1 shows the springs available in the study area. The background of the figure is the geology map, 3319 Worcester 1:250,000 Geological Series from Geological Survey of South Africa, Pretoria published in 1997. In Figure 5.1, the blue circles represent springs occurring on the 3419C 3419D Gansbaai 3420C Bredasdorp 1963 Geological Map. The pink circles represent the springs recently identified by the current study. The current study managed to locate 6 springs in April 2021(dry period) and additional 4 in September 2021(wet) during a field visit to the catchment through ground-truthing. The lesser number of springs identified during the dry season was expected in the catchment due to little/no rainfall. In contrast with the wet season, additional springs were discovered compared to previous season. This implied that the additional springs identified in wet season were seasonally fed springs as they had no flows in dry season and had flows in wet season. With most of the identified springs focused on quaternary catchments G50B and G50C, with their spatial coordinates presented in Table 5.1. Springs, which were selected for this study, were delineated by position within the catchment in connection to the elevation which assisted in delineating the catchment as headwater, mid-section, and low land. Several springs occur in the Nuwejaars Catchment, and they vary with position and lithology (Figure 5.1).

5.2.1.2 Geological subsurface setting

Regionally, the following main geological formations underlain the Nuwejaars Catchment; Malmesbury Group; Table Mountain Group (TMG); Cape Granite Group; Bokkeveld Group and Bredasdorp Group (Table 5.2). The basement geology of the area was made up of the meta-sediments of the Malmesbury Group, while the Table Mountain, Bokkeveld and the others were deposited over the Malmesbury Group. The Nuwejaars Catchment was discovered to be locally confined within the TMG and the Bokkeveld Groups of the Cape Super Group and the Bredasdorp Group. This locally confined system was responsible for a confined aquifer system with high pressure resulting in artesian conditions in some springs in the study catchment, e.g., Sandfontein springs which were flowing during the dry season. Thus, this has an influence on discharge as it regulates the quantity of water that can flow through the rock unit with quaternary sediments (unconsolidated material) being dominant overlying the TMG and Bokkeveld group, which are characterised by high porosity and permeability inducing the flow dynamics.

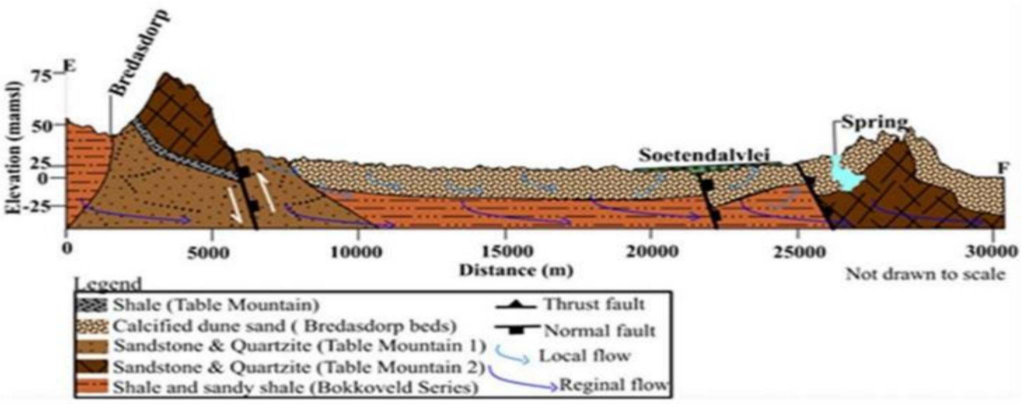
The Bokkeveld Group dominated the middle subdivisions of the catchment consisting of fine-grained sandstones and shales that conformably overlaid the TMG in an off-lapping succession (Thamm and Johnson, 2006). The shales and sandstones were products of the marine continental slope muds of early to mid-Devonian thereby explaining saline nature of the spring water from such rocks. The Bokkeveld Group are prone to weathering, occurrence of fractures and faulting and was intruded by the basement lithologies. Several faults also were cutting through the Napier and Bredasdorp Mountains in a north- east to south-west and east to north- west direction. Fractures and faults were the secondary structures dominant in the area and influenced the main flow paths and direction in the catchment as they acted as conduits. In general terms, the upper confined aquifers occurred within tertiary and quaternary deposits of unconsolidated and weathered sand and shale with a thickness ranging between 10 to 25 m (Table 5.2).

Table 5.2: Hydrostratigraphy of the study area (adapted from Mazvimavi et al. 2017)

Era	Period	Geological groups	Lithology	Hydro-stratigraphy

Cenezoic	Quaternary and Tertiary	Bredasdorp	Unconsolidated to semi-consolidated shelly, calcareous sand	Low yield primary porosity aquifers
Devonian	Paleozoic	Bokkeveld	Shales and sandy shales	Low yield secondary porosity aquifers
Silurian-Ordovician	Paleozoic	Table Mountain	Quartz, sandstone, shale, siltstone, and conglomerate	High yield secondary porosity, occurring at high depths
Pre-Cambrian		Cape granite suite	Basement rock	Aquiclude
		Malmesbury		

5.2.1.3 Subsurface merged with spatial distribution of springs



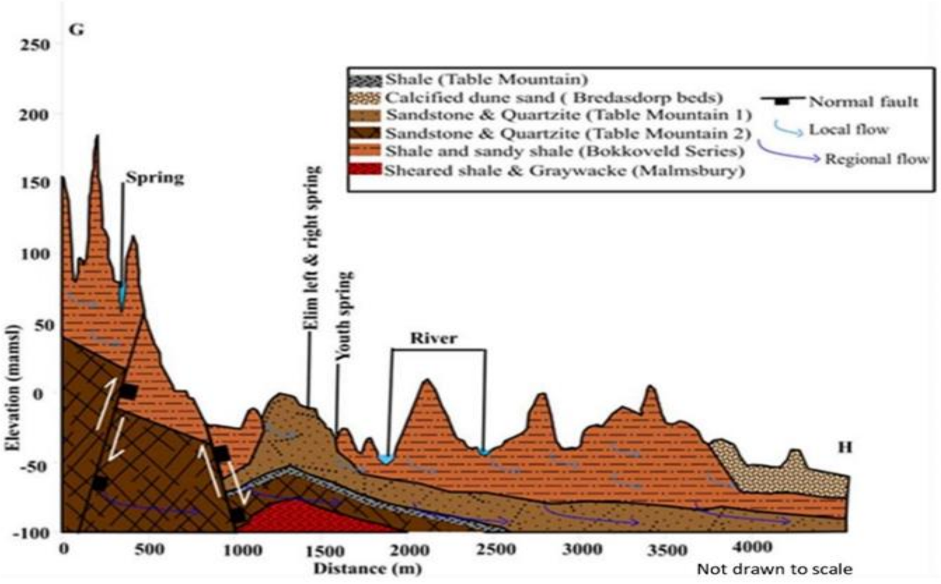


Figure 5.2: A conceptual model of groundwater discharge for Heuningnes Catchment produced from interpolation of results from surfer and Arc GIS

A 2-D hydrogeological conceptual model of the Heuningnes Catchment and vicinity developed using the Vector Tool in Surfer software version 11 is shown in Figure 5.2. The justification to the software was that it could provide quick and automated way of analysis and representation. From Figure 5.2 it is evident that groundwater flow direction is from areas of high elevation to areas of lower elevation mimicking the topographical arrangement which was foreseeable. The regional groundwater flow is from the western side towards the eastern part of the media depicted by the navy-blue arrows. In addition, Figure 5.2 also shows flow lines which indicate the direction of flow of control occurring on the subsurface. The conceptual model also shows that springs are emerging through 3 geological groups namely, calcified dune sands of Bredasdorp group, shale, and sandy shale (Bokkeveld), lastly the sandstone and quartzite (Table Mountain).

5.2.2 Description of flow dynamics of spring water

This section describes data generated from the second objective of the present study. Data obtained from the identification and measurement of spring flows are presented. In the Western Cape generally, summer months are from November to March and winter months are from May till August. At the end of the dry and wet season in April and September 2021, respectively, the study conducted field visits in search for springs, which indicated locations or points on the ground surface, where water from beneath the ground emerges on to the surface. The reason for sampling in April was that it represented the end of summer, while September represented end of winter. To determine the flow dynamics of springs that addresses objective 2 of the study, flow rate data were collected from Float-method used. The time it took for the floating object to move from distance of known length was recorded and these was repeated 5 times. To analyse the collected data the velocity formula was used to estimate flow rate where average time travelled by the float was used.

5.2.2.1 Identification of flows

From the field observations, there were flows identified within some springs and some without actual flow. The identified sampling sites were photographed (Figure 5.3).

Figure 5.3: a) Identified fern plants around each spring and b) Removing leaf litter within spring flow

The observed flows during dry season were slow, as it was dry season with no local rain, and therefore expected to find no flows at all. From the springs, small flows to trickles of water were observed. The seeps did not have a defined outlet. Instead, the surface was wet which was not surprising. Around each spring identified, fern plants were dominant (Figure 5.3-a). This was expected as most fern species require moist soil and shady locations provided by tree branches (Allen & Hay 2011). The observations from the various wet areas and spring flows with leaf litter accumulation, caused little to no flows in the respective areas. However, it was observed that when the litter was removed, the flows increased compared to when there was still plant litter within the channel (Figure 5.3-b).

Figure 5.4: Observed spring flows from various sites in Heuningnes Catchment

Small trickles of water to wet areas were observed from the springs (Figure 5.4-a and d) located in Sandfontein, Elim and Tiersfontein. The Sandfontein spring which was in the upper part of the catchment just above Sandfontein river, the soil in the area was moist with high productivity of fern plant (Figure 5.3-a).

The Rhenostekop spring eye was protected through a concrete spring box covered on top with metal zinc. There was water observed in the spring box. However, the flow was absent as the water was stagnant (Figure 5.4-c). The Youth/Home spring located in Elim town had trickles of water coming from the side of the channels with leaf litter and fallen trees being observed throughout the length of the spring channel (Figure 5.4-b). Initially, little to no water was observed. However, when the leaf litter/tree barks were removed from the channel, there was a visible flow identified than the little flows observed initially, with clear sand within the channel (Figure 5.4-d). The Elim left and right springs had water within channels, but the flow was minimal. However, at the confluence of the two springs flows were higher than individual observed flows. At the confluence, the flows were higher and as a result water was protected in collection box with fencing around and the gate that was locked every now and then. The flows in the Elim area are consistent as a result the water was utilized for supply. Hence the springs can supply the Elim settlement with a population of about 1 500 persons that depend entirely on these springs for domestic water supply and dairying.

5.2.2.2 Measurement of spring flows

Springs are dynamic and evolve with time and flow in response to changes in climatological and geological conditions. The geology where a spring occurs differs from one geological group to the other depending on pressure, permeability, lithology thus determining the amount of discharge that can be expected. In addition, spring responded differently to climate variation as it determines the trends in rainfall, thus influencing groundwater storage. For example, the concept of seasonality influences the rate of flow of water from the spring in various seasons. The spring flows were measured at the end of dry and wet season to deduce the rate of discharge that can safely be relied upon from the various springs in certain seasons. Flows are often not easy to discern in small springs with low flows. Although other springs had flows within their channels, they were low(minimal) to be measured. For instance, from the Elim right spring there was water within the spring run even though the water was flowing slowly and low in quantity. Such flows could not be measured nor estimated as the spring channel was meandering.

To determine the speed, the velocity formula was used (Equation 1) and its equation components were measured in the field which were the change in position (Δs) and the change in time (Δ t).

$$\textbf{Speed (m/s)} = \Delta s / \Delta t = \textbf{Distance travelled(m)/ Average time(sec)} \quad \textbf{Equation 3}$$

Table 5.3: Floating method for 1 meter stretch from Youth/Home spring run during dry period, April 2022.

Reading	Distance (m)	Time (Sec)
1	1	9.56

2	1	8.31
3	1	9.11
4	1	7.58
Average time		8.64
Speed (m/s)		0.12

The Elim home/youth spring in the middle section of the catchment in town of Elim was the only spring where flows could be measured to determine the speed of discharge through application of the float method in end of dry season, April 2021. Four readings were taken and manually recorded (Table 5.3) and the flow velocity was determined using equation 1 where the distance travelled by the float (1m) was divided by the average time (8.64 seconds) taken by the float. The determined speed value for Elim home spring was 0.12 m/s. The greater the velocity of the water, the greater the flow rate of the water.

There were two additional springs from Sandfontein and Spanjaardskloof where flows could be measured for the wet season totaling to three discharge measurements. Table 5.4 shows the estimated flow speed of discharged water from 3 springs in September 2021 which were calculated with the application of Equation 1. Based on the estimates, Sandfontein spring was found to have the highest flow speed with the value of 0.3 m/s. While the springs in Elim youth/home and Spanjaardskloof were found to have the same speed value of 0.2 m/s. The flow rate for the spring in Elim youth/home was higher in wet season (see Table 5.4) than in dry season (see Table 5.3) which not surprising as the wet season measurement was during a rainy period.

Table 5.4: Estimated flow speed from different sites for wet period, September 2021

Site name	**Distance(metre)**	**Average time(sec)**	**Speed(m/s)**
Youth/Home	1	5.3	0.2
Sandfontein	1	3.1	0.3
Spanjaardskloof	1	4.9	0.2

The results indicated that the speed of Youth/Home spring was two magnitudes higher than those from the dry period. This was expected as the season changed from dry to wet with more rainfall. Furthermore, the rainfall which resulted in more recharge and increased storage as well as pressure resulting in the observed flows changing from 0.12m/s in dry season to 0.2m/s in wet season. The high flow rates from the spring in Sandfontein area were due to spring being in headwater that has TMG geology which was characterized by high porosity and permeability with highly fractured network resulting high discharge.

5.2.3 Description of spring hydrochemistry and hydrogeochemistry

This section describes results obtained during an assessment of spring water chemistry within the Heuningnes Catchment, using graphical data analysis, hydrochemistry, and environmental tracer methods. The results presented in this section are based on 8 spring points distributed across the catchment.

5.2.3.1 Results on spring classification

A variety of criteria can be used to classify springs. Spring classifications in the literature examined are often based on either physical qualities or occurrence criteria, such as geology, magnitude, variation, flow permanence, spring water quality and mineralization, and spring water temperature. The current study classified springs using spring water temperature (see Figure 5.5). The general classification of springs uses temperature (Kent 1969), to categorize springs as cold springs (<20°C), hypothermal/tepid spring (20-29°C) and scalding/hyperthermia spring (30-50°C).

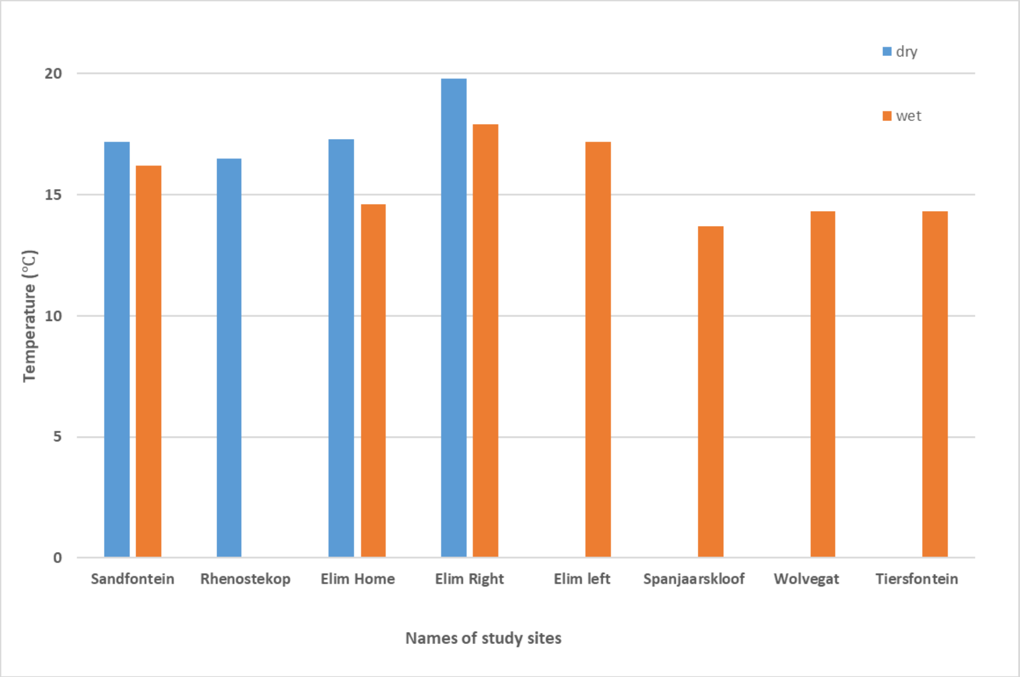


Figure 5.5: Temperature of springs during winter (wet) and summer (dry) period

The variation in temperature was clearly observed from the measurements conducted in the respective seasons, with orange columns representing wet season and blue columns for dry period. The spring water temperature in the study area ranged between 13.7℃ and 19.8℃ (Figure 5.5). The temperature of groundwater changes with depth and is influenced by the background geothermal gradient as well as the ambient temperature at the surface. The spring water temperature measurements had mean of 15.46℃ and 17.7℃ for wet and dry period respectively. Based on the above classification, all the springs namely, Sandfontein, Rhenostekop, Elim home/youth, Elim right and left, Spanjaardskloof, Wolvegat and Tiersfontein were classified as cold springs as their temperature measurements were below 20 °C (Figure 5.5). Thus, implying the depth of the springs were the same and the measurements were all within a narrow range that was below 20 °C. The narrow range of temperature was not surprising as groundwater temperature is not influenced by seasonality as in surface water. Figure 5.5 indicates that there was no spatial association between the location of springs and their temperature. For instance, Sandfontein located in headwater spring had temperature of 16.7 °C while springs in the middle section of catchment specifically in Elim had a temperature range of 16.6℃- 18.6℃.

5.2.3.2 Descriptive statistics summary for spring water physicochemical parameters

Table 5.5 shows a statistical summary of the chemical composition of springs. The results of the measured pH values ranged from 4.34 to 7.43. A slight decrease in the mean values of pH was observed from dry season to wet season with pH values below 7. The lowest and highest mean ranged from 5.05 to 5.72 in September 2021 (wet) and April 2021 (dry) respectively (Table 5.5). The mean range of pH indicated the spring waters to be slightly acidic waters (Malijani 2019). This was expected as some of the springs are associated with shale geology as described in the study area section. In terms of seasonal variation, there was not much difference in pH between dry and wet season during the study period in the catchment.

To define hydrochemical characteristics, the measured EC was employed as a proxy for salinity and degree of mineralization. EC was rapid and cheap and gave a good indication of TDS. The relationship between TDS and EC for most groundwaters is linear hence the EC could be used to calculate TDS. The extent of salinization was indicated using the classification by Freeze and Cherry (1979), see Table 4.1. The calculated TDS were from Equation 2 and is presented in Table 5.6. Based on the salinity classification in Table 4.1, the study grouped the brine and brackish water as being saline water as well. Based on the salinity categorization described above, the study results revealed that springs in the area consists of freshwater type (Freeze & Cherry 1979) with the calculated TDS less than 1 000 mg/l.

Table 5.5: Statistical analysis of chemical composition of spring water samples for April and September 2021

	pH	TDS	EC	Cl	SO_4	HCO_3	Na	K	Mg	Ca
Dry season N=5										
Mean	5.72	341.38	533.40	124.48	14.89	58.85	62.17	1.77	9.83	22.60
Std. Dev.	0.97	194.35	303.67	41.77	6.90	119.60	20.53	1.00	4.19	43.59
Minimum	5.15	167.04	261.00	66.80	9.12	5.00	35.92	0.75	5.94	2.00
Maximum	7.43	673.28	1052.00	177.24	26.51	272.79	91.82	3.45	16.83	100.57
	pH	*TDS*	*EC*	*Cl*	SO_4	HCO_3	*Na*	*K*	*Mg*	*Ca*
Wet season N=9										
Mean	5.05	144.09	225.14	102.39	12.05	9.18	50.69	1.19	6.83	4.79
Std. Dev.	0.62	50.10	78.28	50.71	4.65	4.48	22.56	0.55	2.59	3.25
Minimum	4.34	69.89	109.20	31.96	5.18	5.25	19.15	0.57	2.70	1.77
Maximum	6.16	203.01	317.20	166.30	21.68	18.42	78.23	2.14	10.06	12.30
	pH	*TDS*	*EC*	*Cl*	SO_4	HCO_3	*Na*	*K*	*Mg*	*Ca*

All season N=14										
Mean	5.29	214.55	335.24	110.28	13.07	26.92	54.79	1.40	7.90	11.15
Std. Dev.	0.80	150.96	235.88	47.33	5.47	70.88	21.81	0.76	3.43	25.88
Minimum	4.34	69.89	109.20	31.96	5.18	5.00	19.15	0.57	2.70	1.77
Maximum	7.43	673.28	1052.00	177.24	26.51	272.79	91.82	3.45	16.83	100.57

** Note all ionic concentrations are in mg/L, EC is in µS/cm, pH general units, Std. Dev. is standard deviation, n is sample size*

The electrical conductivity (EC) of the water samples ranged from 129.5 to 1052 µS/cm with the mean of 214.55 µS/cm for all seasons. The spring water samples were characterized as freshwater as the values were between 0 and 1 500 µS/cm (Table 5.6). TDS and EC were increasing towards downstream. The freshwater type from the springs was not surprising as all spring water ultimately originates from precipitation and the water is naturally filtered as it flows through geological media.

Table 5.6: EC values for spring water during the two major sampling periods

Site Name	Sample Identity	Apr-21		Sep-21		Elevation	Location
		EC	TDS	EC	TDS		
Sandfontein	Spring 1	261	167.04	193.4	123.78	219	Upstream
Wolvegat	Spring 8	-	-	109.2	69.89	-	Upstream
Spaanjardskloof	Spring 7	-	-	289.9	185.54	-	Upstream
Elim Home	Spring 3	512	327.68	317.2	203.01	74	Middle region
Elim Right	Spring 4	421	269.44	265.1	169.67	87	Middle region
Elim Left	Left sp.	-	-	173.7	111.17	95	Middle region
Rhenostekop	Spring 2	1052	673.28	-	-	16	Downstream

5.2.3.3 Major ion characteristics

This section describes major ions analysed during dry period (April) and wet period (September). Charge Balance Error (CBE) of ±10% was used as previously discussed in the reliability and validity section of this thesis, all the analysed samples were within the adopted range (Table 4.3). Results obtained from the hydrochemical analysis conducted on spring water are presented in Table 5.5. The order of cation dominance was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$

and anions was Cl^- > HCO_3^- >SO_4^{2-}. Between the two seasons, total average concentrations of major ions for spring water ranged from 1.77 – 124.48 mg/l for dry period and 1.19 – 102.39 mg/l in for wet period. Sodium and chloride are discussed in greater detail, even though the size, pattern, and trends of concentrations of each of the principal ions are included in this section. This is because sodium and chloride are conservative ions that are typically the dominant ions in spring waters in the research area.

Chloride and sodium concentrations in the Heuningnes Catchment springs were lower in wet season than in dry season. Across both seasons, values for chloride ranged between 31.96 mg/l and 177.24 mg/l, while values for sodium ranged between 19.15mg/l and 91.82 mg/l. The largest mean of 62.17 m/l for sodium and 124.48 mg/l for chlorine were both recorded in dry season. Analyzed spring water from the dry season recorded higher concentrations of sodium and chloride as compared to the wet season. The lower concentrations in wet season were attributed to the dilution effect.

The hydrogeochemical data were subjected to a correlation analysis to have a better understanding of the relationship between the measured parameters and to help group the values according to their relevance in the processes under inquiry. Table 5.7 indicates the correlation matrix for the different spring water quality parameters. The correlation between TDS and the other hydrogeochemical parameters was high in strength for the dry season (Table 5.7). The R-value between EC and TDS was 1, which was not surprising as these two variables have a linear relationship. Additionally, the EC value of the spring water samples had a strong positive correlation with Cl-, SO_4^{2-} , HCO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+} and with relative positive coefficient R-values of 0.884, 0.993, 0.953, 0.946, 0.982, 0.997 and 0.959, respectively. Ca^{2+} showed a highly positive correlation with K^+, Mg^{2+} compared to Na^+ and perfect strong positive correlation of 1 with HCO3- and strong positive correlation with SO_4^{2-} at the R-value of 0.946 compared to Cl^-. Mg^{2+} showed a strong positive correlation with all parameters and has the highest TDS compared to all other ions. Therefore, the correlation of Na^+ and Cl^- implies that they are the most dominant ions giving out a Na-Cl water type. Kumar and James (2016) indicated that a sodium-chloride ratio approximately equal to one is mostly attributed to halite dissolution because there will be equal mixing of sodium and chloride.

Table 5.7: Correlation matrix for the different groundwater quality parameters for dry season

Variables	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	*TDS*	*EC*
Cl^-	1	0.896	0.703	0.987	0.856	0.910	0.717	0.884	0.884
SO_4^{2-}	0.896	1	0.940	0.949	0.954	0.998	0.946	0.993	0.993
HCO_3^-	0.703	0.940	1	0.805	0.936	0.934	1.000	0.953	0.953
Na^+	0.987	0.949	0.805	1	0.926	0.962	0.817	0.946	0.946
K^+	0.856	0.954	0.936	0.926	1	0.969	0.942	0.982	0.982
Mg^{2+}	0.910	0.998	0.934	0.962	0.969	1	0.941	0.997	0.997
Ca^{2+}	0.717	0.946	1.000	0.817	0.942	0.941	1	0.959	0.959
TDS	0.884	0.993	0.953	0.946	0.982	0.997	0.959	1	1.000
EC	0.884	0.993	0.953	0.946	0.982	0.997	0.959	1	1

** Note all ionic concentrations and TDS are in mg/L, EC is in µS/cm*

Additionally, the EC values of spring water samples analysed for the wet period had a positive correlation with Mg^{2+}, K^+, Na^+, SO_4^-, Cl^- with relative positive coefficient r values of 0.869, 0.673, 0.929, 0.497, and 0.933, respectively (Table 5.8). There was a strong positive correlation between Ca^{2+} and HCO_3^- with an R value of 0.756, but a negative TDS correlation with both ionic parameters. There was a strong negative correlation with Ca^{2+} and HCO_3^- and all other ionic parameters. Electrical Conductivity (EC) and Total Dissolved Solids (TDS) are both presented in Table 5.7 and Table 5.8 as EC was the measured parameter while TDS was the calculated parameter. Both water quality parameters, EC, and TDS, can be used to describe salinity level. During the high rainfall periods (September) there is more chloride than sodium in most samples suggesting the dilution of sodium due to groundwater recharge, considering that chloride is largely a conservative ion.

Table 5.8: Correlation matrix for the different groundwater quality parameters for wet season

Variables	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	*TDS*	*EC*
Cl^-	1	0.476	-0.630	0.998	0.728	0.873	-0.733	0.933	0.933
SO_4^{2-}	0.476	1	-0.384	0.518	0.417	0.685	-0.544	0.497	0.497
HCO_3^-	-0.630	-0.384	1	-0.654	-0.336	-0.767	0.756	-0.674	-0.674
Na^+	0.998	0.518	-0.654	1	0.726	0.894	-0.757	0.929	0.929
K^+	0.728	0.417	-0.336	0.726	1	0.472	-0.562	0.673	0.673
Mg^{2+}	0.873	0.685	-0.767	0.894	0.472	1	-0.811	0.869	0.869
Ca^{2+}	-0.733	-0.544	0.756	-0.757	-0.562	-0.811	1	-0.786	-0.786
TDS	0.933	0.497	-0.674	0.929	0.673	0.869	-0.786	1	1.000
EC	0.933	0.497	-0.674	0.929	0.673	0.869	-0.786	1	1

** Note all ionic concentrations and TDS are in mg/L, EC is in µS/cm*

Figure 5.6 shows the classification of hydro-chemical facies for groundwater and surface waters of the study area during dry season. These are based on percentage meq/L concentrations of major ions (Piper 1944). Based on the piper diagram, two spring water types were identified. These were Ca-CI and Na-CI type. The piper diagram (Figure 5.6) revealed that most of the spring water was grouped in the sodium-chloride type (Na-CI water type) except for the Rhenostekop spring (Spring 2) which fell under calcium-chloride type (Ca-CI water type), and these two water types were therefore the dominant ions in all waters during dry period. The piper diagram generated for all the dry period sampling indicated that the Rhenostekop spring (spring 2) deviated from the clustering of the other samples. This spring fell on the center of the plot characterized by mixed water type of water (Ca-Mg-CI) from more than one quadrant within the diamond shape, which means no cations and anions exceeds 50%.

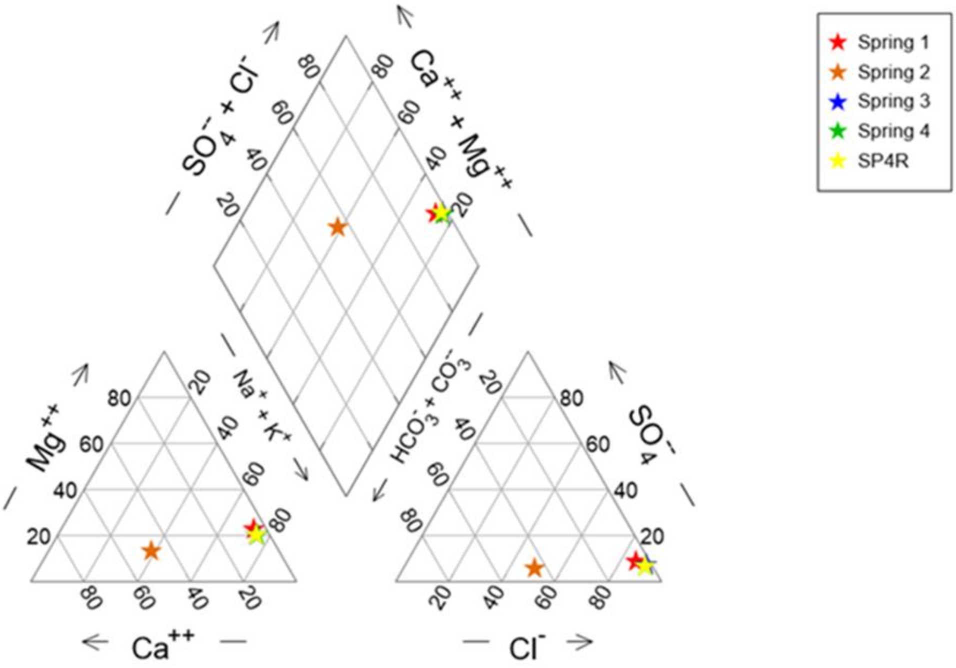


Figure 5.6: Piper diagram for spring water samples in April 2021(dry)

The piper diagram for the spring hydrochemistry of springs in Heuningnes hydrochemical data are presented in Figure 5.7 for the wet season. The water type in piper plots are generally classified into one group as all water samples were identified to have common ions, this was the sodium chloride (Na-Cl) type.

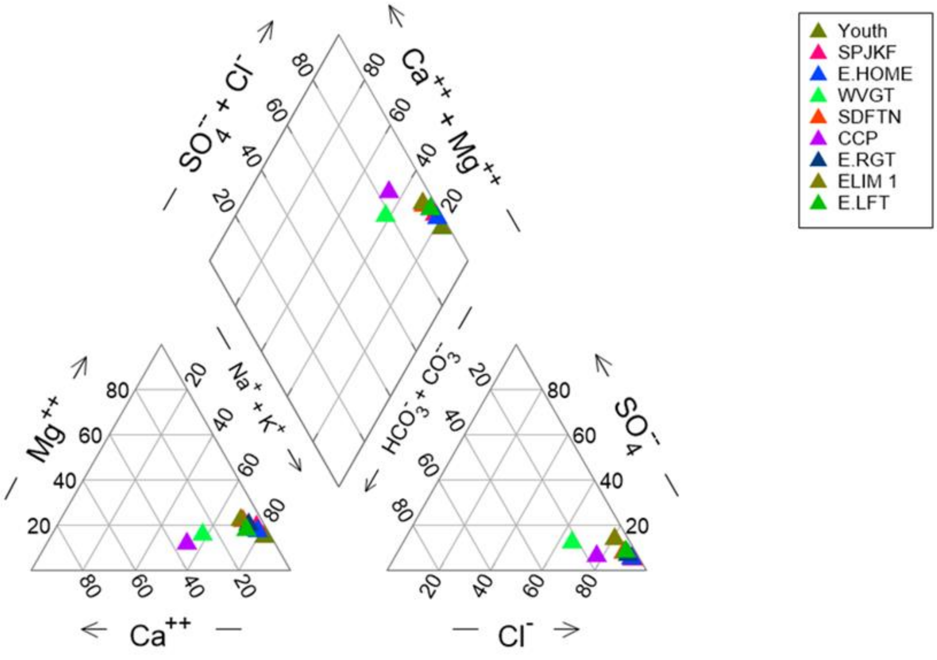


Figure 5.7: Piper diagram of springs in September 2021, wet period.

5.2.3.4 Geochemical processes controlling groundwater chemistry

Gibbs (1970) demonstrated the gochemical processes that influence the chemistry of groundwater. In additional to Piper diagram, Gibbs diagram was also used to gain better insight into hydrochemical processes such as precipitation, rock-water interaction and evaporation on spring water chemistry in the study area (Figure 5.8 & 5.9). The plotted samples on Gibbs diagram were based on TDS and the concentration of cations, namely sodium and calcium as well as anions specifically bicarbonate and chloride for the full data during the study period.

The data points on the Gibbs diagram (Figure 5.8 & 5.9) suggests that spring water chemistry was controlled principally by rock-water interaction. The plots explicitly indicate that all the cations and anions in spring waters had a rock dominance origin. Thus, chemical weathering of rock-forming minerals controls spring water chemistry in the study areas. Therefore, this implied that weathering of the subsurface material (water-rock interaction mechanisms) has influenced the spring water chemistry in the study area. This was expected, as spring water is stored on the subsurface and the water reacts with host rock hence the rock dominance.

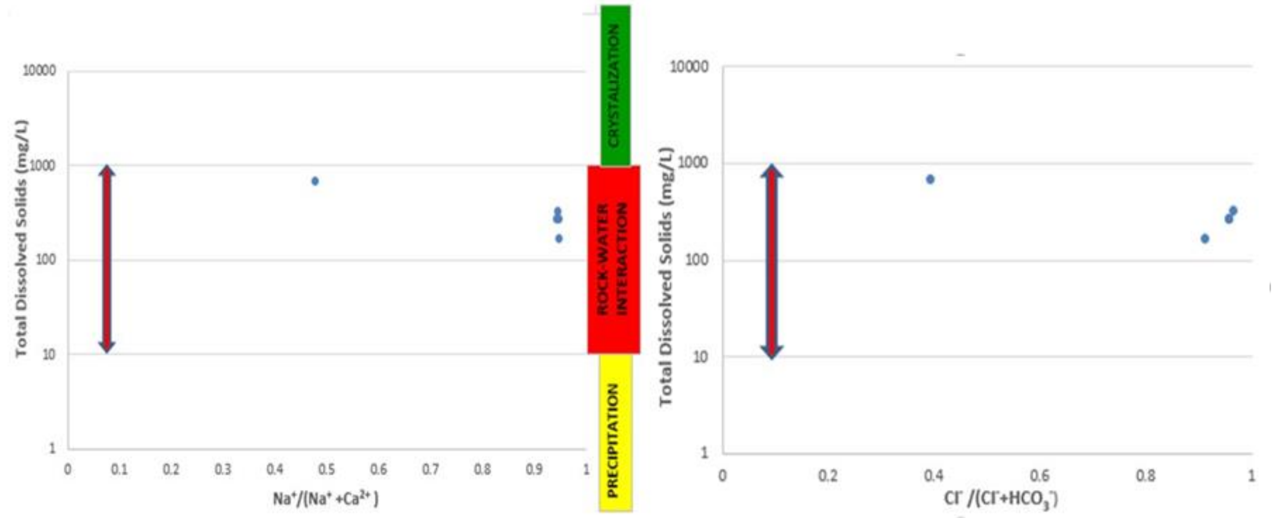


Figure 5.8: Gibbs plot for dry season (April 2021)

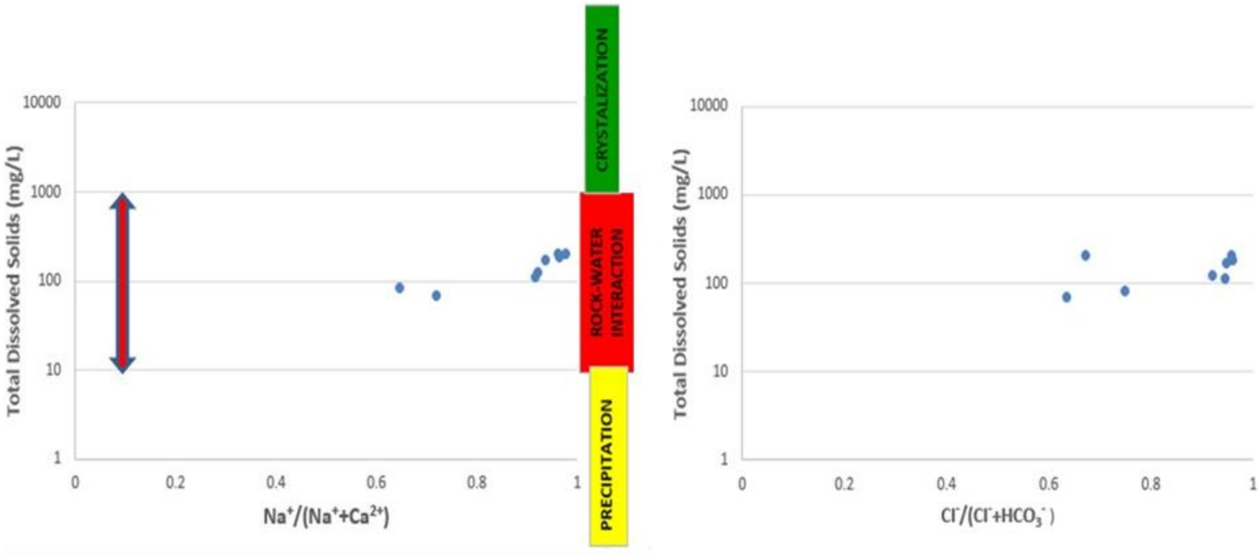


Figure 5.9: Gibbs plot for wet season (September 2021)

5.2.3.5 Radon analysis results

Radon is an odorless, colorless, and tasteless radioactive gas. Radon is generated when uranium, which can be found in all rocks and soils, decays naturally. Radon^{222} isotope concentration was considered as a tracer. Groundwater interacts with rocks on the subsurface and such water can contain radon. Figure 5.10 presented the radon concentration detected in spring water. The radon concentrations in the spring water samples ranged between 99.3 Bq/L and 119.4 Bq/L, with an average of 87.7 Bq/L (see Figure 5.10). As a result, radon was naturally occurring in spring water due to water-rock interaction, hence most spring waters were highly enriched in Rn^{222} as compared to open water bodies from which radon escapes into the atmosphere.

The radon in spring water was not surprising, as groundwater interacts with the rocks on the subsurface resulting in dissolution of the gas mixing with water. Then the water discharges to the surface with radon. Thus, Rn^{222} concentrations were significantly higher in spring water than in surface water bodies.

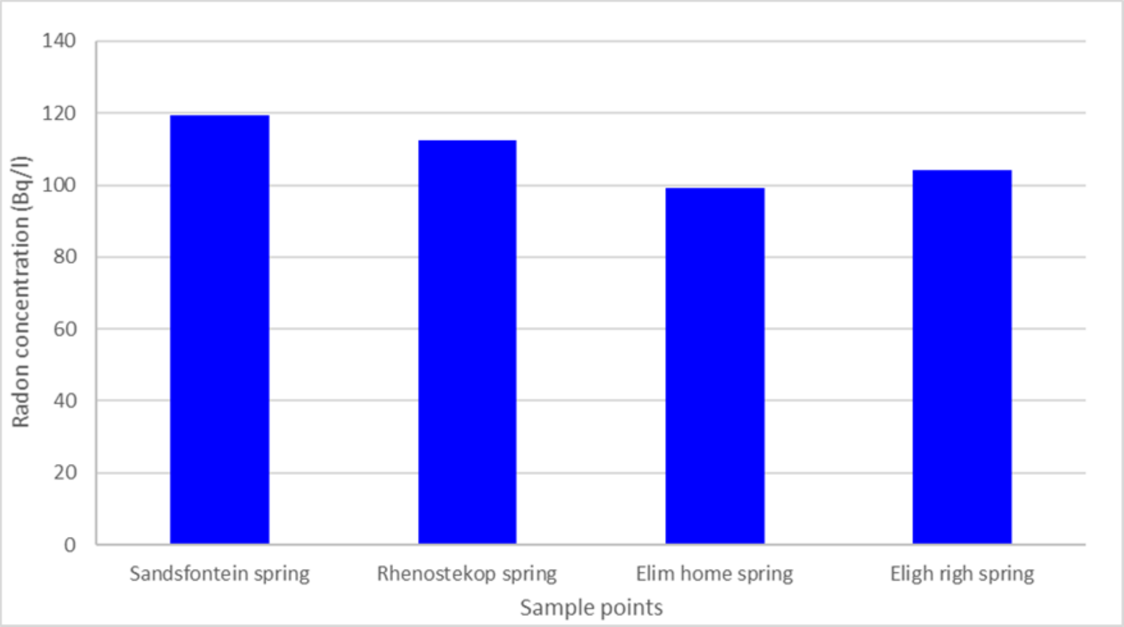


Figure 5.10: Radon concentration in springs during April 2021 as an indicator for groundwater-surface water interaction

The concentration of radon in surface water samples ranged from 905 Bq/m³ to 64550 Bq/m³ (0.905-64.55 Bq/L) measured at Blomkraal and Sandfontein river respectively (Figure 5.11). The higher radon concertation in headwater streams (Sandfontein, Koue River) implied that there was higher proportion of groundwater contribution (discharge) to the river. Furthermore, the radon concentration results showed that there was connectivity between the two water bodies, groundwater discharging through springs to surface water. Rn^{222} concentrations measured in surface water indicated groundwater contribution into surface water serving as evidence of interaction (groundwater-surface water).

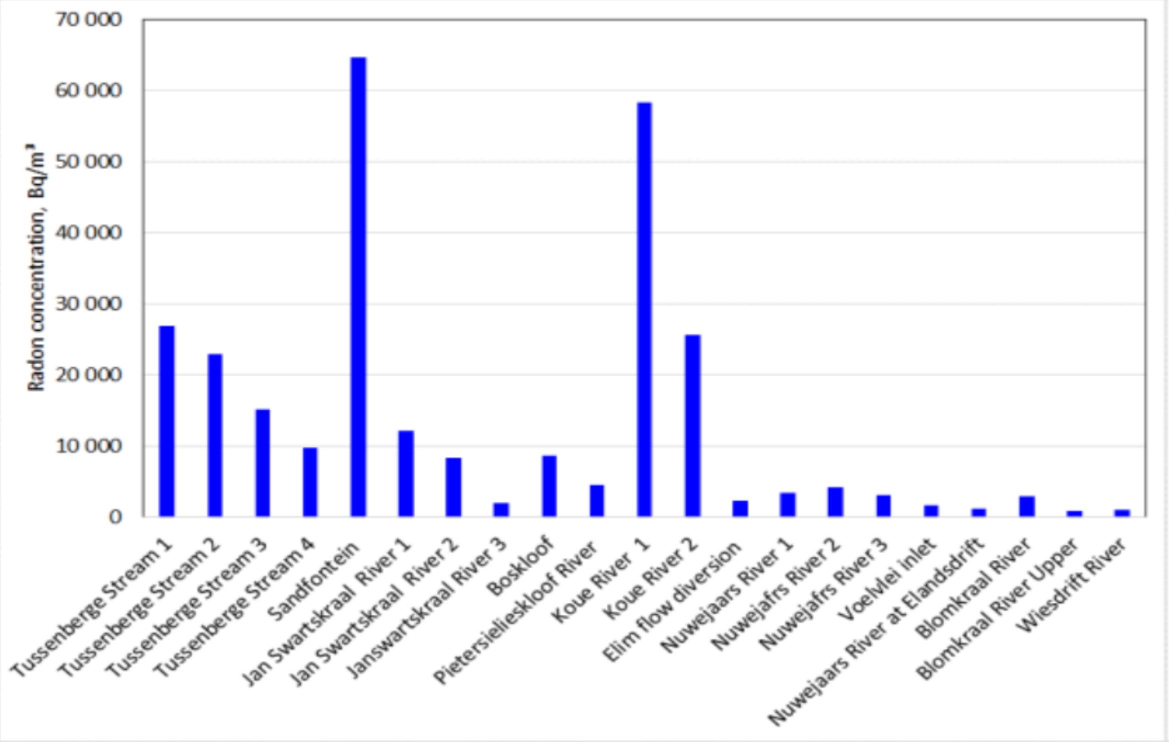


Figure 5.11: Radon concentration in rivers.

5.3 Interpretation of results

5.3.1 Interpretation of results on subsurface conditions for spring occurrence

The origin of the springs was associated with lithology such as TMG formations and linked to fractures and faults (Figure 5.1 and 5.2). Three types of springs were identified in the study catchment as shallow circulating springs, lithology-controlled springs, and fault-controlled springs. Fractures and faults were the dominant secondary structures that influenced the main flow paths and direction within the geological formation. The local and regional groundwater flow systems which influenced the occurrences of springs were controlled by lithology and faults. The fractured rock system of Table Mountain Group (TMG) overlaid the Malmesbury rocks, with the lithology of shale, sandstone, and quartzite dominates the catchment. These fractures were significant in the explaining discharge of groundwater to the surface as they provided preferential pathways for groundwater discharge to the surface through the springs. The connectedness of the fractures provides more preferential flow paths, that resulted in more discharge/yield in springs located in such geology. The Elim home spring was underlain by the Bokkeveld Group that was characterized by low yield (see Figure 5.2; Table 5.2) dominated the middle subdivisions of the catchment consisting of fine-grained sandstones and shales that conformably overlie the TMG in an off-lapping succession. However, due to the pressure system available in the subsurface and influence of Bokkeveld geological group, springs in the middle catchment always had water and supported substantial activities in the catchment. For example, the Elim settlement with a population of about 1 500 persons depends entirely on spring discharge for domestic water supply and dairying.

5.3.2 Interpretation of results on flow dynamics of the springs

This section addressed the second objective of the present study that aimed to determine the flow dynamics of spring water. It has been observed that despite no rainfall occurrence in the summer season visits, there was groundwater discharge through springs in the dry season as flows were observed. This showed that springs that were flowing in dry season were fed by deep, regional flow system. While those springs that were not flowing during the dry season showed that they were fed by the shallow, local flow system. The springs that were supported by shallow systems were sustained only by the winter rainfall since they are disconnected from the regional and intermediate flows. The estimated flow measurement in dry period indicated that there was pressure system in the subsurface that constantly pushed water to the surface hence the flows were observed throughout the seasons. This implied that the Elim youth/home spring was fed by the deeper system as there is higher pressure in such systems that further meant that the discharged water was not recharged by local rain from the area but somewhere else. The additional two spring flows from Spanjaardskloof and Sandfontein had no flows in dry season but had flows in wet season. This meant that such springs were fed by shallow system which was unconfined further implying that there was no pressure as the springs were topographically recharged in the mountains seeping down then discharged hence the flow response to rainfall pattern trends.

5.3.3 Interpretation of results on hydrochemistry analysis

Temperature of the spring below 20°C implied the springs that were investigated were cold springs. The measured pH of 4.34 to 7.43 meant that the water that emerged from the springs was slightly acidic to alkaline in nature (Malijani 2019). The low pH values were indicative of acidity in spring water in the uplands which can be attributed to the presence of quarzitic TMG rocks and the leachates from fynbos vegetation (Xaza 2020). The alkaline water could be indicative of the presence of carbonate bearing formations in lower sections of the catchment, that allowed for rapid reaction rates of carbonate minerals, resulting in acid neutralization and therefore alkaline spring water. Using the hydrochemical data, EC values of less than 1 500 µS/cm indicated that water samples from springs were characterized as freshwater, as well as based on the salinity categorization, the results revealed that water from spring in the area was of freshwater type with TDS less than 1 000mg/l. The Piper diagram showed that Na-Cl water type was the main water type in the area. This meant that the spring water was derived from marine or deep groundwater. The one spring from Rhenostekop (spring 2) was of Ca-Cl water type, indicative of mixed waters between more than 2 end member solutions with no dominant type. Suggesting the dilution of sodium due to groundwater recharge (rainfall), considering that chloride is largely a conservative ion. Using Gibbs plot, most samples in the study region were confined in the rock dominance zone. This meant that the chemical composition of spring water in the Heuningnes catchment was a result of chemical weathering of aquifer lithology. The dominance of rock-water interaction suggested that water had sufficient time to interact with host rock hence different ions were released into the water. This was confirmed by the radon concentration in spring water. However, in surface water the results of Radon^{222} analysis confirmed the presence of groundwater in surface water thereby providing scientific evidence-based results on groundwater-surface interaction.

5.4 Comparative analysis of findings from current study

This section of the thesis provides a comparative analysis of results from the current study and previous studies within the catchment and outside. Such analysis compared the current study with the reviewed literature that was presented in Chapter 2 (literature review) of the thesis. This comparative analysis is provided systematically per findings for each of the study objectives.

5.4.1 Comparative assessment of results on sub-surface conditions for spring occurrence

The findings of the study indicated that most springs in the study area were associated with TMG formations and closely linked to faults, fractures, and geology. The findings support earlier results reported in literature that geology and secondary structures were among the key aspects influencing spring occurrence (Banda 2019, Mazvimavi et al. 2017, Manyama 2017). Mazvimavi et al. (2017) reported the hydrogeology of the area being influenced by the changes in geology which resulted in the main flow not being across the geological boundaries but along the faults. Banda (2019) developed a conceptual hydrogeological model which explained the role of groundwater in non-perennial river systems. Banda reported that the fault seemed to act as conduit and barrier at other locations. However, the results from the above-mentioned studies generally deduced the groundwater flow direction with very specific information about springs. Therefore, the current study confirmed the actual conditions that resulted in spring occurrences at the respective locations within the catchment.

Gleason et al. (2020) assessed the hydrogeology of desert springs to determine the geologic controls on, flow paths, and mean residence times of springs in the Panamint Mountains, California, USA. The objective of the study was to identify rock units that supports groundwater flow to springs. The study reported that major geologic control on spring occurrence were discovered to be the normal fault system as groundwater flow path emerged at faults for most sampled springs. The results agree with what was found in the Heuningnes Catchment with faults being among important controls on spring occurrence.

5.4.2 Comparative assessment of results on spring water flow dynamics

In terms of the second objective, the present study assumed that springs that were flowing during the dry season were fed by deep, regional flow system while those were not flowing in dry season but in wet season were fed by shallow, local flow system. In comparison with general groundwater flow in the catchment, Mazvimavi et al. (2017) reported that springs from the upper catchment provide water derived from deep groundwater flow systems and maintained constant river base flows throughout the year. The current study observed that spring discharge was continuous in certain areas and in some the springs dried up. These results were similar to findings of other scholars (Mokoena 2019, Mazvimavi et al. 2017, Xaza 2020, Malijani 2019) that groundwater discharge decreases due to dense invasive alien plants occurring along points of discharge. The dense invasive trees in the upper catchment have access to groundwater and cause a significant reduction of spring flow and interflow. This decreases water flowing downstream to the rest of the catchment. The results by Mazvimavi et al. (2017) agreed with what was found during the assessment of spring hydrogeology using principle of flow and field observation method, thereby proving that the method was successful in the area.

5.4.3 Comparative assessment of results on the hydrogeochemistry of spring water

Comparison of the hydrochemical analysis results from the current study with other studies by Xaza (2020), Banda (2019), Malijani (2019) and Mokoena (2019) within the same catchment that applied the concept of hydrogeochemical facies to understand the chemical character in aquifer systems. These studies analyzed similar parameters with the current study which included major ions from samples collected in the surface water and groundwater.

The results generated from the mentioned studies used similar plots and methods to confirm the dominance of sodium and chloride ions in waters of the Heuningnes Catchment. However, the study improved the methods by applying them in a different water resource and they worked successfully. Major ions data through piper plots showed that surface water and groundwater in the area were of Na-Cl types. Waters of a Na-Cl type was typical for a coastal aquifer characterised by saline, deep ancient groundwater. The results from the current study were found to be similar to those found in other studies, therefore proving usefulness of hydrochemical analysis when used to assess the hydrogeology of springs within the area. Xaza (2020) focused on hydrochemistry and Malijani (2020) worked on interaction with focus on surface water quality. Both scholars demonstrated in their results that there was a strong geological influence on water chemistry. The current study found similar results through use of Gibbs diagram with dominant geochemical process influencing spring water being water-rock interaction mechanism.

Al-Khashman et al. (2017) used hydrochemistry methods to assess the physical, chemical and hydrochemical quality of spring water in the southwestern basin of Jordan considered as a very arid to semiarid area. The samples were analyzed for temperature, electrical conductivity, dissolved oxygen, pH, major cations and anions parameters which were the same with the current study. The results from the study revealed strong positive correlation between Na^+ and Cl^- indicating the dominance of Na-Cl rich recharge water from coastal origin. Even though the current study did not determine recharge water type, but the high correlation between sodium and chloride, parameters monitored agreed to those discovered by Al-Khashman et al. (2017). Study by Durowoju (2019) and current study has used Gibbs plot to conclude on various geochemical processes that control the hydrochemistry of groundwater. The main geochemical process that controlled the geothermal spring chemistry was rock-water interaction which was the same with this research study. Strydom et al. (2021) used Rn^{222} as an environmental tracer in groundwater discharge studies to understand the concept of interaction which was regarded as a feasible option in highly fractured aquifer systems. The study by Strydom et al. (2021) reported that high Rn^{222} concentrations in surface water were attributed to the contribution of groundwater to the surface water thus confirming interaction. This corresponded well with the findings of the current study as radon confirmed groundwater-surface water interaction.

5.5 Implication of the results

5.5.1 Implication of results on subsurface conditions for spring occurrence

The purpose of undertaking an investigation on the first objective of the current study was to shed light on the spatial distribution of springs and to establish the subsurface conditions that developed these springs. In undertaking the investigation, the study hypothesized that groundwater discharge needs to be evaluated first before establishing the influence of springs in the environment. The results from the investigation provided insight on geological groups and structures that influenced the occurrence of the identified springs that further provided an insight into the classification of the different type of springs that were present in the catchment. This information revealed that geological structures such as fractures and faults provided pathway for water emerging at spring points. The outcome of the study contributed immensely to the academic spheres by adding to the literature on spring hydrogeology. In addition, these findings can be used as a reference point by other researchers as a database, source for literature review, and for knowledge contribution in science when dealing with spring hydrogeology. In practice, the results can be used for teaching purposes, for example information can be used as a case study and add material for learning.

5.5.2 Implications of springs flow dynamics

The outcomes of the second objective have an operational relevance which would benefit variety of stakeholders ranging from policy makers, water resource managers, water users such as industries and the public at large. The spring waters can be used for different activities such as for drinking water, irrigation activities and maintaining dry season flows of rivers they drain into. The study provided flow dynamics that would be beneficial to those who rely upon spring water, as to estimate the amount of water each spring could yield from the velocities measured and the best times for utilization of the springs. In terms of the operational relevance, it is likely that the estimated spring flow rates demonstrated in this investigation can be readily extrapolated to other settings particularly in cold springs where flows from small springs have not been measured over time and seasons. Practioners such as farmers and municipalities need to know these flow dynamics that can support water supply thus providing an insight for policy modification which can further protect the water resource. The spring flow dynamics may also be used for an environment that depends on groundwater. Plants that relied on groundwater discharge during different seasons or during various stages of their lifecycle, the dependency on groundwater can fluctuate. If groundwater levels become inaccessible to native vegetation, the new groundwater conditions may favor opportunistic invasive plants that displace and degrade natural habitats. Such seasonal variation in spring flows implied that two systems for springs existed in the study catchment i.e., regional, and local fed systems of springs. Such findings are important for protecting, monitoring, and allocating water resources in the water management area

5.5.3 Implication of spring water chemistry

The implications of the results on the third objective have an economic value and social development relevance in addition to operational aspects. In terms of economic value and social development, the outcomes of the investigation projects that when water and environment are considered as harmonizers rather than competitors, goals for Sustainable Development and environmental integrity can be achieved sooner than 2030, especially when chemistry and quantity are understood in the catchment. In terms of the operational aspects, the investigation provided practical evidence of spring water chemistry which would benefit a variety of stakeholders in terms of water resources. With ideas of quantity and hydrogeochemistry from the springs these results would be beneficial in terms of allocating the discharged water for utilization which would then protect the resource from deteriorating. The benefit would be around protection processes of the water resource to improve spring utilization thus protecting the resource.

5.6 Evaluation of the study

Firstly, the study was strengthened by the followed study design which was an experimental design that was field based. This design included planning the experiment properly as it was important to ensure that the right type of data and sufficient sample size are available to answer the research question of interest as clearly and efficiently as possible. This was achieved by noting down all the data that was needed and its sources, then field visits to the site were done. For example, the field involved data collection with the specific activities of observing the study area, collecting the spatial locations of springs and spring water sampling. All the data were recorded in a field book and pictures were captured which were further used for analysis. The data acquired was analyzed to meet the specified objectives and to answer the research question. This demonstrate the effectiveness of the field experimental design.

Secondly, the methods used in the study were useful as they assisted in well organized and systematic thoughts or actions of compiling the research. The desktop study, for example, included literature review which helped in identifying the gap in spring hydrogeology and previous data that was available in the study catchment. In addition, the measurement method of physicochemical parameters in-situ and spring flows enhanced the practical experience in the field. For example, readings and samples were collected from the eye of the spring which was representative of the subsurface condition instead of side measurements which were influenced by other processes, such as evaporation, changing the spring water chemistry. Furthermore, the software used, such as ArcMap for mapping the spatial distribution of springs and Surfer for subsurface had better spatial topological analytical capabilities which made the developed maps reliable. These methods assisted in understanding the study area and making inferences on the possible factors that influenced spring occurrence, water chemistry and their relationship with each other in the catchment. This is how these methods positively enhanced the results of the study.

Thirdly, the integrity of this research was good due to teamwork that allowed sharing of ideas, as some colleagues had worked in the catchment and had more insight into how the system functions as well as guidance and data acquisition. Through teamwork, my colleagues made secondary data available for inference with long time series data. For example, they helped in making me understand the catchment and we exchanged ideas and some conceptual models. Despite the strengths mentioned above, time to conduct the study was limited. The research data collected was for a period of one year due to the effects of Covid-19 lockdowns in March 2020 that restricted travelling and brought fieldwork activities to a standstill. Thus, comprehensive, and intensive fieldwork could not be done to investigate in depth all springs in the area thus affecting the data collected for seasonal variations of spring water flows and quality. However, this work could be improved by increasing the sample size and long-term monitoring for trend analysis. In addition, the study could be strengthened by analyzing more water quality parameters, such as hydrogeochemistry which includes environmental isotopes, dating as well as suitability of spring water utilization.

5.7 Summary on results and discussion

Chapter 5 presented and discussed results on the assessment of spring hydrogeology using environmental isotope (radon), graphical data analysis, correlation and hydrochemical analysis. Field observation method was used as a quantitative method to identify possible sites for spring water occurrence, and environmental isotope and hydrochemical analysis were used for confirmatory analysis to trace the source within the identified sites.

This chapter highlighted results from different objectives. A total of 10 sites had been identified through field observation method, 4 identified in uplands at Sandfontein (two springs), Wolvegat, Tiersfontein, 3 at middle slope region in Elim town and 3 at Rhenostekop, Rater River and Spanjaardskloof located in low-lying region of the catchment. The conceptual model revealed groundwater flows were from high elevated areas to low elevated areas. The highly fractured rock system TMG dominated the upper part of the catchment. Bokkeveld group was more dominant in the middle and low-lying part of catchment. Fractures and faults were dominant structures that provided preferential flow paths and direction for groundwater discharging through the spring points in the catchment. Therefore, that resulted in three types of springs that were identified as shallow circulating springs, lithology-controlled springs, and fault-controlled springs. Hydrochemical analyses showed that in both wet and dry season, all the springs in the catchment were cold springs which were classified by their temperature and by EC classification as freshwater.

Despite no rain fall, springs flowed which showed that springs that were flowing in dry season were assumed to be fed by deep, regional flow system. While those springs that were not flowing during the dry season showed that they were fed by the shallow, local flow system. The springs that were supported by shallow systems were sustained only by the winter rainfall since they are disconnected from the regional and intermediate flows. The estimated flow measurements in dry period indicated that there was pressure system in the subsurface that constantly pushed water to the surface hence the flows were observed throughout the seasons.

Hydrochemical analyses showed that in both wet and dry season, the water in the area was of Na-Cl type typical for a coastal aquifer characterized by saline, deep ancient groundwater. The water in the area was acidic to alkaline (4.34 to 7.43) and this attributed to the presence of quarzitic TMG rocks and the leachates from fynbos vegetation. The alkaline water could be indicative of the presence of carbonate bearing formations such as limestone in lower sections of the catchment, allows for rapid reaction rates of carbonate minerals, resulting in acid neutralization and therefore alkaline spring water. The findings of this study demonstrated the influence of hydrogeochemical processes in changing the water chemistry along the flow paths, with indication of strong geological influences on spring water chemistry (water-rock interaction). Radon as a tracer confirmed the contribution of groundwater to surface water bodies. The hydrochemistry confirmed that the studied springs were local springs as they were from shallow aquifer system, recently recharged hence freshwater type.

Chapter 6: Conclusion and Recommendation

6.1 Introduction

Chapter 5 of the thesis presented summary of the major findings and discusses results of the first, second, and the third objectives of the study. Chapter 6 presents conclusions derived from the analysis of the results obtained for each study objective, contributions of the study to scientific research, and it further proposes recommendations from the findings including related future research. The main objective of the study was to understand the hydrogeology of springs in the coastal region of the Heuningnes Catchment in the Western Cape. In order to provide improved knowledge and understanding on spring hydrogeology in terms of geological condition for their occurrences, distribution, flows and quality. That improved knowledge on spring hydrogeology enhanced monitoring and protection of ecosystem environment. The present study argued that if spring hydrogeology is not characterized first, then the influence of such springs on the environment and human needs cannot inform their importance and stakeholders.

To achieve the main objective, the study provided information to the research question: ‘What are the subsurface conditions responsible for spring occurrences?’ The study had three specific objectives, namely, objective 1 was on characterizing spring hydrogeology. The intention was to identify and map each spring and validate existing springs in the study catchment, as well as conceptualizing subsurface conditions for each spring occurrence on the surface. Objective 2 focused on determining the flow dynamics of springs. The intention was to measure the spring flows to estimate the discharge rate as well as identify potential sources of the identified flows and understand their variation in time and space. Objective 3 focused on assessing the hydrochemistry of springs. The intention was to identify hydrogeochemical processes responsible for temporal and spatial changes in the chemistry of groundwater, in-order to draw inferences concerning the processes that may occurred within the subsurface.

6.2 Subsurface conditions for spring occurrences

For objective 1 focused on characterising spring hydrogeology. The purpose was to demonstrate the spatial distribution of springs and to examine the geology of the area. With aim to produce conceptual model of spring hydrogeology by combining/overlaying spatial distribution and geology map.

The spatial distribution map showed the locations of springs generally in catchment which were already mapped in the geology map of Bredasdorp and Gansbaai and the validated springs by the current study. Most of the identified springs were grouped on quaternary catchments G50B and G50C. The springs validated were distributed within all three elevation groups within the catchment, with 4 springs in upland, 3 springs located in the middle section and 3 in lowland of the catchment.

Regionally, the main geological formations underlain the catchment were as follows; Malmesbury Group as basement rock; TMG with high yield, secondary porosity, occurring at high depths; Bokkeveld Group with shales and sandy shale lithology that had low yield and secondary porosity; Bredasdorp Group with unconsolidated to semi-consolidated shelly, calcareous sand lithology and low yield, primary porosity. Fractures and faults were the secondary geological structures dominant in the area.

The site-specific conceptual groundwater model developed to improve the understanding of the science of groundwater discharge through springs revealed that groundwater discharge occurred through fractures and faulting of the geological formation. Most studied springs were discovered to be associated with TMG and Bokkeveld formation. Based on these findings, the study concluded that three types of springs exist in the study catchment as shallow circulating springs, lithology-controlled springs, and fault-controlled springs. Therefore, the first objective of the study focused on characterization of spring hydrogeology was achieved and the research question was answered with valid and reliable data sets.

6.3 Flow dynamics of springs

The flow dynamic results showed that despite no rainfall occurrence in the summer season, there was always groundwater discharging through some of the springs. The results of flow rates observed from the identified springs located in headwater were due to the underlying TMG geology with fractured network and characterized by high yielding with speed of 0.3 m/s compared to studied springs. The moderate flows of 0.2 m/s revealed lithological characteristics due to differences in permeability and pressure system thus allowing groundwater to diffuse through springs outcropping on the surface. The fault and fracture system provided preferential flow path, in addition to the pressure system present in the subsurface resulting in high volume of water flow. The observed vegetation growing next to spring point reduced spring flows by the transpiration process. Based on these finding, the study concluded that springs that were flowing during periods of no rainfall were fed by deep, regional flow system. While the springs that were not flowing during the dry season were fed by the shallow, local flow system. In addition, vegetation dependency in groundwater and diversion of spring flows had an influence on the dynamic flow rates. Therefore, the second objective of the study focusing on determining the flow dynamics of springs was achieved and the research question was answered with valid and reliable data sets.

6.4 Assessment of spring hydrogeochemistry

The physicochemical characteristics results have led to the conclusion that temperature plays a significant role in the chemical composition of spring waters and the depth at which the water emanated from. Based on the general temperature classification of springs, temperature of the studied springs within Heuningnes concentrated ranged between 13.7℃ and 19.8℃. All the springs were characterized as cold springs. Spring water within the Catchment was characterized as the Na-Cl and Ca-Cl water type. The water types are typical of mixed waters between more than 2 end member solutions and marine, deep ancient groundwater respectively which are influenced by the ion exchange processes. Gibb’s plot indicated that rock-water interaction process led to chemical weathering of the rock forming minerals. ^{222}Radon isotope concentration was considered as a tracer for groundwater contribution. The radon results showed high radon values measured in spring waters, which were linked to the geological environment as the source. Radon concentration in surface water confirmed the groundwater-surface water interaction. Thus, the study concluded that sampling was indeed from groundwater discharge points (spring eye) as confirmed by radon concentration and water-rock interactions from Gibb’s plot results. Therefore, the third objective of the study that focused on assessing the hydrochemistry of springs was achieved and the research question was answered with valid and reliable data sets.

6.5 Recommendations

This research on spring hydrogeology within Heuningnes Catchment in Western Cape Province, South Africa, has contributed to the body of knowledge of cold springs in South Africa, it also provided space for future research. The following are recommendations for future research:

- Comprehensive assessment of GDEs to inform updated methods for protection, monitoring, and utilization/ allocation of water resources at catchment scale.
- Long-term monitoring of the springs for hydrochemical and isotopic analysis in order to determine and map recharge zones of springs
- Assess the spring water quality for drinking and irrigation including environmental water requirements
- Trace and date spring water

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