

**Use of Environmental Isotopes to Investigate Groundwater and Surface
Water Interaction in the South Phuthiatsana Catchment, Lesotho**

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The International Atomic Energy Agency (IAEA) financially supported the research.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION 1: PLAGIARISM

I, Thabang Sehloho Leo Phori, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

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(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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ABSTRACT

Lesotho, often referred to as the "Water Tower of Southern Africa," plays a crucial role in regional hydrology due to its high-altitude water sources, which significantly contribute to the Orange-Senqu River system. Despite its importance, comprehensive data on the country's catchment hydrology remains limited. This underscores the need to enhance understanding of Lesotho's water resources to support sustainable management under the pressures of population growth and climate change. Isotopic techniques provide valuable insights that complement conventional hydrological methods and are critical in identifying groundwater recharge, essential for effective policy development and implementation.

This study investigates groundwater and surface water (GW-SW) interactions in the South Phuthiatsana catchment, addressing a significant knowledge gap in Lesotho's hydrology. A multi-parameter, multiscale approach was applied, employing stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), the radioactive isotope ^{222}Rn , baseflow separation, and in-situ electrical conductivity (EC) measurements to systematically analyse flow dynamics. Over 21 months from April 2022 to January 2024, water samples were collected from 50 springs, five precipitation stations, four rivers, five wetlands, and 11 boreholes. These were supplemented by additional datasets collected between 2018 and 2023, offering a comprehensive hydrological snapshot of the catchment.

Stable isotope analysis led to the development of Lesotho's Local Meteoric Water Lines (Ox-LMWL, Ms-LMWL, and Abia-LMWL), which revealed key isotopic signatures associated with the amount effect, altitude effect, and seasonal variability in precipitation. These LMWLs served as essential baselines for assessing recharge processes and determining the origins of water sources.

The results show that highland wetlands are recharged primarily by precipitation and groundwater (subsurface) inflows, playing a critical role in sustaining upstream rivers with baseflow. Downstream river segments exhibited significant evaporative fractionation, marked by enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, indicating prolonged residence times, warmer temperatures, and wider channel areas. Moreover, river classification using $\delta^{18}\text{O}$, ^{222}Rn and EC revealed a

systematic altitudinal trend: isotopic depletion at higher elevations and enrichment downstream, alongside decreasing ^{222}Rn concentrations, highlighting reduced groundwater discharge with decreasing elevation. However, elevated ^{222}Rn near the confluence of the Liphiring and South Phuthiatsana Rivers suggests localised zones of increased subsurface inflow.

Boreholes, plotting above the LMWL, displayed isotope signatures consistent with rapid recharge from meteoric water. In contrast, spring samples exhibited more varied isotope values and plotted below the Abia-LMWL, suggesting evaporation before recharge, possibly due to shallow flow paths or delayed infiltration.

While ^{222}Rn measurements were intentionally excluded from boreholes and springs to avoid groundwater contamination during isotope sampling, EC was measured across all water sources. Although no consistent spatial pattern emerged in EC values for boreholes and springs, some localised areas exhibited elevated EC levels, warranting further investigation. Importantly, all EC readings remained below 1000 $\mu\text{S}/\text{cm}$, indicating generally low mineralisation and limited salinity issues within the catchment.

Overall, the study demonstrates strong interconnectivity between GW-SW in the catchment, with hydrological processes governed by elevation, geology and climate. Key contributions include the establishment of local isotopic baselines, enhanced understanding of wetland recharge mechanisms and identification of spatial variability in GW-SW interactions.

The findings provide a robust scientific foundation for integrated water resource management in Lesotho. By illustrating the hydrological connectivity between GW-SW water systems, the research supports a shift from isolated to joint resource management approaches. The insights gained can inform catchment planning, protection of the highlands recharge zone and adaptive water allocation strategies in response to environmental change. This study thus strengthens the evidence base necessary for safeguarding Lesotho's water security through informed decision-making and sustainable resource governance.

Keywords: Stable Isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$), Radon-222 (^{222}Rn), Electrical Conductivity (EC), Local Meteoric Water Line (LMWL), groundwater and surface water (GW-SW) interaction,

Catchment Hydrology, baseflow separation, Wetland Recharge, Altitude Effect, Integrated Water Resources Management (IWRM), Climate Change Impacts.

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Throughout the practical training sessions, I independently conducted all isotope analyses with guidance from Professor Seifu Kebede, who served as my supervisor, and in collaboration with my fellow MSc students, Ms. Thobeka Mpungose and Mr. Mutondi Tshikororo.

Most data was collected by myself with assistance from my family, which collected daily precipitation when I was not at home since my house is within the study catchment. Other assistance on data collection is through my work colleagues from the Department of Water Affairs and Lesotho Meteorological Services who collect monthly samples from GNIR and GNIP stations respectively. To all who have contributed in one way or another, I am profoundly grateful. This dissertation is as much a product of your support as it is of my effort.

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Transmissivity and storativity values are incorporated for each geological formation, offering insights into aquifer properties and their role in subsurface water movement and storage across the catchment..... 96

List of Abbreviations

Abia-LMWL	Abia Local Meteoric Water Line
BH	Borehole
DWA	Department of Water Affairs Lesotho
DWS	Department of Water and Sanitation South Africa
D-excess	Deuterium Excess
^2H or D	Deuterium
GMWL	Global Meteoric Water Line
GNIP	Global Network of Isotopes in Precipitation
GNIR	Global Network of Isotopes in River
GPS	Global Positioning System
GW-SW	Groundwater and Surface Water
H	Hydrogen
IAEA	International Atomic Energy Agency
JLMWL	Johannesburg Local Meteoric Water Line
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project
LES7002	Lesotho IAEA supported project
LLWDP	Lesotho Lowlands Water Development Project
LTC	Lesotho Telecommunication Company or Econet Telecom Lesotho
LEL	Local Evaporation Line
Ms-LMWL	Maseru Local Meteoric Water Line
Metolong LEL	Metolong Local Evaporation Line
Ox-LMWL	Oxbow Local Meteoric Water Line
O	Oxygen
PLMWL	Pretoria Local Meteoric Water Line
^{222}Rn	Radon 222
RSA	Republic of South Africa
^{18}O	Oxygen 18
Sp-LEL	South Phuthiatsana Local Evaporation Line
S	Storativity or Storage Coefficient
TC	Technical Cooperation
T	Transmissivity

^3H

VSMOW

Tritium

Vienna Standard Mean Oceanic Water

Symbols and Units

α	Alpha
Bq/m ³	Becquerel per cubic meter
δ	Delta
>	Greater than
\geq	Greater than or equal to
<	Less than
\leq	Less than or equal to
m.a.s.l	Meters Above Sea Level
μ	Micro
-ive	Negative
‰	Parts per thousand
+ive	Positive

Definitions

Aquifer:	A geological formation which has structures or textures that can hold water or permit appreciable water movement through them.
Darcy's Law:	States that the rate of flow through a porous medium is proportional to the loss of head, and inversely proportional to the length of the flow path.
Depleted:	Refers to a substance with a lower proportion of a specific isotope than the standard or natural abundance.
Drawdown:	The distance between the static water level and the surface of the cone of depression.
Enriched:	Refers to a substance with a higher proportion of a specific isotope than a standard or natural abundance.
Formation:	Classification or characterisation of rocks to processes that led to their occurrence.
Framework:	Legal documents used to govern government initiatives and activities.
Gaining Stream:	A river fed directly by groundwater meaning surrounding water table or piezometric surface is above the base of the stream. Also known as Effluent Stream.
Hydrological Cycle:	Continuous circulation of water between the earth's hydrosphere.
Isotope Fractionation:	The process by which different isotopes of the same element are separated or partitioned due to differences in their physical or chemical properties.
Lithology:	The physical characteristics of the rock (colour, grain size and particle sorting).
Losing stream:	A river that is dependent on surface run-off after precipitation and flows are seasonal with a limited base-flow component, with no groundwater discharge to sustain river flow during drier periods, it is positioned above the water table and discharges into the underlying groundwater system. Also known as the Influent River
Permeability:	The ease of fluid to flow through a porous media which is expressed as a volume of fluid discharged from a unit area of an aquifer under a unit hydraulic gradient in unit time.

Precipitation:	Any form of water from the clouds in the atmosphere to be received on the ground within the hydrological water cycle (e.g. rainfall, snow or hail).
Recharge:	An additional of water to the saturated zone either by downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.
Stage:	Level or height of water in the stream or river.
Storativity:	The volume of water an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in head.
Stream/river:	A physical channel in which runoff will flow from higher to lower ground and to the sea.
Transmissivity:	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

The relationship between GW-SW is often overlooked, yet it is a vital part of understanding how water moves within the hydrological cycle. These two systems are not isolated but are complicatedly linked, and this interaction plays a significant role in determining how much water is available, where it goes and what quality it maintains over time (Hunt et al., 2005; Winter et al., 1998). This understanding becomes even more important in a country like Lesotho, where water is one of the most valuable natural resources. The sustainability of this dissertation seeks to uncover critical insights contributing to more sustainable and informed water resources management practices.

Water resources are central to Lesotho's socio-economic landscape, significantly contributing to national development and facilitating regional and international engagement. Lesotho's water is often referred to as "white gold" due to its exceptional quality (Grab, 2013; Mahlakeng, 2023), these resources have become a defining feature of the country's identity. The availability of relatively abundant and clean freshwater positions Lesotho as a critical player in promoting regional water-use efficiency and improving water security, particularly in adjacent regions expressing water stress. This comparative advantage enables the country to contribute meaningfully to cooperative regional water governance and broader sustainability agendas (Hitchcock, 2015).

Lesotho is recognised as the "water tower of Southern Africa," largely due to its high altitude and relatively clean water (Mahlakeng, 2023; World Bank Group, 2016). This natural advantage has positioned it as a key supplier of water to South Africa and other neighbouring countries. Projects like the Lesotho Highlands Water Project and the Lesotho Lowlands Water Scheme are evidence of how central water is to the country's economy and political landscape. However, the effects of climate change, such as delayed rainfall, extended dry seasons and more frequent droughts, are putting strain on this system. The 2015 drought when many rivers dried up and dam levels dropped alarmingly low, reminded us of how vulnerable surface water alone can be.

This growing uncertainty around rainfall patterns, combined with increasing population and development, calls for better-informed management of water resources. It is no longer enough to look at GW-SW separately. It is paramount to understand how they work together, particularly during dry periods when rivers heavily rely on groundwater to maintain flow. Without this knowledge, it becomes difficult to plan or ensure that the water supply remains reliable, not only for today's needs but for the demands that will come with population growth and economic development.

In the South Phuthiatsana catchment, where this research is based, past studies have looked at water resources and archaeological interests, but few have explored the interaction between GW-SW in depth. Similarly, the area is undergoing significant land use changes, which affect water quality, especially downstream from a major infrastructure like the Metolong Dam. This signals the need for an integrated approach that considers the full hydrological system, including wetlands, aquifers and the people depending on them.

By focusing on the connection between GW-SW, this research aims to provide insights that can improve how we manage water in the face of climate variability and increasing human pressure. Ultimately, understanding this relationship is not just a scientific exercise, it is a necessary step towards building a more resilient water system for Lesotho and its neighbours.

1.2 Justification

Comprehending the flow dynamics within a catchment is vital for the effective management of GW-SW interactions, as well as for optimising recharge mechanisms. This knowledge can significantly enhance water resource sustainability.

The South Phuthiatsana catchment has been studied before for archaeology (Arthur et al., 2018; Mitchell, 1994; Pearce et al., 2021) and water resources assessments (Fobo, 2009; Rossouw and Walker, 2014). Furthermore, the catchment has seen growth and development resulting in an increase in competing water uses and users, which puts a strain on the water resources concerning quality and quantity (Maliehe, 2012). Although anthropogenic activities influence water availability, climate change contributes to scarcity and compromised quality. However,

recent climate changes have increased the vulnerability of Lesotho to the impacts associated with climate change (Fobo, 2009; UNFCCC, 2021).

Moreover, water-related studies done in this catchment indicate high competition for water from different stakeholders (Maliehe, 2012) as well as the variability of climate (Fobo, 2009) that portrays a threat to the draining of water resources. Meteorological drought and hydrological drought are related in the study area (Fobo, 2009). It can never be over-emphasised when looking at the potential shift of the seasons due to climate change, that the South Phuthiatsana catchment needs better water resources management and water allocation (UNFCCC, 2021).

Although water quantity presents a notable challenge, an even more urgent issue in the South Phuthiatsana catchment is the progressive decline in water quality downstream. Like most of the catchments in Lesotho, water sourced from the highland regions typically maintains high quality due to limited human disturbance. However, as the river traverses the landscape beyond the Metolong dam, its quality steadily deteriorates. This degradation stems primarily from intensified human activities and evolving land use patterns in the lower catchment. Key contributors include intensified subsistence and commercial agriculture, where fertiliser and pesticide application promote nutrient-laden run-off into the river system.

Additionally, the rapid expansion of settlements and urbanisation introduces pollutants through untreated sewage discharge and improper waste disposal. Livestock grazing along riverbanks further exacerbates the situation by introducing pathogens and accelerating erosion and sediment deposition. Collectively, these land use pressures significantly weaken the ecological health of the river and threaten the safety and usability of the water resource for downstream communities.

Furthermore, headwaters through wetlands play a significant role in the environment by maintaining biodiversity and serving as sources for most rivers. Endangered wetlands are due to poor land management, which makes them unable to attenuate floods during rainy seasons due to severe degradation and erosion.

Projected climate variability and population growth are expected to increase pressure on water resources, particularly in catchments like South Phuthiatsana, where rainfall patterns are becoming more sporadic and delayed (Fobo, 2009; UNFCCC, 2021). The severe drought experienced in 2015 exposed the vulnerability of the river system, as even the deliberate environmental flows from the Metolong dam failed to maintain adequate river levels. This highlights the importance of understanding the broader hydrological context, particularly the role of groundwater in sustaining baseflow during dry periods. Fobo (2009) suggests that the South Phuthiatsana River relies, in part, on groundwater discharge and snowmelt, particularly in the upper reaches.

However, during periods of extended drought, reduced rainfall limits the recharge of aquifers, thereby diminishing the groundwater contributions that typically help sustain the flow when surface water inputs are insufficient. The inability of groundwater and regulated dam releases to fully support the river's flow during the extreme dry spell points to a complex and independent relationship between these water sources. This requires deeper investigation to inform sustainable water resources management under changing climatic conditions.

Moreover, existing research on water resources in Lesotho and specifically within the South Phuthiatsana catchment has predominantly treated groundwater and surface water as a separate entity. While valuable, these standalone investigations overlook the dynamic interactions that often govern hydrological responses, particularly under climate pressures. Some studies focused on wetlands or sponges, recognising their function in temporarily storing precipitation and gradually releasing it to sustain flows.

However, these studies often fail to incorporate the complete hydrological system, particularly the interactions between GW-SW. This lack of holistic understanding becomes increasingly problematic when considering the cumulative pressures of land use change, rapid population growth and climate variability. These factors are not only altering the quantity and quality of available water but also influence the nature and extent of interactions between GW-SW. For instance, intensive land use through infrastructure (houses, roads, paving, etc) increases runoff

and reduces infiltration capacity, therefore limiting aquifer recharge and consequently diminishing baseflow contributions to rivers.

In addition, headwater sponges/wetlands and precipitation are essential in conceptualising flow dynamics within a catchment. However, the increased population and more activities in the catchment affect water quality. For these reasons, it is vital to identify and mitigate these potential contamination sources to assist policy implementation.

Future water availability under climate change and population pressure will depend on the response of the river to this pressure. The response of the river to this pressure largely depends on the GW-SW interaction. This is because most groundwater-sustained rivers will defend against the irregularity in climate variations. While the surface water-dominated rivers will respond quickly to the changing climate forces. Therefore, it is imperative to determine the connection between GW-SW interactions on a catchment scale.

1.3 Aims

This study aims to develop a conceptual model of GW-SW water interaction in the South Phuthiatsana catchment, where integrated hydrological investigations remain limited. It directly addresses this gap by generating knowledge essential for managing water resources under increasing land use pressures, population growth and climate variability.

1.4 Objectives

The study objectives are as follows;

1. To characterise the isotopic composition of rainfall.
2. To determine areas of groundwater discharge and recharge in the river system.
3. To determine the impacts of different land uses and GW-SW interaction on the water quality.
4. To determine the sources of water that sustain wetlands/sponges in the headwaters region

1.5 Outline of dissertation/thesis structure

Chapter 1 discusses the study area background, including its rationale and problems faced in Lesotho. It introduces what the research aims to achieve and the gaps to be addressed by the study.

In Chapter 2 the existing literature on the global, regional and local groundwater-surface water interaction will be discussed. It also introduces the methods that are proposed for this research and their application. This includes the knowledge gap that is to be filled by the study in the science fraternity and its relevance in a country like Lesotho.

The literature review is based on studies that have been done using isotope hydrology in particular radioactive radon (^{222}Rn) isotopes and stable water isotope ratios of $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$ in water to assess groundwater–surface interaction in a micro/quatarnary catchment. In addition, a review of other methods for assessing GW-SW interaction which complement isotope hydrology are discussed in this section.

Chapter 3 focuses on the description of general and localised study area characteristics. These characteristics are the regional and local geological setting, hydrogeology as well as rainfall and climate variations. Map location, geology (cross-section), drainage, cities, climate and many more have been used to describe the study area characteristics.

Chapter 4 is devoted to the methods and sampling campaign done for data collection and the frequency of the sampling.

In Chapter 5, the discussion of results from data collected, analysis made and interpretation of already existing data.

The final chapter, Chapter 6, integrates the work and provides conclusions of this research with a developed conceptual model. Also included are the future water-related research possibilities and gaps that the study has addressed to contribute to current knowledge.

CHAPTER 2: LITERATURE REVIEW

Introduction

Lesotho has experienced severe droughts repeatedly over the past two decades (2000 to 2020), experiencing significant disruptions due to these extreme climatic conditions. Rivers have dried up, wetlands have degraded, and groundwater levels have decreased. Most perennial rivers, including major ones in Lesotho, have experienced low flow, leading to the formation of pools in their channels. In some reservoirs, such as the Katse Dam, the water level went below 10% during those dry spells (UNFCCC, 2021).

Understanding catchment hydrology is crucial in the field of water resources management, especially considering the ongoing climatic variations (Scanlon et al., 2023). These variations can significantly impact GW-SW systems, altering their availability and quality. To effectively manage these resources, the investigations of how GW-SW interact are important (Hunt et al., 2005).

This includes examining factors such as precipitation patterns, evaporation rates, and land use changes, all of which can influence the hydrological cycle within a catchment (Winter et al., 1998). By analysing these interactions, insights can be gained on the resilience of water resources in the face of climate change and develop strategies to mitigate potential negative impacts, ensuring sustainable water management for the future (UNFCCC, 2021).

2.1 Groundwater and Surface Water Interaction

The interaction between GW-SW is vital because it provides information on transit periods from the surface water source to the borehole and vice versa (Hunt et al., 2005). When GW-SW are seen as a single source of water (Hunt et al., 2005; Winter et al., 1998), the vulnerability and sustainability of a catchment are studied, enabling suitable water resource developments and investments to be established.

2.1.1 Types of GW-SW interaction

The surface water body interacts with groundwater through a series of processes which can be distinguished through their unique properties. This characterisation takes place through an exchange of water from one body to the next. More than two types of exchange can occur in characterising GW-SW interaction. The first exchange takes place when surface water (stream or river) is being recharged by groundwater is known as a gaining river (Figure 2.1-A), whereas the second exchange occurs when surface water recharges groundwater which is known as the losing river (Figure 2.1-B). Lastly but not limited to is bank storage condition, this is a phenomenon whereby the river stage rises due to a flood and stores water in the river bank then releases the water from the river bank after a flood has passed (Figure 2.1-C) (Winter et al., 1998).

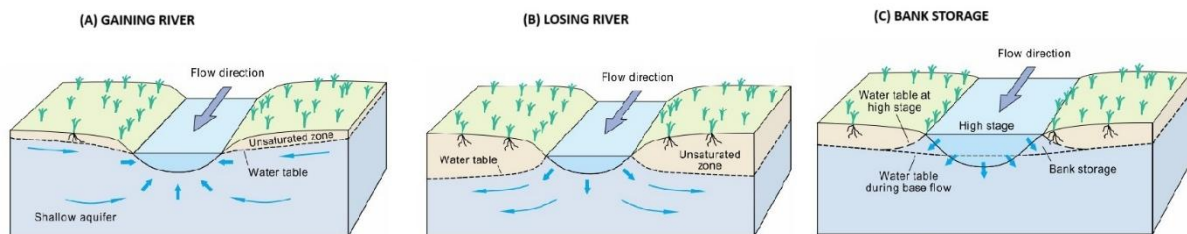


Figure 2.1 Conceptual models of groundwater and surface water interactions modified from Winter et al. (1998). (A) Gaining river: Groundwater discharges into the river, sustaining the river flow. (B) Losing river: River water infiltrates into the subsurface, recharging the aquifer. (C) Bank Storage: river water temporarily enters the banks during high flow and may return as baseflow during recession.

The section addresses primary exchange conditions, focusing on a gaining river. It also briefly mentions two additional exchange types: losing river and bank storage.

2.1.1.1 Gaining River

The gaining river is the condition whereby the groundwater sustains the river through baseflow during periods of low precipitation received. These rivers are known to be perennial rivers and are best assessed during periods of low river flows as most of the water being witnessed is entirely baseflow which can be associated with groundwater recharge into the river (Woessner, 2020).

This type of condition can be characterised using monitoring boreholes drilled along the river which through their time series data on water level fluctuations can provide water flow direction through piezometric water levels. The piezometric water levels from boreholes and river stages have been used as one of the ways to physically characterise GW-SW interaction. These gaining rivers are normally perennial, meaning they flow throughout the year and are not seasonal like losing rivers, which flow during rainfall seasons (Winter et al., 1998; Woessner, 2020).

2.1.1.2 Losing River

The losing river is usually a case whereby a storm or intense amounts of precipitation is received, resulting in surface runoff within the catchment area. This surface runoff and precipitation amount are recorded by river gauges and precipitation gauge stations, respectively (Winter et al., 1998).

The losing river can be distinguished by the seasonal flow which is highly dependent on the present precipitation (Winter et al., 1998). This condition whereby the exchange between groundwater and the river occurs through groundwater recharge from the river bank can also be described as an influent. The river ecologists as another group of scientists dealing with GW-SW interactions, describe a losing or influent river as the downwelling (Woessner, 2020).

2.1.1.3 Bank Storage

Several studies have documented how GW-SW interaction is influenced by hydrological extremes such as floods (Brunke and Gonser, 1997; Sophocleous, 2002; Winter et al., 1998). During flood events, rivers that ordinarily receive groundwater input (gaining rivers) can temporarily shift to losing conditions. This typically occurs when the river stage rises above the adjacent water table, causing water to be stored within the permeable banks of the river. This process, known as bank storage, allows floodwater to infiltrate and be held within the riparian sediments (Winter et al., 1998).

As the river stage subsequently declines, the hydraulic gradient reverses, and the water stored in the banks gradually returns to the river. This delayed return flow contributes to river discharge during the recession phase, effectively sustaining baseflow after the flood peak has passed (Sophocleous, 2002). Such interactions are critical in understanding the hydrological

connectivity between rivers and aquifers, particularly in systems with variable flow regimes (Woessner, 2020).

The morphology of the river system and the underlying geology significantly influence this exchange. This phenomenon is particularly evident in catchments where surface topography and subsurface geological structures possess characteristics that facilitate lateral movement of water flow from a high river stage into adjacent groundwater reservoirs. In such settings, alluvial sediments and porous materials along the riverbanks enhance the potential for temporary subsurface storage. Once the river stage drops, the stored water is gradually released back into the river channel, highlighting the cyclical nature of bank storage and its importance in flow regulation (Woessner, 2020).

Beyond the hydrological function, GW-SW interaction through bank storage also has significant ecological and socioeconomic implications. Environmental scientists across various disciplines have highlighted that these interactions are vital to maintaining aquatic and riparian ecosystems (Woessner, 2020). Wetlands and sponges can indicate the relationship between GW-SW, representing the interface between the two ecological systems, namely the terrestrial and aquatic ecosystems (Biksey and Gross, 2001; Woessner, 2020).

2.1.2 Different scale of GW-SW interaction

Scientists study GW-SW interactions through various methods. One common approach is the use of tracer studies, where harmless dyes or isotopes are introduced into groundwater or surface water to track where the water flows. Tracer studies have been widely applied to understand groundwater pathways and their connections to surface waters (Coplen et al., 2000; Hunt et al., 2005; Kalbus et al., 2006). Researchers can map out groundwater's hidden paths to reach surface waters by observing where these tracers emerge.

Temperature measurements are also useful; groundwater is often cooler than surface water in summer and warmer in winter. These temperature differences can reveal where groundwater is entering a river (Conant et al., 2019). Thermal infrared imaging and riverbed temperature sensors are advanced tools used to identify groundwater upwelling zones (Tirado-conde et al., 2020).

At a local scale, GW-SW often meet in subtle ways. For instance, a small river trickling through a forest may appear to flow solely from recent rainfall, but groundwater often plays a crucial role beneath the surface. Springs, where groundwater naturally emerges, sustain these rivers even during dry periods, ensuring consistent water flow. This connection is vital for habitats that rely on steady water levels, such as those of wetland plants and certain fish species (Winter et al., 1998).

When we zoom out to the scale of a watershed, the interaction between GW-SW becomes more complex. A watershed is an area where all water drains into a common outlet, like a river. Groundwater contributes to river flows and sustains them during dry spells, particularly in gaining rivers (Sophocleous, 2002). The balance between GW-SW in a catchment impacts water availability for agriculture and the health of aquatic ecosystems.

To understand these interactions, scientists often use hydrological models. These computer models simulate the movement of water through a watershed, considering factors like rainfall, evaporation, and soil permeability. Researchers refine their understanding of how these systems interact by comparing model predictions with actual measurements of river flows and groundwater levels. Another method involves analysing water chemistry; differences in chemical composition between GW-SW help identify mixing zones and flow paths (Kendall and Caldwell, 1998).

On a larger scale, regional interactions between GW-SW involve vast aquifers, underground layers of water-bearing rock spanning hundreds of miles. These aquifers are connected to surface water bodies like rivers and wetlands (Winter et al., 1998). Over-extraction of groundwater for irrigation can significantly reduce river flows far downstream, impacting water availability for ecosystems and communities.

Understanding GW-SW interactions is critical for sustainable water management, especially as climate change alters rainfall patterns and increases drought frequency. Effective water management requires a holistic approach that integrates these interactions across all scales, from local springs to regional aquifers (Scanlon et al., 2023; Winter et al., 1998).

In conclusion, the interaction between GW-SW is a complex, multi-layered process. By studying these systems through methods like tracer studies, temperature monitoring, hydrological modelling, and satellite observation, we can better manage the water resources essential for life on Earth (Kalbus et al., 2006). These connections highlight the intricate and interconnected nature of our planet's water systems, from the quiet emergence of groundwater in a forest river to the vast flow of regional aquifers (Winter et al., 1998).

2.1.3 Factors Controlling GW-SW Interaction

The interaction between GW-SW is a fundamental aspect of the hydrological cycle, influencing water availability, ecosystem health, and human water usage (Sophocleous, 2002; Winter et al., 1998). This interaction is shaped by various factors, each contributing to the complex dynamics of how GW-SW influence one another (Kalbus et al., 2006).

2.1.3.1 Geological and hydrological conditions

One of the primary factors affecting GW-SW interaction is the geological and hydrological characteristics of an area. The permeability of soil and rock plays a crucial role. In regions with highly permeable materials, such as gravel or sand, groundwater can easily flow into surface water bodies like rivers and lakes, significantly affecting their flow and quality. Conversely, in areas with low permeability, such as clay or granite, the interaction is more limited, and groundwater tends to remain isolated from surface waters (Sophocleous, 2002).

The presence of aquifers also influences this interaction. Aquifers are underground layers of water-saturated rock or sediment that store and transmit groundwater (Department of Water and Sanitation (DWS), n.d.). The connectivity of these aquifers with surface water bodies determines how groundwater contributes to or draws from surface water. For instance, a well-connected aquifer can sustain river flows during dry periods, while a poorly connected one may have little impact on surface water (Alley et al., 1999; Winter et al., 1998).

2.1.3.2 Climatic and Seasonal Variations

Climate and seasonal changes are also critical factors in the interplay between GW-SW. Increased precipitation replenishes groundwater levels during wet seasons and improves surface water flows. The excess rainfall infiltrates the ground, replenishing aquifers and contributing to river and lake levels. In contrast, during dry periods, reduced rainfall decreases

groundwater recharge and can lead to lower surface water levels, affecting water availability for ecosystems and human use (Döll and Fiedler, 2008).

Seasonal temperature fluctuations also play a role. In colder climates, the presence of ice and snow can delay groundwater recharge until the spring thaw, while in warmer regions, seasonal variations in evaporation rates and plant water use can affect how GW-SW interact (Ferguson and Maxwell, 2010).

2.1.3.3 Human Activities

Human activities have a profound impact on GW-SW interactions. Urbanisation and land use changes can alter the natural flow of water. Impervious surfaces like roads and buildings prevent water from infiltrating the ground, leading to increased runoff and reduced groundwater recharge. This runoff often carries pollutants into surface water bodies, impacting water quality (Winter et al., 1998).

Agricultural practices also affect this interaction. The use of irrigation can deplete groundwater reserves and alter the natural flow patterns of surface water. Additionally, the application of fertilisers and pesticides can lead to nutrient runoff, which affects water quality and can disrupt aquatic ecosystems (Zhang et al., 2018).

Water management practices, such as the construction of dams and the diversion of rivers, can significantly alter the balance between GW-SW. Dams can create reservoirs that change the natural flow of rivers and influence groundwater levels in the surrounding areas. Similarly, the withdrawal of groundwater for irrigation or drinking water can reduce the flow of nearby rivers (Winter et al., 1998).

2.1.3.4 Vegetation and Land Cover

The type and extent of vegetation cover in an area also influence GW-SW interactions. Vegetation plays a critical role in the water cycle by affecting both the infiltration of rainwater into the ground and the rate of evaporation. Forests and wetlands, for example, can enhance groundwater recharge by promoting infiltration and reducing runoff. Conversely, deforestation and land clearing can lead to increased runoff and decreased groundwater recharge, altering the natural balance between GW-SW (Le Maitre et al., 1999).

2.1.3.5 Topography and Land Features

Topography and landscape features further affect how GW-SW interact. Mountainous regions, for example, often experience significant groundwater-surface water interactions due to the steep gradients and high precipitation rates. Groundwater can emerge as springs in these areas, contributing to river flows and maintaining river systems (Toth, 1963).

In flatter landscapes, the interaction may be less pronounced, but still significant. In such areas, the direction of groundwater flow can influence the location and health of wetlands and other surface water bodies (Winter et al., 1998).

In conclusion, the interaction between GW-SW is a dynamic process influenced by a myriad of factors, from geological and climatic conditions to human activities and landscape features. Understanding these factors is essential for managing water resources effectively and ensuring the sustainability of both GW-SW systems. By considering the complex interplay of these factors, we can better address the challenges of water management and protect the vital resources that support ecosystems and human communities alike (Winter et al., 1998).

2.1.4 Different methods for assessing GW-SW interaction studies

In recent years, there has been a growing body of research emphasising that the interaction between GW-SW requires a multidisciplinary approach, as it involves complex processes across hydrology, geology, ecology and biochemistry. Lewandowski et al. (2020) conducted a comprehensive synthesis of recent research efforts that employed a range of methodologies to understand GW-SW interactions. Since the interaction between GW-SW is complex, a framework describing numerous factors to investigate in either surface water or groundwater is available (Conant et al., 2019). However, it is vital to note that the framework is merely a guideline and not a solution in the investigations, as conditions vary across spatial and temporal scales (Putman et al., 2019). Therefore, scientists must adapt their approaches depending on site-specific conditions, objectives and available resources. Different methods used to assess GW-SW interaction are explained below, each contributing in its way to a holistic understanding of hydrological connectivity.

2.1.4.1 Hydrological Methods

Hydrological methods involve the analysis of water levels, flow rates, and other related data to understand the interaction between GW-SW. One of the simplest approaches is the use of water balance calculations. By quantifying the inputs and outputs of a water system, such as precipitation, evaporation, and river flow, researchers can infer the exchange between surface water and groundwater. Additionally, the use of hydrographs, which plot water levels or flow rates over time, can reveal patterns of interaction, such as the influence of groundwater on river flow during dry periods (Wittenberg and Sivapalan, 1999).

Another hydrological method is baseflow separation, where the total river flow is divided into baseflow (groundwater contribution) and direct runoff. This method helps understand the proportion of streamflow sustained by groundwater. Recent studies have enhanced baseflow separation techniques by integrating empirical filters with environmental tracers, such as specific electrical conductance (SEC), to optimise the quantification of baseflow contributions (Mei et al., 2024).

2.1.4.2 Geochemical and Isotopic Methods

Geochemical and isotopic methods involve analysing the chemical composition of water samples to trace the sources and pathways of water movement. GW-SW often have distinct chemical signatures, which can be used to identify mixing zones and interaction points. Commonly measured parameters include major ions, nutrients, and trace elements (Coplen et al., 2000).

Isotopic tracers, such as stable isotopes of hydrogen (^2H) and oxygen (^{18}O), are particularly useful in distinguishing between GW-SW contributions. These isotopes reflect the history of water molecules, including processes like evaporation and recharge. By comparing the isotopic composition of GW-SW, researchers can identify areas of interaction and quantify the exchange between the two systems (Kendall and Caldwell, 1998).

Recent studies have reinforced the prominence of this approach. For instance, Yang and Han (2020) utilised stable isotopes to evaluate the relationship between GW-SW. Similarly, Loh et al. (2022) applied hydrochemical and stable isotope tracers to evaluate the relationship between

Lake Bosumtwi and the underlying groundwater system in Ghana, highlighting the method's effectiveness in assessing GW-SW interactions.

2.1.4.3 Hydraulic and Tracer Tests

Hydraulic and tracer tests are essential methods for assessing GW–SW interactions. Pumping tests measure changes in water levels caused by extracting groundwater, revealing hydraulic connectivity when nearby surface water levels respond (Botha et al., 1998; Rus et al., 2001). Slug tests, involving rapid water level changes in a well, are useful in low-permeability zones and help estimate hydraulic conductivity, particularly in riverbed sediments (Eldridge and Medler, 2019). Tracer tests track the movement of introduced substances (e.g., dyes or isotopes) to map flow paths and connectivity between GW-SW, although they require careful design and interpretation (Davis et al., 1980). Combined, these methods offer valuable insights into subsurface flow dynamics and support sustainable water management.

2.1.4.4 Numerical Modelling

Numerical modelling uses mathematical simulations to analyse groundwater-surface water interactions under various scenarios. These models range from simple conceptual frameworks to fully integrated hydrological models coupling surface and groundwater processes. They are invaluable for exploring the effects of changes in land use, climate, or water management practices (Klaus, 2001; Sophocleous, 2002). However, the quality of input data and underlying assumptions significantly impact model accuracy.

2.1.4.5 Remote Sensing and Geophysical

Advancements in remote sensing and geophysics offer powerful tools for studying GW-SW interactions. Remote sensing uses satellite or aerial imagery to monitor surface water changes, vegetation, and land surface temperature, indirectly indicating groundwater dynamics (Tirado-conde et al., 2020).

Geophysical techniques, such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR), provide subsurface imaging and can contribute to information gathering for GW-SW interaction (Riddell et al., 2012). These methods map aquifer structures, recharge zones, and interaction areas, offering a non-invasive study of these systems.

2.1.4.6 Field Measurements and Monitoring

Field measurements and long-term monitoring are fundamental for understanding temporal variations in groundwater-surface water interactions. Monitoring wells, river gauges, and sensors record data on water levels, flow rates, and quality parameters. Long-term datasets are crucial for identifying trends, seasonal fluctuations, and responses to extreme events. They also serve as essential inputs for validating hydrological models.

2.2 Stable Hydrogen and Oxygen isotopes

Isotopes are atoms of the same element with the same number of protons but differing numbers of neutrons in the nucleus. The variation in the number of neutrons causes the element's mass to vary. Figure 2.2 shows that protons are used to identify elements therefore an isotope will have the same number of protons as the element to which it is connected (Coplen et al., 2000; Sharp, 2017).

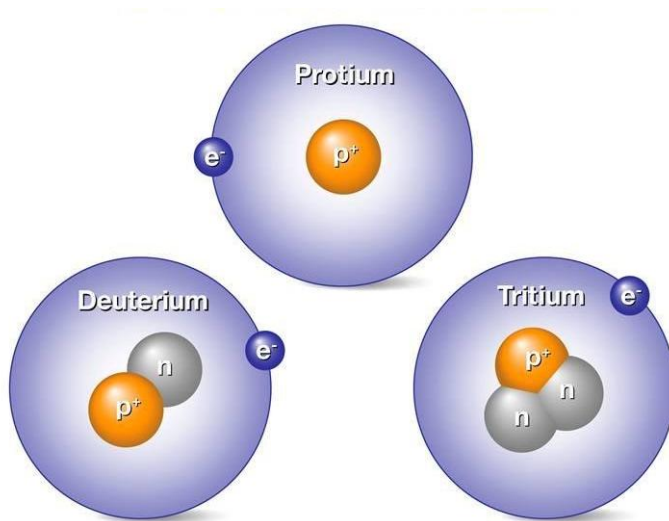


Figure 2.2 The three naturally occurring hydrogen isotopes—Protium (^1H), Deuterium (^2H), and Tritium (^3H)—differ by neutron number and are used as tracers in hydrological studies to analyze water sources, age, and movement.

Water (H_2O) is a molecule composed of hydrogen and oxygen, both of which can exist in various isotopic forms. The resulting combinations influence the molecule's mass. Common isotopic forms used in hydrological studies include $^1\text{H}_2^{16}\text{O}$, $^1\text{H}_2^{18}\text{O}$ and $^1\text{H}_2\text{H}^{18}\text{O}$ (Craig and Gordon, 1965). These isotopes form the basis of studies in isotope hydrology, a field that

emerged following the discovery of stable hydrogen and oxygen isotopes in precipitation during the 1950s (Rozanski et al., 1993).

The International Atomic Energy Agency (IAEA) initiated the Global Network of Isotopes in Precipitation (GNIP) to collect and analyse these isotopic variations globally. Early research identified correlations between ^2H and ^{18}O , which were foundational in understanding hydrological cycles, including ocean-atmosphere exchanges, cloud condensation and precipitation (Craig and Gordon, 1965; Terzer et al., 2013).

Understanding isotopic signatures of water expressed as deviations in isotope ratios from Vienna Standard Mean Ocean Water (VSMOW) and reported as $\delta^2\text{H}$ and $\delta^{18}\text{O}$, enabling hydrologists to trace the origin and history of water masses. For example, meteoric water, glacial meltwater, groundwater recharged under different climatic conditions, and surface water bodies all exhibit characteristic isotope compositions. These signatures can be used to distinguish water sources, track mixing between sources, and quantify recharge contributions. For instance, evaporated water typically shows enrichment in heavy isotopes (more positive δ -values), while recharge from high-altitude precipitation shows depletion (more negative δ -values) (Clark and Fritz, 1997; Gat, 1996).

Thus, stable isotopes are powerful tracers in studies of GW-SW interactions, groundwater recharge, and catchment hydrology, offering insights into spatial and temporal dynamics of water resources (Aggarwal and Froehlich, 2016; Clark and Fritz, 1997; Gat, 1996; Kendall and Caldwell, 1998).

2.2.1 Isotopic Effects

The isotopic composition of precipitation depends on various factors, including temperature, altitude, precipitation amount, geographic location, and seasonal changes. These influences lead to isotopic fractionation, where lighter isotopes evaporate more readily, while heavier isotopes condense more easily.

2.2.1.1 Temperature Effect

Air temperature strongly influences the isotopic composition of precipitation, a relationship commonly referred to as the temperature effect (Diamond, 2022). As temperatures decrease, precipitation exhibits more negative $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values due to enhanced isotopic fractionation during evaporation and condensation processes. In colder regions, evaporation from ocean surfaces results in water vapour that is depleted in heavier isotopes, while colder cloud temperatures promote more complete condensation, further removing heavier isotopes from the vapour phase (Dansgaard, 1964; Gat, 1996).

Additionally, the progressive rainout effect toward higher latitudes compounds the isotopic depletion, leading to distinctly lighter isotopic signatures in polar precipitation compared to those in tropical regions (Rozanski et al., 1993). This temperature-isotope correlation has been demonstrated in long-term precipitation records, such as those from Vienna, where statistical smoothing revealed consistent interannual trends (Aggarwal et al., 2007).

2.2.1.2 Altitude Effect

As moist air masses ascend mountainous terrain, they cool, causing precipitation and condensation. Heavier isotopes are preferentially removed at lower elevations, leaving lighter isotopes in the remaining water vapour. This creates an isotopic depletion gradient with increasing altitude (Ambach et al., 1967). For example, in mountainous regions of Southern Africa, the isotopic composition of precipitation becomes progressively lighter with elevation (Fitchett et al., 2024).

2.2.1.3 Amount Effect

The amount effect refers to the observed decrease in heavy isotopes (^{18}O and ^2H) with increasing rainfall amounts. In tropical and subtropical climates, such as Southern Africa, heavy rainfall events lead to isotopically lighter precipitation due to rapid condensation and removal of heavier isotopes. This pattern is significant in regions with high rainfall variability (Dansgaard, 1964).

2.2.1.4 Continental Effect

As the air masses move inland from coastal areas, they lose moisture through successive precipitation events. Each event preferentially removes heavier isotopes, leaving progressively

lighter isotopes in the remaining vapour. This results in a distinct isotopic gradient from coastal regions to inland areas, as observed in Southern Africa. The complex topography and climatic variations further modulate this effect (Rozanski et al., 1993).

2.2.1.5 Seasonal Effect

In Southern Africa, isotopic composition varies seasonally due to shifts in moisture sources and atmospheric dynamics. During the wet season, monsoonal winds transport moisture from the Indian Ocean, initially enriched in heavier isotopes. As precipitation progresses inland, isotopic signatures become lighter. In the dry season, the minimal precipitation often contains heavier isotopic signatures due to reduced atmospheric moisture and recycling effects. These seasonal trends are valuable for hydrological modelling and climate reconstruction (Craig and Gordon, 1965; Terzer et al., 2013).

2.2.2 Case Studies and Applications in Temperate Areas

Isotope hydrology, particularly the application of stable hydrogen (^2H) and oxygen (^{18}O) isotopes, has become instrumental in investigating water resources in temperate climatic regions such as Lesotho. These isotopes, being conservative tracers, provide insights into the origin, recharge, and mixing processes within hydrological systems. In Lesotho, several studies have laid the groundwork for understanding the country's water dynamics using isotope methods. A key contribution is from Mots'ets'e et al. (2017), who applied $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in the high-altitude wetland of Khalong-la-Lithunya. Their study revealed that while rainfall contributes to wetland hydrology, baseflow sustains river discharge during dry periods, implying limited direct recharge and highlighting the wetland's role as a buffer system.

Complementing this, Abiye et al. (2013) offered a regional synthesis through the Water Research Commission, where Lesotho's isotope data featured in multi-site comparisons across southern Africa. The "Rainfall and Groundwater Isotope Atlas" section of their report, compiled by AS Talma and E van Wyk, includes $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data from the Oxbow region in Lesotho, indicating a depleted isotopic composition due to altitude effects and providing a baseline for evaluating groundwater recharge. Their findings revealed that Lesotho's highland precipitation lies close to the Global Meteoric Water Line (GMWL), suggesting minimal

evaporative modification and efficient recharge under temperate high-altitude conditions (Abiye et al., 2013).

Further, isotope mapping in the region demonstrated spatial isotopic gradients that correlate with elevation, precipitation amount, and temperature, aligning with global findings from other temperate mountainous regions.

Globally, the use of stable isotopes in temperate zones echoes similar themes. For instance, McGuire et al. (2002) assessed riverflow residence times in the Appalachian region of the United States, utilising $\delta^{18}\text{O}$ to differentiate between shallow and deep subsurface water contributions. In the Bavarian Alps, Stichler and Herrmann (1983) observed altitude-driven isotope depletion, a phenomenon paralleled in Lesotho's mountainous terrain. The study in Georgia by Holko et al. (2023) emphasised that temperature, elevation, and moisture source trajectories significantly affect isotopic variability, with precipitation in these regions also plotting along or slightly below the GMWL.

In southern Africa, isotope applications in regions climatically like Lesotho have strengthened conceptual models of recharge. For example, in Cape Town, Diamond and Harris (2019) used seasonal isotope variations to confirm winter-dominated recharge of the Table Mountain Group aquifer.

These regional and international studies collectively confirm the suitability of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ as tracers in temperate climates with altitudinal variation and seasonal precipitation patterns (Holko et al., 2023; McGuire et al., 2002). Lesotho, situated at the hydrological heart of southern Africa, benefits from this global framework and stands to deepen its water resource assessments by expanding isotope monitoring and incorporating these proven methodologies.

2.3 Radioactive Radon isotope (^{222}Rn)

Radon-222 (^{222}Rn) is a naturally occurring radioactive noble gas that plays a significant role in environmental studies, particularly in hydrology. It is the most stable isotope of radon, possessing a half-life of approximately 3.82 days. This isotope is produced through the alpha decay of radium-226, which is part of the uranium-238 decay series. Due to its gaseous nature,

radon-222 can migrate from soils and rocks into the atmosphere and water bodies, making it a valuable tracer for studying groundwater-surface water interactions.

In hydrological applications, ^{222}Rn is utilised to identify and quantify groundwater discharge into surface waters such as rivers, lakes, and coastal zones. Its concentration in groundwater is typically higher than in surface water, allowing researchers to detect areas where groundwater enters surface water bodies (Botha et al., 2019; Eilers et al., 2015; Masevhe et al., 2017).

Furthermore, the application of radon gas measurement in South Africa has been tested in investigations related to GW-SW interaction (Botha et al., 2019; Strydom et al., 2021) and mine waste contamination through radon concentrations in rivers (Masevhe et al., 2017). The inception of these radon gas measurements in South Africa within the Karoo basin was focused more on potential sites for hydraulic fracking (Botha et al., 2019; Eilers et al., 2015).

Measurements of ^{222}Rn are useful in examining GW-SW interaction. Similar studies have been conducted in South Africa, including the Table-Mountain Group research (Strydom et al., 2021), which used ^{222}Rn to investigate complicated hydrogeological processes and determined that high radon levels in groundwater are associated with underlying granitic geology as well as fractured aquifers. The Karoo Uranium Province, where ^{222}Rn was utilized to construct a baseline study before shale gas development and hydraulic fracturing (Botha et al., 2019; Eilers et al., 2015), found that shallow groundwater might be damaged by the upward migration of poor deep aquifer water quality as a result of hydraulic fracking or existing fractured rocks.

Even though ^{222}Rn has been used in GW-SW interaction for assessments, it is also applicable to solve health-related concerns. In South Africa within Gauteng Province, there are numerous mining dumpsites and from these deserted sites, surface runoff ends up in the nearby rivers, posing a huge health concern. To scrutinise the impacts these abandoned sites have to the rivers, Masevhe et al. (2017) used ^{222}Rn to determine if the radioactive decay of uranium from the gold mine waste dumps run-off into nearby rivers since ^{222}Rn is a daughter in the U-decay chain. This study through ^{222}Rn measurements indicated that the radon dosage in the rivers do not pose any health threat as the dose is below international safety levels.

All four previous studies in South Africa (Botha et al., 2019; Eilers et al., 2015; Strydom et al., 2021) that measured radon concentration in water using a Solid State α – Detector (RAD 7), were done in the laboratory using RAD H₂O and did not account for decay because samples were analysed within six hours after collection. Even though the results are reliable, for this study, field measurements will be done using Rad Aqua to measure radon gas at the sources. This will be helpful due to the remoteness of the sampling points with poor access.

In conclusion, Isotope Hydrology has become an invaluable tool in understanding and managing water resources worldwide. In southern Africa, the application of stable and radioactive isotopes has enabled researchers to trace groundwater recharge, assess the impacts of climate variability and identify pollution sources. Local studies, provide critical data for managing water resources in regions highly susceptible to climate change and human pressures.

CHAPTER 3: DESCRIPTION OF STUDY AREA

Introduction

The study area is a micro catchment called South Phuthiatsana, situated in Lesotho which the Republic of South Africa surrounds as shown in Figure 3.1. Lesotho is a mountainous country with a surface area of 30 648 km² and situated between 28⁰ and 30⁰ South with 27⁰ and 29⁰ East. The country has the lowest elevation of 1400 meters above sea level at Morifi and the highest elevation of 3482 meters above sea level at Thabana-Ntlenyane.

Moreover, the country's population is just above 2 million with most people living in the urban areas while the minority is in the rural areas due to urban migration (Lesotho Ministry of Development Planning, 2016).

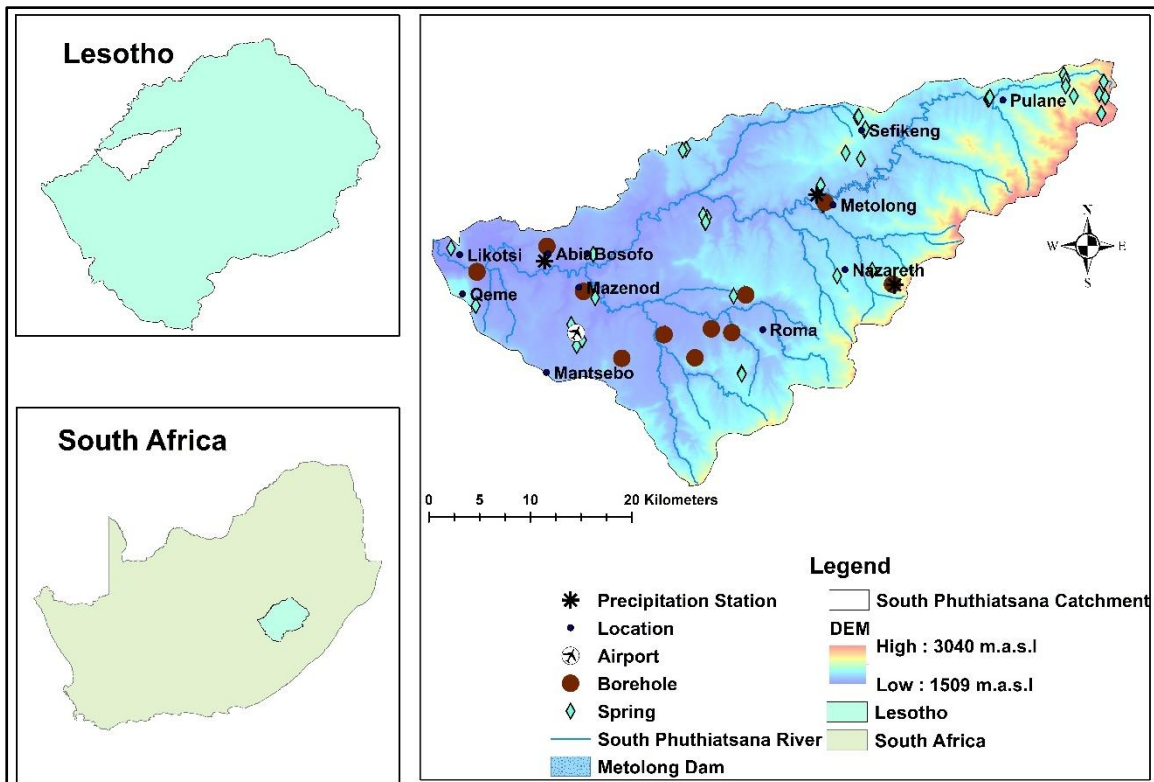


Figure 3.1 Location of the South Phuthiatsana Catchment within Lesotho. The map highlights the study area with South Africa and Lesotho, displaying the digital elevation model (DEM) of the catchment and the distribution of sampling sites used for hydrological and isotope data collection.

South Phuthiatsana catchment appears to be amongst the most studied catchments in Lesotho on archaeology and heritage initiatives, because of previous archaeological studies (Arthur et

al., 2018; Mitchell, 1994; Pearce et al., 2021). Even though archaeological studies are dominant, few studies have been done on water resources management and assessments (Davies, 2003; Fobo, 2009; Maliehe, 2012; SMEC Group, 2017).

Despite its environmental significance and growing socioeconomic reliance on water resources, the South Phuthiatsana catchment has seen limited research dedicated to understanding GW-SW interactions. Previous hydrological studies in the country (Fobo, 2009; Maliehe, 2012; Rossouw and Walker, 2014) have primarily focused on surface water dynamics, often overlooking subsurface contributions due to sparse groundwater datasets and limited hydrogeological monitoring. This data gap has led to the systematic exclusion of groundwater processes in basin-scale hydrological models, resulting in incomplete representations of the water balance.

In a temperate climate system like the South Phuthiatsana catchment, where rainfall is seasonal and elevation gradients encourage vertical and lateral flow paths. Groundwater may provide a crucial baseflow component, especially during dry periods (UNFCCC, 2021). Ignoring this connection undermines efforts to develop integrated water resource management strategies, particularly in a catchment that supports smallholder agriculture, peri-urban water supply and sensitive riparian ecosystems. Therefore, building a more comprehensive understanding of GW-SW dynamics is not merely an academic pursuit but a practical necessity.

3.1 Location of the study area

The study catchment area is 1103 km² and is found in two districts, namely Maseru and Berea, with Maseru occupying most of the catchment area (Maliehe, 2012).

Furthermore, the catchment comprises different land uses which have evolved over the years, when looking at the history of the study catchment through archaeological studies that have been done. The studies indicate that there are settlements and a range of numerous water uses, namely: 1) Domestic water supply through a reservoir called Metolong dam; 2) Irrigation from South Phuthiatsana river water; 3) Industrial from South Phuthiatsana river water; and lastly, 4) Quarry mining from South Phuthiatsana river water.

South Phuthiatsana catchment is not an exception to the variation of rainfall patterns. The catchment has a varying terrain which has a peak elevation of about 3040 m and a lowest point of 1509 m as shown in Figure 3.1 above.

3.2 Geological Setting

The regional geology of Lesotho is predominantly the Karoo Supergroup which is characterized by the two-rock forming classification type namely igneous composition type being the Drakensberg group and Sedimentary composition type being the Stormberg group and Beaufort group also including the recent alluvial deposits. The South Phuthiatsana catchment is amongst the unique catchments that comprise the zoomed representation of the Karoo Supergroup stratigraphy that the country has which comprises of the Drakensburg group, Stormberg group and the Beaufort group. Figure 3.2 shows the Drakensburg group covers the majority of the catchment (about 60% of the catchment) while the rest of the remaining groups share the remainder (40% of the entire catchment) within the study area and this is very close to the generalised geological distribution of Lesotho (Arduino et al., 1994; Schmitz and Rooyani, 1987).

Moreover, the Karoo Supergroup has multiples of intrusive structures namely, dolerite dykes, dolerite sills and lineaments which results into secondary porosity (Davies, 2003).

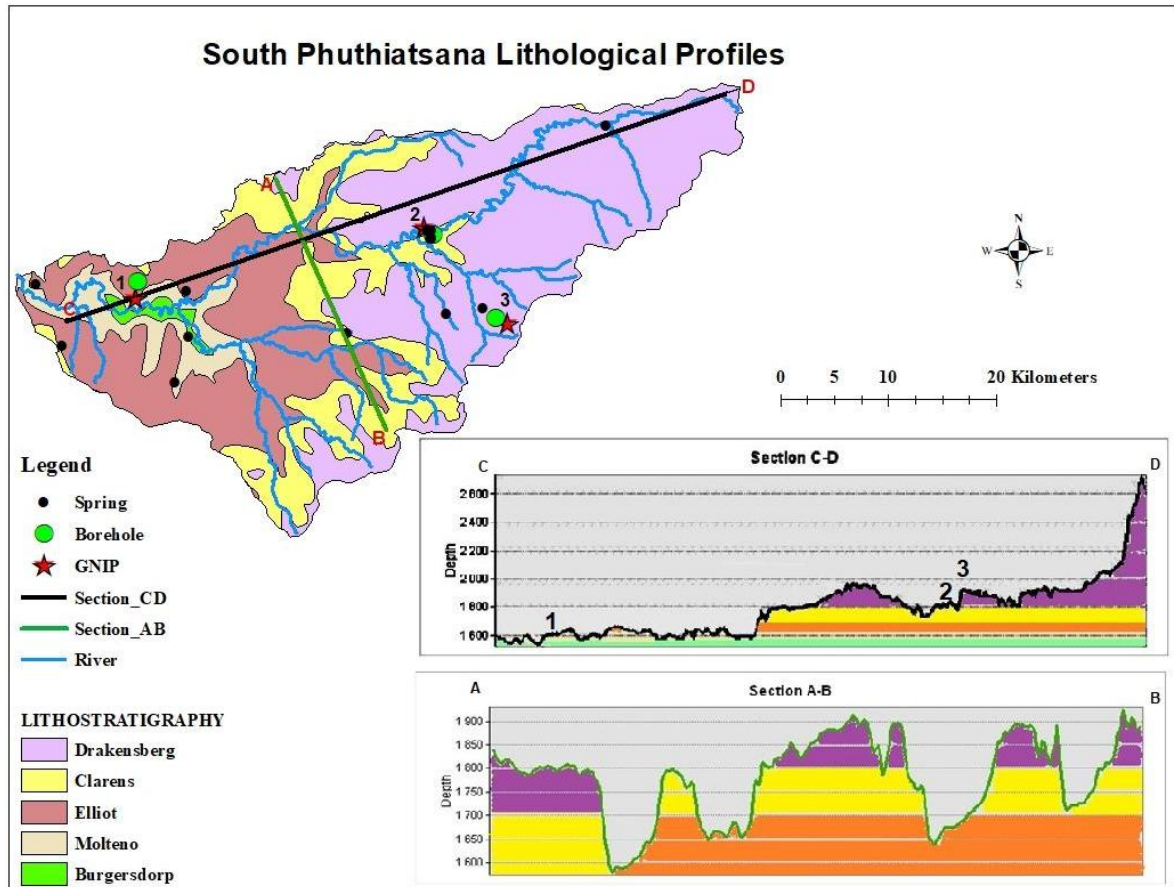


Figure 3.2 Geological cross-sections A–B and C–D across the South Phuthiatsana Catchment, showing the subsurface lithological structure and stratigraphy. The figure also presents the spatial distribution of precipitation stations, as well as key springs and boreholes that were frequently sampled during the study for isotope analysis and in-situ measurements.

3.2.1 Drakensberg group

This group mainly comprises the magmatic and tectonic episodes that occurred during different geological times. The different depositional periods of the basaltic floods are being observed by the interbedding of vitric tuff with Elliot formation in some areas in Lesotho. These Karoo volcanic episodes have been traced back to Dwyka Formation which is dated 300 Ma (Palaeozoic era) while Elliot Formation is dated 215 Ma (Mesozoic era) (Schmitz and Rooyani, 1987).

3.2.1.1 Lesotho Formation

The Tholeiitic Basalt lava characterises this formation flows that vary with thickness throughout the country and known to be the highlands of Lesotho due to elevations as high as

about 3500 meters above sea level. It is a result of the magmatic eruption that took place in the early to the end of mid Jurassic period (Mesozoic Era). The basalts are believed to have covered the whole country (Lesotho) but due to erosion, the sedimentary formations (Stormberg and Beaufort Group) were exposed. The actual thickness of basalt deposits before erosion is not known but currently only the thickness from Clarens formation to the highest point of the Lesotho can be estimated, and through borehole drilling in different areas within the highlands of Lesotho (Schmitz and Rooyani, 1987).

The basalts in this formation display layering, which is indicative of episodic lava flows. This layering also has signs of weathering or erosion in between flows.

3.2.2 Stormberg Group

The Stormberg group comprises of the three formations namely, Clarens, Elliot and Molteno formations. The formations chronology starts with Clarens being the youngest and found at the topmost part of the group succession while Molteno is the oldest of the three and found at the bottommost part of the group succession. This group is characterised by the upward fining megacycle due to the coarse-grained basal deposits mainly of braided rivers, followed by fine-grained, sandy deposits of meandering and by largely argillaceous deposits of the floodplain sedimentation (Schmitz and Rooyani, 1987).

The depositional environment conditions in this group changed over sometime and gave rise to different formations. The three formations have different facies that explain the paleoclimate and depositional environments as well as an indication of the upward fining megacycle. The sedimentary facies from the Stormberg Group is provided in Table 3.1.

Table 3.1: Stormberg group facies by geological formations and depositional environment. Modified (Schmitz and Rooyani, 1987)

Geological Formation	Name of Facies	Depositional Environment
Clarens Formation	<ul style="list-style-type: none"> ● Dune facies 	Aeolian
Elliot Formation	<ul style="list-style-type: none"> ● Flood fan – Dune facies ● Flood basin facies ● Fine grained meandering river facies 	Fluvial
Molteno Formation	<ul style="list-style-type: none"> ● Coarse-grained meandering river or braided river facies 	Fluvial

3.2.2.1 Clarens Formation

The youngest sedimentary deposit within the Karoo sequence and it is known to be the cave sandstones. This formation is from an aeolian origin and because wind energy can transport finer particles, this formation is characterised by fine-grained sandstones and siltstones. The Clarens Formation is subdivided into Lower Transition beds and higher Massive Sandstone (Botha et al., 1998; Schmitz and Rooyani, 1987).

The lower Transition beds in Lesotho consist of a compact, pale red to red or cream-coloured fine-grained sandstone basal bed. The high Massive Sandstones are characterised by green or pink siltstones and mudstones, which generally display a mudstone cleavage type (laminated less than shale due to microorganism activity after deposition).

3.2.2.2 Elliot Formation

This formation is known to be red beds due to the presence of red and purple mudstones and shales. This formation was formed in the Triassic period (Mesozoic Era). Many of the sandstones in this formation are calcareous and often coarse and gritty at the base. The Tuffaceous layers (indication of volcanism activity during deposition) in the Elliot sandstones have been reported to be present at Roma, National University of Lesotho sports grounds and also near Avani Lesotho (Schmitz and Rooyani, 1987).

3.2.2.3 Molteno Formation

The Molteno formation is characterised by buff and white coloured bench-forming and arkostic sandstones that range from coarse grained to gritty. The depositional environment is braided, low sinuosity rivers that may have formally be meandering river and this environment characterisation is supported by the cross-bedding patterns found in the formation (Schmitz and Rooyani, 1987).

3.2.3 Beaufort Group

In the geological sequence of the Karoo Supergroup, the Beaufort group was deposited after the Ecca Group. The geological age of the Beaufort group was from the middle Permian Period to early Triassic Period (Palaeozoic Era). The transition between Ecca and Beaufort boundary is continuous not sharp therefore the chronology of this contact is referred to be diachronous (Schmitz and Rooyani, 1987).

The depositional environment of this group was largely fluvial due to the large water body that covered the Karoo Basin. The development of the group occurred gradually but not a sudden environmental change. The lithology in this group has been characterised by its homogeneous sequence of bright-coloured shales and sandstones (often red to purple) (Schmitz and Rooyani, 1987).

3.2.3.1 Burgersdorp Formation

Mudstones and siltstones, with sandstone intercalations, are common in this geological formation. It is the lowermost part of the South Phuthiatsana catchment as it is exposed at the tributaries and on South Phuthiatsana River near Lihasang at Thaba-Bosiu to the Mohokare confluence (Davies, 2003).

3.2.4 Geological Structures

The faults, folds, dykes, and sills are amongst the geological features or structures that results into weak zones on the host and surrounding rocks.

Figure 3.3 below shows the distribution of dolerite dykes within the catchment display WNW-ESE and NNE-SSW strikes. These dolerites were formed during the extrusion of basalts and

died out with increasing height within the lava pipe. The contact between the dolerites and the host rocks gives rise to contact metamorphism resulting in the creation of preferred pathways or secondary porosity (Schmitz and Rooyani, 1987).

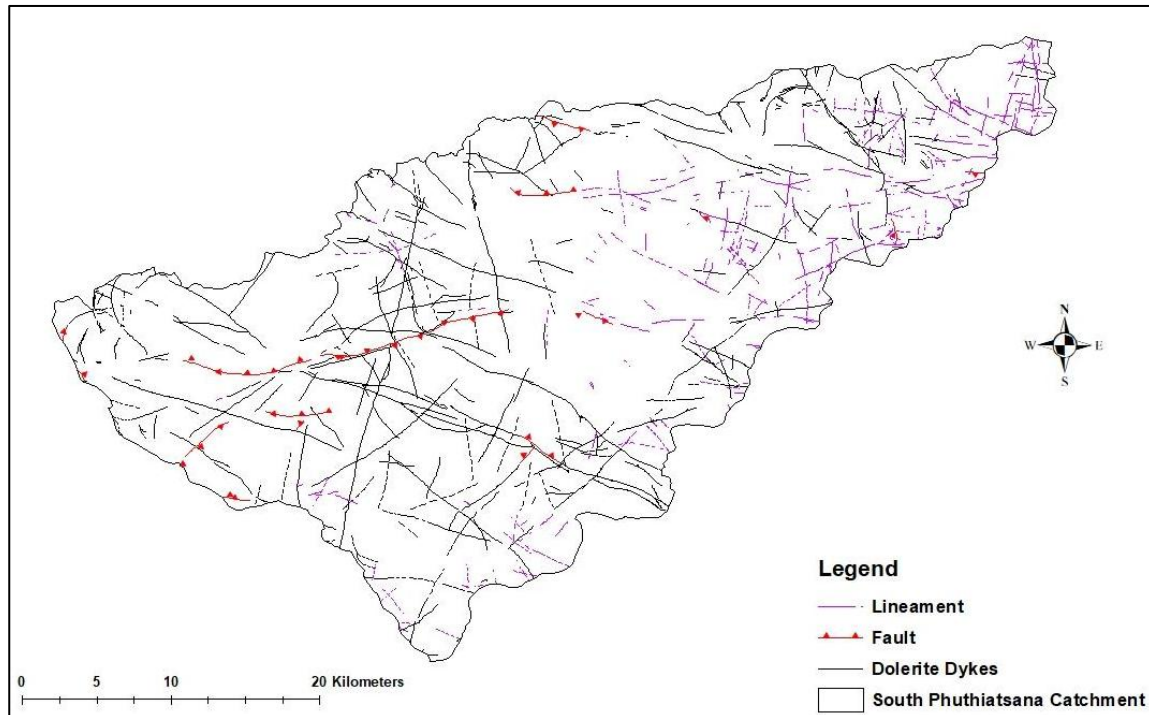


Figure 3.3 Geological structural map of the South Phuthiatsana Catchment illustrating the distribution of key structural features, including dykes, faults, and lineaments. These features influence groundwater flow pathways and surface–subsurface interactions within the catchment.

The geological structures such as dykes, faults, lineaments, and folds significantly influence groundwater flow by acting as preferential pathways or barriers, depending on their orientation, continuity, and degree of fracturing. In fractured aquifer systems, particularly in basaltic and sedimentary formations common in Lesotho, these structures control secondary porosity and permeability (Schmitz and Rooyani, 1987; Woodford and Chevallier, 2002).

Faults and lineaments often enhance groundwater movement by creating conduits that increase hydraulic conductivity along their zones of influence (Schmitz and Rooyani, 1987). Where fractures are well-connected, they form an interconnected network that facilitates rapid infiltration and lateral groundwater flow (MacDonald et al., 2005). Dykes, depending on their composition and alteration, can either impede or redirect flow; weathered or fractured dykes

may host significant groundwater, while unaltered ones typically act as barriers (Woodford and Chevallier, 2002).

Similarly, fold axes and associated fracture zones can localize recharge and influence the anisotropy of flow paths, especially in areas where folding has resulted in jointed or sheared zones that retain water (Foster et al., 2000). These structural controls must be carefully considered in groundwater assessments, as they govern the availability, direction and sustainability of groundwater resources in complex terrains (Schmitz and Rooyani, 1987).

3.3 Geohydrology

This section will consider geological properties to explain the localised groundwater occurrence.

3.3.1 Groundwater Storage and Recharge

The Karoo Supergroup functions as an essential groundwater reservoir in many semi-arid regions. Recharge primarily occurs through direct infiltration of precipitation, particularly in areas with permeable surficial deposits or fractured rocks. However, the recharge rates can be limited due to the low permeability of overlying shales and mudstones. Groundwater storage is often confined to specific sandstone units or fractured zones, leading to highly localized aquifer systems (Arduino et al., 1994).

3.3.1 Hydraulic Conductivity and Aquifer Properties

The hydraulic properties of the Karoo Supergroup vary significantly depending on the lithology and structural features.

3.2.1.1 Sandstones and Siltstones as Primary Aquifers

Sandstones within the Karoo, particularly in the Clarens, Molteno and Burgersdorp Formations, are typically the most productive aquifers. These rocks exhibit moderate to high porosity and permeability due to their granular texture and intergranular void spaces (Davies, 2003; Woodford and Chevallier, 2002). However, diagenetic processes such as cementation and compaction can reduce porosity, leading to significant spatial variability in hydraulic conductivity (Arduino et al., 1994).

3.2.1.2 Shales and Mudstones as Confining Layers

Shales and mudstones, common in the Elliot Formation, act as aquitards or aquicludes due to their low permeability and high clay content (Woodford and Chevallier, 2002). These units restrict vertical groundwater flow, often leading to confined or semi-confined aquifer conditions in underlying sandstones (Schmitz and Rooyani, 1987).

3.2.1.3 Influence of Fractures and Joints

Tectonic processes have significantly influenced the structural integrity of the Karoo Supergroup, leading to the development of fractures, faults, and joints. These features enhance secondary permeability, particularly in otherwise low-permeability units such as basalts and mudstones. Groundwater flow in these fractured systems can be anisotropic, with preferential pathways along major fracture zones (Schmitz and Rooyani, 1987).

3.2.1.4 Basalts and Volcanic Rocks

The Drakensberg Basalts, forming the uppermost unit of the Karoo Supergroup, typically have low primary porosity and permeability (Schmitz and Rooyani, 1987; Woodford and Chevallier, 2002). However, cooling joints, fractures, and weathered zones can create localized aquifers. The hydraulic properties of these volcanic rocks depend heavily on the degree of fracturing and weathering (Schmitz and Rooyani, 1987).

Groundwater storage and movement depend on numerous factors such as transmissivity and rock permeability which differ in different lithological units. Table 3.2 below illustrates the various geological formations and how they influence groundwater. Properties of each formation are provided in the geology section above.

Table 3.2: Summary of geological formations in the South Phuthiatsana Catchment, showing borehole and spring yields, lithological characteristics, and relative aquifer potential (on a scale of 1–4, with 4 being the best aquifer potential). Data adapted from Botha et al. (1998) and Schmitz and Rooyani (1987)

Geological Formation	Yield	Lithology, Porosity and grain size	Aquifer characteristics (Scale 1-4)
Lesotho formation	<ul style="list-style-type: none"> • Boreholes 0.7l/s 	<ul style="list-style-type: none"> • Basalts (fresh, fractured and weathered) 	Poor aquifer (2)
Clarens Formation	<ul style="list-style-type: none"> • No information available 	<ul style="list-style-type: none"> • Fine grained Sandstones • Siltstones 	Poor aquifer (2) based on lithology
Elliot Formation	<ul style="list-style-type: none"> • Boreholes 0.1 to 0.2l/s • Spring discharge ~0.05l/s 	<ul style="list-style-type: none"> • Mudstones • Shales • Fine sandstone • Occasionally has medium-coarse grained sandstone 	Good aquifer (3)
Molteno Formation	<ul style="list-style-type: none"> • Boreholes 0 to 1.6l/s • Spring discharge ~0.5l/s 	<ul style="list-style-type: none"> • Coarse-grained sandstone • Siltstone • Mudstone 	Best aquifer (4)
Burgersdorp Formation	<ul style="list-style-type: none"> • Boreholes ~1.12l/s 	<ul style="list-style-type: none"> • Fine and medium grained sandstone • Shale • Siltstone 	Good aquifer (3) Most boreholes were drilled near the dykes, making it appear to be a good aquifer.

3.3.2 Springs and Boreholes

The Figure 3.4 below shows the distribution of identified springs and boreholes within the catchment. Most springs emerge near geological features such as dolerite dykes, faults and

lineaments. These geological features are preferred pathways for groundwater movement as they create secondary porosity to aquifer properties.

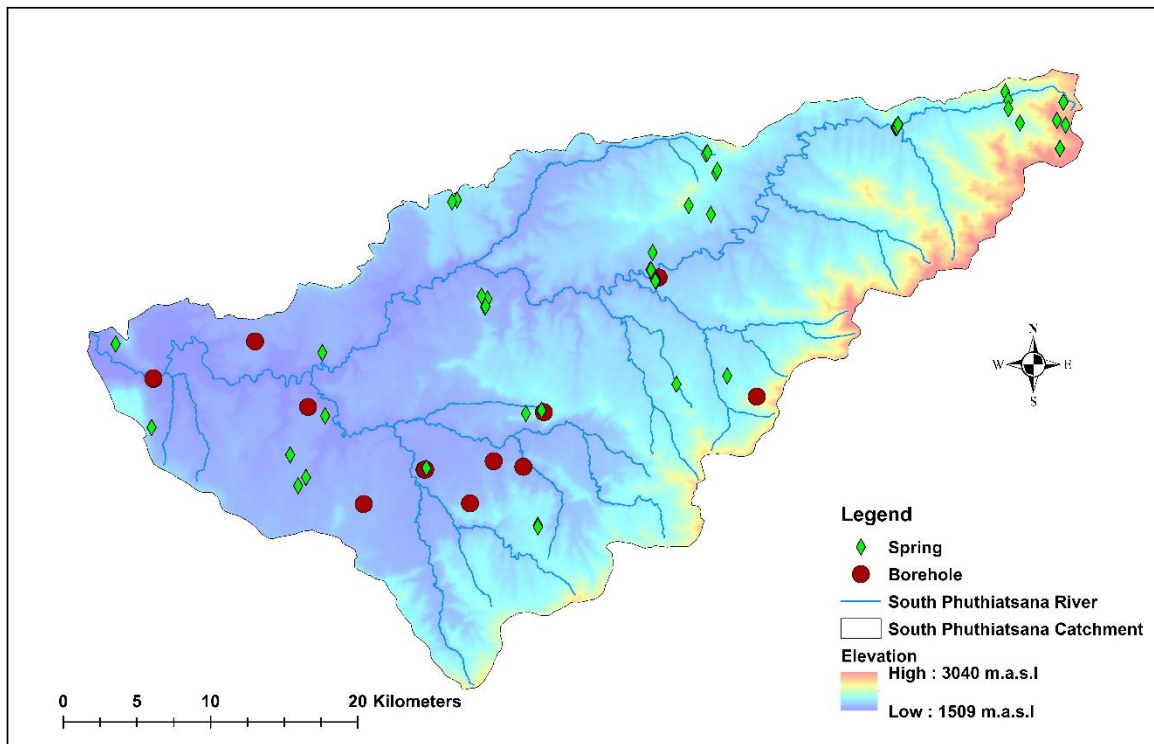


Figure 3.4 Distribution of boreholes and springs within the South Phuthiatsana Catchment overlaid on the Digital Elevation Model (DEM). The figure illustrates the spatial relationship between groundwater sampling points and topographic variation across the study area.

Lesotho is known to be the southern African water tower (Grab, 2013; World Bank Group, 2016) and it is of high importance to protect and manage this precious natural resource. The study area boasts a diverse array of water resources. Numerous springs, both protected and unprotected, serve various purposes, including domestic use, cultural activities, and providing drinking water for animals. Additionally, the region features a multitude of wetlands, rivers, and boreholes distributed throughout the catchment. The wetlands, located in the highlands, are the primary sources for many rivers across the country.

3.3 Surface Hydrology

Lesotho's catchment area boasts a variety of water resources, such as springs, boreholes, reservoirs, rivers, and wetlands. The Department of Water Affairs is responsible for monitoring these resources, but they face challenges due to limited resources, leading to gaps in data on

water quality and quantity. To enhance monitoring, there is a need to shift from manual to telemetric measurement methods. Having precise and detailed water data is essential for developing infrastructure, as it helps predict potential natural hazards and ensures the success and sustainability of projects.

Climate change has caused a decrease in spring yields, which impacts rural water supplies. Over the years, several important groundwater studies and surveys have been carried out in Lesotho, funded by international donors. Recent projects, like the Lesotho Lowlands Water Supply Feasibility Study, continue to guide water resource management and infrastructure development. This study guided policy towards development of the Metolong dam constructed within the South Phuthiatsana catchment.

The South Phuthiatsana catchment has a main river (South Phuthiatsana River also called Phuthiatsana-ea-Thaba-Bosiu) with numerous tributaries namely; Mohlaka-oa-Tuka, Liphiring, Thupa-Kubu and Koro-Koro that join it before it goes into a transboundary river called Mohokare/Caledon River shared by both Lesotho and South Africa. The South Phuthiatsana sources are in the Berea district at the rangelands of a village called Pulane and it is at this place whereby the sources are numerous and in the form of springs and wetlands patches distributed across the mountainous range.

The South Phuthiatsana River stretches approximately 95.4 km and flows year-round as a perennial river system. Along its course, it feeds into the Metolong Dam, a key reservoir within the basin. The river drains a catchment area of about 268 km², with a mean annual runoff reaching an estimated 66.7 million m³ at Metolong Dam. The dam has inundated 16 km of the river after dam completion from the dam wall to the tail while the dam will store 63.7 million m³ of water (Rossouw and Walker, 2014). The Metolong dam first reached its full capacity in December 2021 following heavy rains received within the catchment.

The history of the river indicates that the river in 2015 was also affected by the droughts and the Environmental Flow Requirements released from the dam were unable to reach further downstream towards the Mohokare River confluence (Maliehe, 2012). The river experienced

a severe hydrological drought and sand mining even took place within the river channel due to zero flow. In the sand mining that took place just before Ha Tikoe industrial factories, river water made pools at areas where sand excavation took place, revealing the low hydraulic head.

The Metolong Dam has an Environmental Flow Requirement (EFR) Policy that guides the water to be released throughout the year to sustain the river health and aquatic ecosystem as well as downstream users to utilize the river resource. During the high rainfall periods, a flood is released from the dam to cater for river health downstream as well as its aquatic life cycle because floods are naturally occurring events that renew the river health through a natural process shown in Figure 3.5. Moreover, floods are released from the dam to relieve the storage and allow flood input to the dam for mixing stored stagnant water with the flood inflow into the system.



Figure 3.5 Metolong Dam at full supply level releasing floodwaters through its ogee spillway on 25 December 2020. The controlled discharge highlights the dam’s operational role in attenuating peak flows and regulating downstream hydrology within the South Phuthiatsana Catchment.

3.4 Topography

Figure 3.1 above shows the catchment has a rugged terrain with a peak of about 3040m and a lowest point of about 1509m altitudes. There are numerous gullies caused by erosion due to

steep slopes and poor vegetation cover. The elevation distribution from highlands to lowlands is from the east to the west.

3.5 Land Use

There is a huge distribution of land uses currently, which has also been captured in archaeological studies, showing an evolution since the existence of the Bushmen (Mitchell, 1994). Moreover, the existence of mankind and how they establish a settlement is linked to the availability of water and other essentials. Therefore, these archaeological studies can provide information that can support reliable sources in the past. However, urban migration is the main driver for overpopulation in urban and semi-urban areas. This is linked towards the abundance of opportunities in the urban and peri-urban areas.

Figure 3.6 presents the land use and land cover (LULC) distribution within the South Phuthiatsana Catchment, offering a spatial overview of the region's ecological and anthropogenic characteristics. The map distinguishes between various land cover types, including built-up areas, croplands, wetlands, water bodies, and multiple vegetation classes such as dense and sparse vegetation, dense and open tree cover. It also highlights areas undergoing environmental change, such as tree cover gain and loss, as well as semi-arid and desert zones. This classification is essential for understanding the interactions between land use practices and hydrological processes, particularly in assessing runoff generation, evapotranspiration rates, and potential zones of groundwater recharge or degradation.

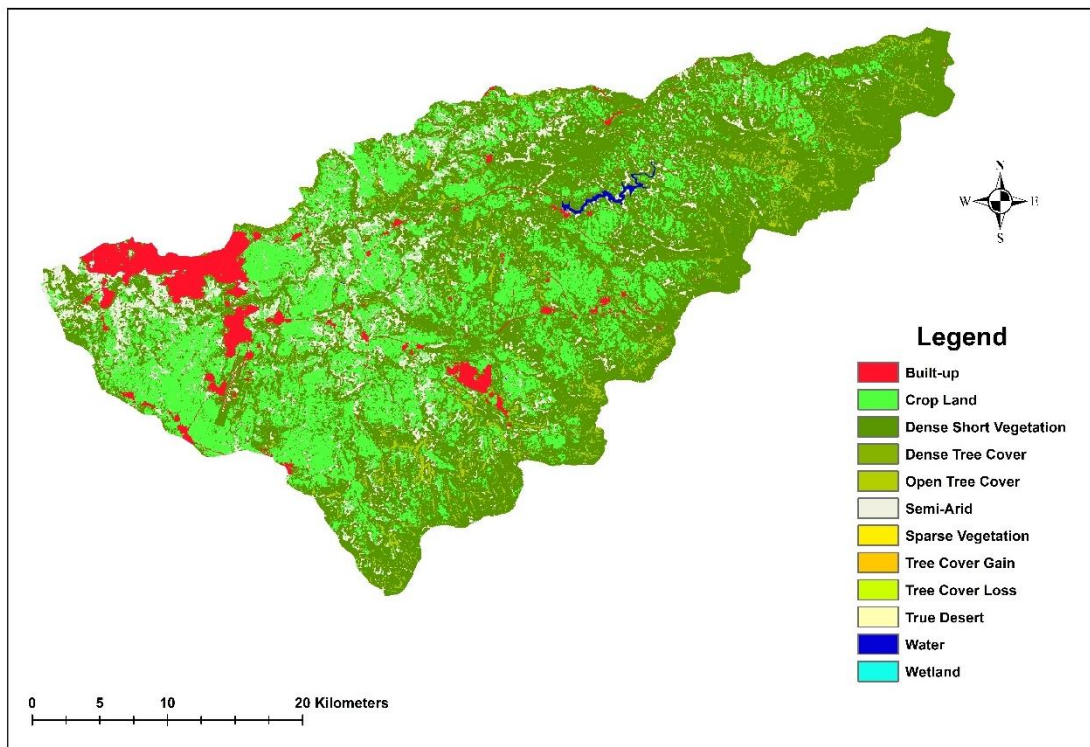


Figure 3.6 Land use and land cover map of the South Phuthiatsana Catchment, showing diverse vegetation types, land uses, semi-arid zones, and areas of tree cover change, highlighting ecological and human influences across the catchment.

3.6 Climate

Rainfall varies throughout the country and the national terrain also contributes to the variation of rainfall. This is monitored through a distribution of rain gauges across the country. South Phuthiatsana catchment is not an exception to the variation of rainfall patterns.

The climate in Lesotho is classified as temperate but also has characteristics of alpine conditions because of the country's high altitudes. The overall climate temperatures are lower than the other continental countries with similar elevation and this is the result of varying or erratic terrain of the country (UNFCCC, 2021).

There are two distinct seasons (winter and summer) and two transitional seasons (spring and autumn). The summer season is scorching and moist with most of the annual rainfall received during this season. Summer is from October to March also known as the austral summer or wet season because of high precipitation amount occurrence. Lesotho receives an average annual

precipitation of approximately 700–800 mm, with the highest amounts concentrated in the summer months (UNFCCC, 2021).

The winter in Lesotho is cold and dry while the summer is hot and moist. During winter, snowfall is experienced in the highlands of Lesotho while frost is present for the entire country throughout the winter season. These seasonal variations are linked to Southern Africa’s weather synoptic (Figure 3.7), which incorporates the north-south migration of the Intertropical Convergence Zone (ITCZ), Subtropical High-Pressure Zone (SHPZ) and Temperate Zone (Atlantic low-pressure system). The air mass (moisture uptake) from the warmer Indian Ocean differs from that of the cooler Atlantic Ocean, however, this makes precipitation derived from either air mass unique (Leketa et al., 2018; van Wyk et al., 2011).

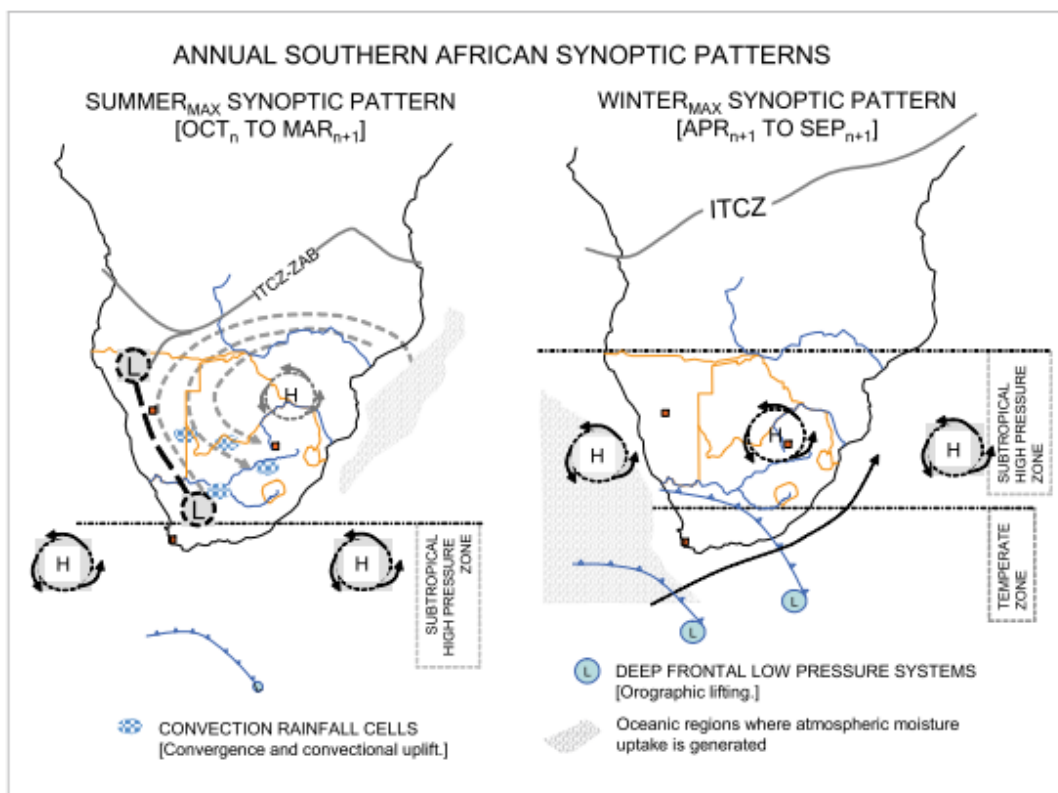


Figure 3.7 Synoptic patterns over Southern Africa during summer and winter seasons in relation to the generation of airborne moisture and the general migration pathways.
Source: van Wyk et al. (2011).

Moreover, during 2016, the Southern Africa experienced one of the historical droughts due to the prevailing El Nino. This phenomenon affected the Southern African Development Community (SADC). Lesotho being one of the countries within community declared a national drought and state of emergency followed by a regional drought declared by SADC in 2016 (WFP-Lesotho, 2016).

Even though El Nino is associated with droughts in Southern Africa, minimum rainfall can still be received. It is rather an unfavourable rainfall condition and therefore, not all El Nino events result in drought but limited rainfall during an austral summer.

In addition, Figure 3.8 below shows that the rainfall distribution in the catchment is not any different from the national distribution whereby the highlands are humid and receive higher rainfall when compared to the lowlands which are hot and dry with less rain. Furthermore, snow is common in the higher altitudes within the study area during the winter season but not with high intensity like in other parts of the country. The snow plays a vital role in the catchment hydrology to sustain river or recharge groundwater when it melts (Fobo, 2009).

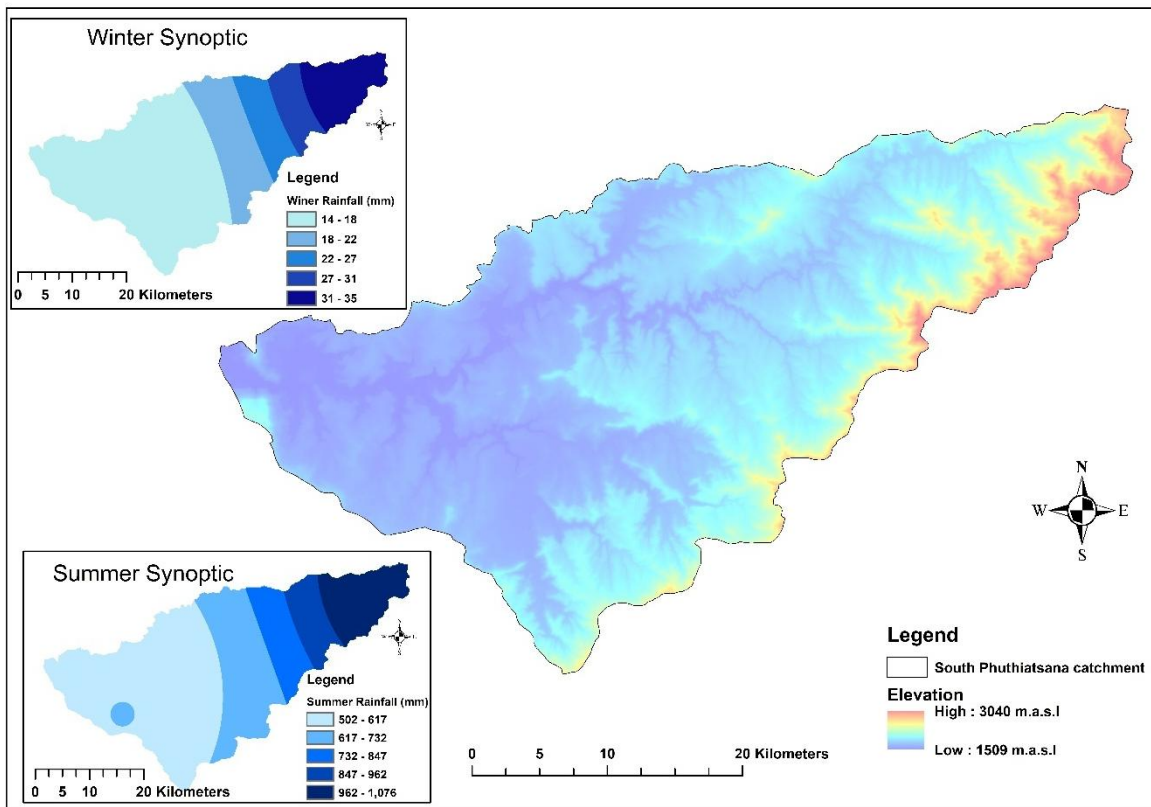


Figure 3.8 Rainfall distribution under summer and winter synoptic conditions and the Digital Elevation Model (DEM) of the South Phuthiatsana Catchment, highlighting seasonal variability and topographic influence.

The study descriptions mentioned above are important as they govern GW-SW interaction and catchment flow dynamics.

CHAPTER 4: METHODOLOGY

Introduction

The stable isotopes have been proven to being good tracers in the hydrological studies and they are naturally occurring tracers. These isotopes are components that form a water molecule therefore are environmentally friendly.

An isotope is defined as an atom of the same element with a similar number of protons but a different number of neutrons in the nucleus, resulting in a different mass number of the same element (Coplen et al., 2000). Isotopes in a water molecule can be successfully employed in understanding the hydrological cycle by providing information about the origin, time taken since recharge and the pathways that water has taken.

This application of isotopes in hydrological studies is given a general term of Isotope Hydrology and it involves the use of both stable (non-radioactive) and unstable isotopes (radioactive) (Ortega and Gil, 2019). The water molecule (H_2O) can have a combination of different isotopes from hydrogen (^1H , ^2H and ^3H) and oxygen (^{16}O and ^{18}O) that are mainly used for isotope hydrology analysis. The mentioned water isotopes are mainly used due to their natural abundance but at a trace concentration. Because of their trace concentration, specialized equipment is used for these measurements and presented in unique units. The mass difference of these isotopes is important as it assists in controlling the physical and chemical conditions of the water molecule, with an example of hydrogen which has a double mass difference from protium to deuterium (Geyh, 2000).

The use of stable and radioactive isotopes is important in determining groundwater-surface water interaction in shallow and deep aquifers, rivers and local precipitation (Lapworth et al., 2021). In addition to this water isotopes, radon isotopes, electrical conductivity and baseflow are also used to strengthen the assessment of catchment flow dynamics within the hydrological cycle.

Table 4.1 Stable isotope abundance (Aeschbach-hertig, 2006)

Element	The abundance stable isotopes (in%)	
Hydrogen	$^1\text{H} - 99.985$	$^2\text{H} - 0.015$
Nitrogen	$^{14}\text{N} - 99.63$	$^{15}\text{N} - 0.37$
Oxygen	$^{16}\text{O} - 99.758$	$^{18}\text{O} - 0.038$

Table 4.2 Examples of environmental isotope tools in hydrological studies (Froehlich et al., 1998) modified

Isotope	Substance	Application
$^2\text{H}/^1\text{H}$ $^{18}\text{O}/^{16}\text{O}$	H_2O	<ul style="list-style-type: none"> • Recharge mechanism identification • Interaction of surface water with groundwater or wetlands or precipitation • Engineering mitigation programmes • Identification of palaeowater • Recycling of irrigation water
$^{15}\text{N}/^{14}\text{N}$ $^{18}\text{O}/^{16}\text{O}$	NO_3^- NH_4^+ N_2	<ul style="list-style-type: none"> • Identification of pollution sources • Identification of microbial denitrification
^3H	H_2O	<ul style="list-style-type: none"> • Identification of recent recharge
^{222}Rn	H_2O	<ul style="list-style-type: none"> • Identification of groundwater-surface water interaction

4.1 Theoretical Background

4.1.1 Isotope Hydrology

4.1.1.1 Meteoric Water Lines

Figure 4.1 shows information that can be abstracted from an $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ plot that has a combination of rainfall data and surface water. It is evident from this figure that surface water that has experienced losses to evaporation will maintain a distinct slope signifying enrichment in heavier isotopes as compared to a local meteoric water line. Additionally, the figure also shows that such a plot can reveal information about the atmospheric conditions at precipitation

as well as altitude. It shows the various uses of the meteoric water line and evaporation line within the isotope hydrology fraternity.

The Meteoric Water Lines are used to characterise precipitation (Craig and Gordon, 1965), and they enable the determination of the vapour source (Gonfiantini et al., 2018; Zega et al., 2020).

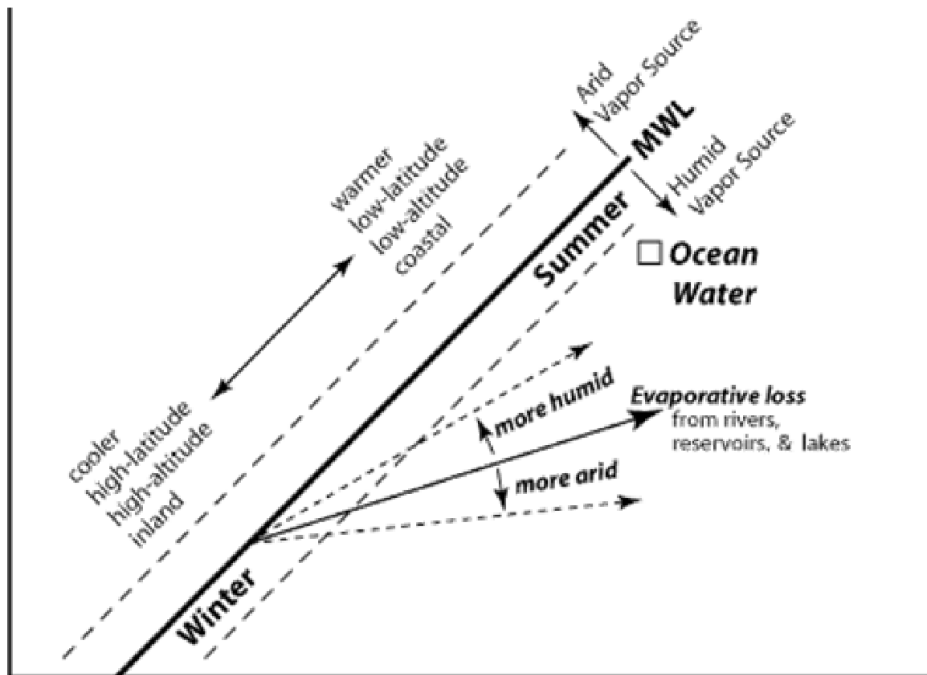


Figure 4.1 The diagram illustrates isotopic variations under different hydrological and climatic conditions. Source: Zega et al. (2020).

4.1.1.2 Isotopic Effects

As shown in figure 4.1 above, the isotopic effects are governed by the different molecular mass of a water molecule and some factors control isotopic changes of a water molecule. These factors are humidity, temperature, altitude, trajectory of a cloud from the ocean to further inland and many more. A water molecule consisting of lighter isotopes (lower molecular mass) will be enriched in a volatile as opposed to a less volatile phase during phase change such as condensation, sublimation and evaporation. This process is known as Isotope fractionation or temperature effect as it depends strongly on temperature.

Furthermore, the movement of a cloud from the ocean to further inland will be depleted in heavy isotopes as it loses heavy isotopes through rainfall, known as the rain-out effect or continental effect. Coupling temperature and continental effects, there is a difference in altitude

since low altitudes are warmer than higher altitude areas. This is known to be the altitude effect, and it is paramount in determining groundwater recharge altitude (Geyh, 2000).

4.1.2 Hydrochemistry

In-situ parameters have been used in the study as hydrochemistry but not through major ions. These in-situ parameters provide vital information about sample properties on-site and can be used for characterisation of water resources as an additional tool for groundwater-surface water interaction.

4.1.3 Baseflow

Another method of assessing groundwater input into the surface water (river) is using baseflow separation which uses different approaches to model the interaction. Baseflow is the groundwater input into the river flow, making a river flow through the dry season (Department of Water and Sanitation (DWS), n.d.). This interaction is important in water resources management since groundwater contribution in baseflow sustains perennial rivers during the low flows, especially in arid and semi-arid areas.

4.2 Sampling and Analysis

The study applied different methods to assess GW-SW interaction at multiple scales within the catchment. Methods used are as follows; (1) Stable Deuterium and Oxygen isotopes. (2) Radioactive ²²²Radon noble gas. (3) In-situ parameters in particular Electrical Conductivity (EC). (4) River discharge.

The distribution of sampling sites involved the collection of samples and in-situ measurements. Figure 4.2 below is the sampling coverage that was primarily concentrated on the South Phuthiatsana catchment in Lesotho. Additionally, two precipitation stations which are located outside the study area namely the Department of Water Affairs Maseru offices and Lesotho Meteorological Service Oxbow Station, were included in the research.

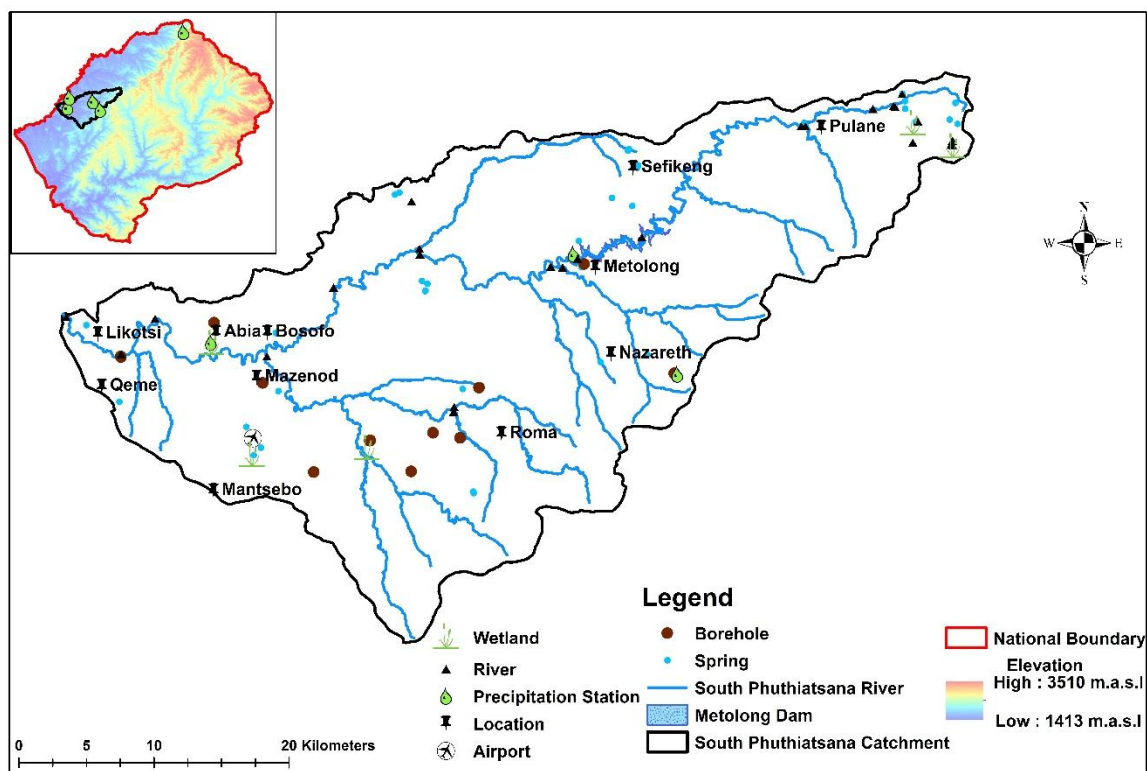


Figure 4.2 Distribution of national precipitation sampling sites and water resources within the South Phuthiatsana Catchment, including springs, wetlands, rivers, and boreholes.

4.2.1 Isotope Hydrology

In this research, the sampling of stable isotopes took place in the main river and tributaries, springs and boreholes for groundwater as well as wetlands and in the reservoir. Precipitation was sampled as a reference regarding modern rainfall signature to deduce the mobility of a water molecule since recharge (Mook, 2000).

The precipitation isotope data in Lesotho from Maseru and Oxbow are part of a Global Network of Isotopes in Precipitation (GNIP) database collected from 2018 to 2022. No publications have been produced using these datasets. There are 29 samples from Oxbow GNIP and 32 samples from Maseru GNIP analysed.

Moreover, this study used these datasets to compare and improve precipitation isotope data of the South Phuthiatsana Catchment collected from April 2022 to January 2024, covering a complete hydrological year and beyond. The precipitation isotope data in the study area has

been collected from three precipitation stations, two of which are monthly sampling, and one is daily sampling. A total of 139 daily samples from Abia, 32 monthly samples from Metolong and 9 monthly samples from Nazareth were analysed for the mentioned period above. The precipitation stations are in three differently located elevations.

The Abia daily dataset will be used to develop the Local Meteoric Water Line and assist on the interpretation of catchment hydrology. In addition, more data on stable isotopes has been collected in the catchment from a Global Network of Isotopes in Rivers (GNIR) station at Metolong Dam to improve surface water characterisation. This GNIR station was established in 2020, and data collection is ongoing. Long-term data of 28 samples from the GNIR station was used to develop the Local Evaporation Line (LEL) of the catchment.

Table 4.3 Summary of GNIP/R stations where $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were collected

Station Name	Latitude	Longitude	Type	Frequency	Date (Period)	Number of samples
Maseru GNIP	-29.298345	27.54755	Precipitation	Monthly	2018-2022	32
Oxbow GNIP	-28.680992	28.62622	Precipitation	Monthly	2018-2022	29
Metolong GNIR	-29.336793	27.773192	River	Monthly	2020-2024	28
Nazareth GNIP	-29.413891	27.837886	Precipitation	Monthly	2022-2024	9

Metolong GNIP	-29.332073	27.768329	Precipitation	Monthly and daily	2022- 2024	32
Abia GNIP	-29.392779	27.530155	Precipitation	Daily	2022- 2024	139

In addition to the GNIP and GNIR, more water resources data were collected from 50 springs, 13 boreholes and 5 tributaries. Key springs and boreholes were sampled every 2 or 3 months for stable isotopes. The stable isotope sampling from 19 key springs and 2 key boreholes were collected twice or more for different months, with some covering both wet and dry seasons.

Despite having recurring samples from GNIP, GNIR, spring and boreholes, the once-off sampling took place in the headwaters and was spatially distributed within the catchment. This was achieved through the collection of samples from 31 springs, 5 wetlands, 5 tributaries and 18 on the main river. All stable isotope samples were collected using 60- or 30-ml HDPE bottles with no bubbles and stored in a cooler box while in transit. Upon arrival, samples were stored in a fridge and filtered with a 0.22 μ m cellulose acetate syringe filter before being analysed in the laboratory by a Liquid Water Isotope Analyser GLA431.

Figure 4.3 below shows the equipment in the University of KwaZulu-Natal Isotope Hydrology Laboratory that was used to analyse $\delta^{18}\text{O}$ and $\delta^2\text{H}$.



Figure 4.3 Liquid Water Isotope Analyser picture.

In addition, ^{222}Rn was measured on the rivers with the Metolong dam outlet as the reference point followed by tributaries and their confluence with the main river. ^{222}Rn measurements in the river were done using the DurrIDGE RAD 7. This is a solid-state alpha detector that measures ^{222}Rn in water using the RAD Aqua system. The system consists of a submersible pump, spray chamber, temperature logger, drierite, tubing, filters and a 12-volt car battery. Figure 4.4 below illustrates the schematic diagram of the Rad AQUA system.

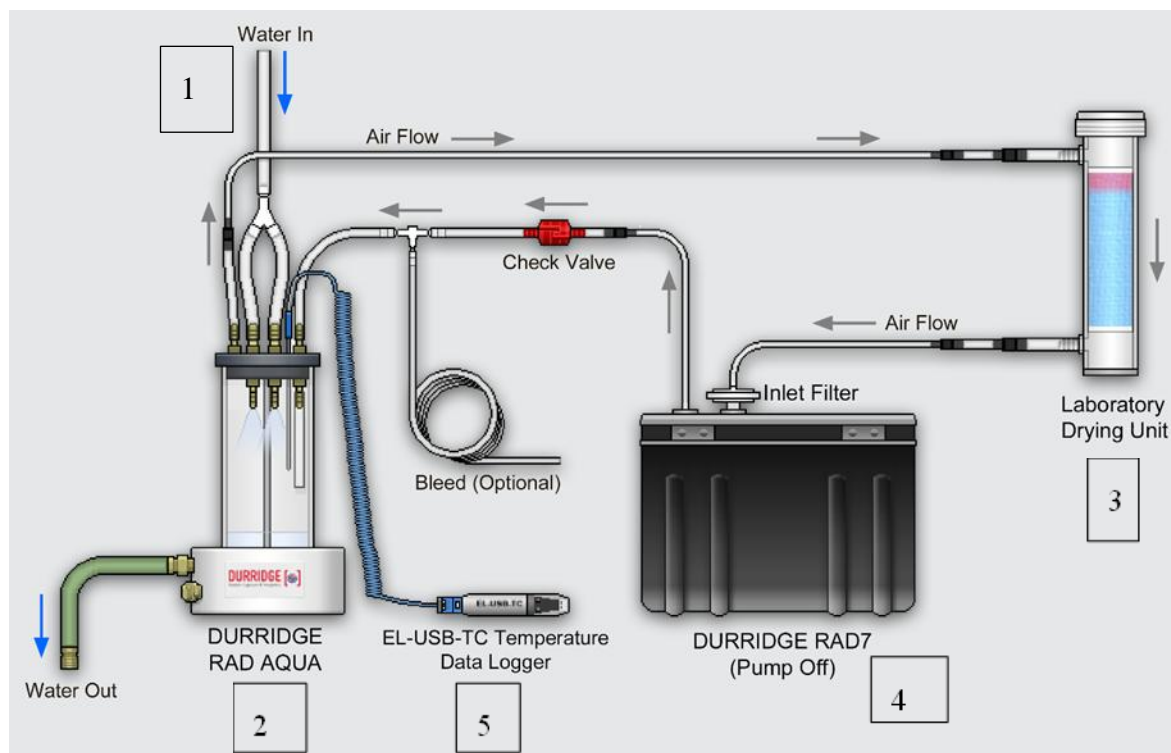


Figure 4.4 Schematic diagram of Schematic diagram of the RAD-Aqua system used for field measurements of radon in surface water, particularly in environments with low radon concentrations. Source: RAD7 User Manual (DurrIDGE Company Inc.).

The procedure followed during the field measurements was 10 minutes of purging, 3 recycles, and 20 minutes of cycles with a sniff mode protocol. Radon in the air comes into equilibrium with radon in the water.

As shown in Figure 4.4 above, water passes continuously through the RAD AQUA exchanger with continuous inflow. Figure 4.5 below shows measurements taking place in the field using the RAD-Aqua system on a flowing river.

The RAD-Aqua field assembled comprised of a submersible pump to continuously supply water to the RAD-Aqua. For the smooth operation of the pump, the power supply is through a 12-volt battery. Whereas the DurrIDGE RAD 7 has an internal battery which is charged before fieldwork. In addition, there is a laptop used to activate the temperature logger and download temperature data after every site measurement.

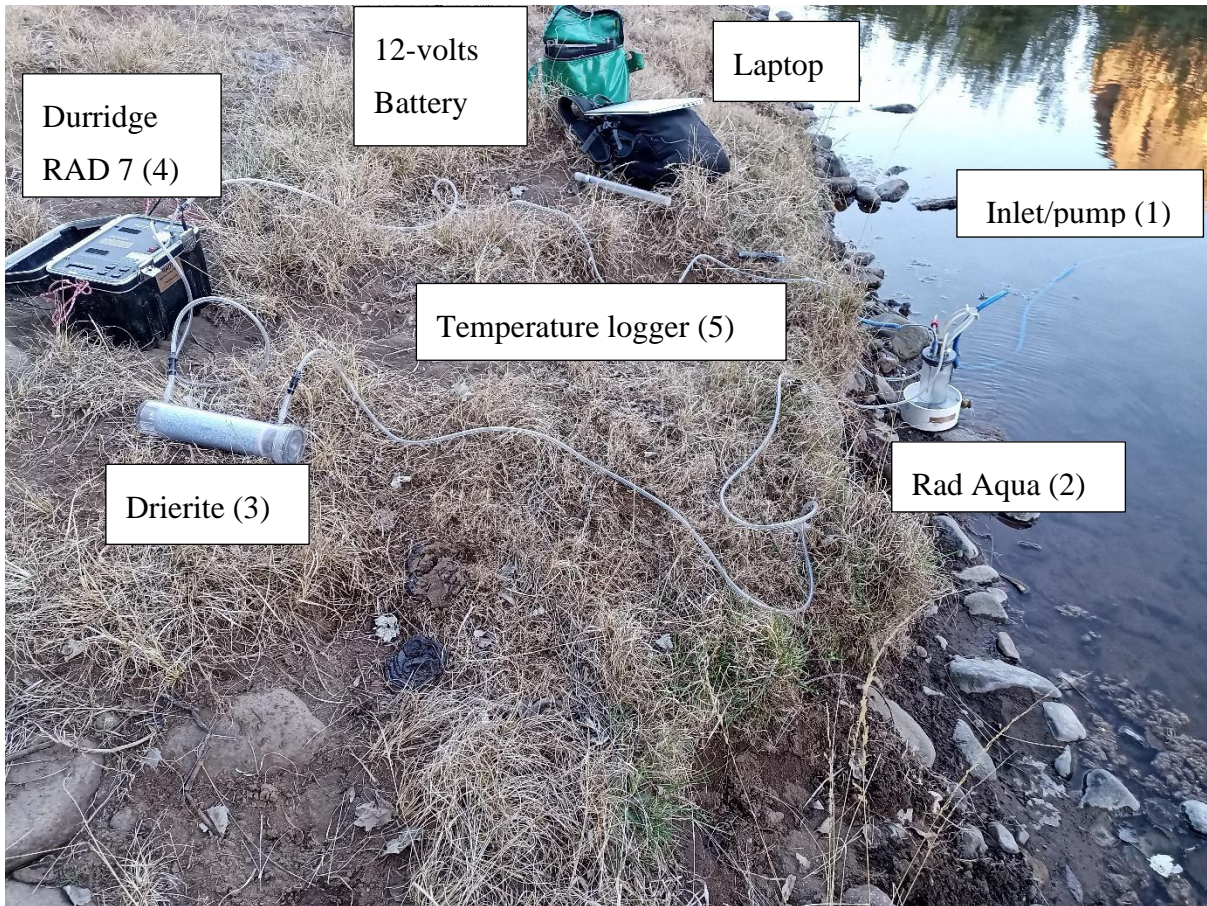


Figure 4.5 Field measurements of radon in surface water using the RAD-Aqua system, demonstrating in situ sampling techniques for detecting low concentrations of radon

The radon concentration in the air and the temperature of the air/water interface determines the radon concentration in the water. This is the fastest, most sensitive method of measuring radon in water, and it can monitor both radon and thoron levels continuously.

4.2.2 Hydrochemistry

In addition to the isotopes collected, there were in-situ measurements of EC, temperature, pH and dissolved oxygen using a Hach multiparameter probe, WTW EC probe and WTW DO probe. This equipment was used for all samples including boreholes. Figure 4.6 below shows borehole water sampled using a bailer where there is no existing pump. A plastic beaker is later used to collect water for measurement of in-situ parameters using the probes mentioned above.



Figure 4.6 Sampling of borehole water using a bailer, illustrating a manual method for groundwater collection during field investigations.

Through the studies that were done in South Africa, Lesotho can replicate the use of water isotopes (stable and radioactive), hydrochemistry and radioactive noble gas isotopes (Radon 222). Since Lesotho is landlocked by South Africa, some of the data limitations have been compensated by the vast availability of data in South Africa for areas with similar properties inter alia topography, geology and climate.

4.2.3 Baseflow

Long-term data from the Masianokeng gauge station has been used to estimate baseflow. This station accounts for water from all tributaries to the South Phuthiatsana River and will be used to determine the baseflow component.

There are only three functional river gauge stations namely Masianokeng, Koro-Koro and Pulane in the catchment. In addition to gauge station records, the river discharge has been measured using an Electromagnetic meter at areas with no gauge stations or missing data.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Isotope Hydrology

5.1.1 Precipitation Characterisation

The Meteoric Water Lines are used to characterise precipitation (Craig, 1961) and they enable the determination of the vapour source (Gonfiantini et al., 2018; Zega et al., 2020).

5.1.1.1 Meteoric Water Lines

The Figure 5.1 below represents the precipitation of the highlands in Lesotho using stable isotopes from an established Oxbow GNIP station. The dual isotope ($\delta^{18}\text{O}$ vs $\delta^2\text{H}$) plot shows a strong correlation of 94%, a slope of +7.17 and a d-excess of +12.83‰ with an enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signal compared to GMWL and consistent with studies from temperate climates like Georgia (Holko et al., 2023).

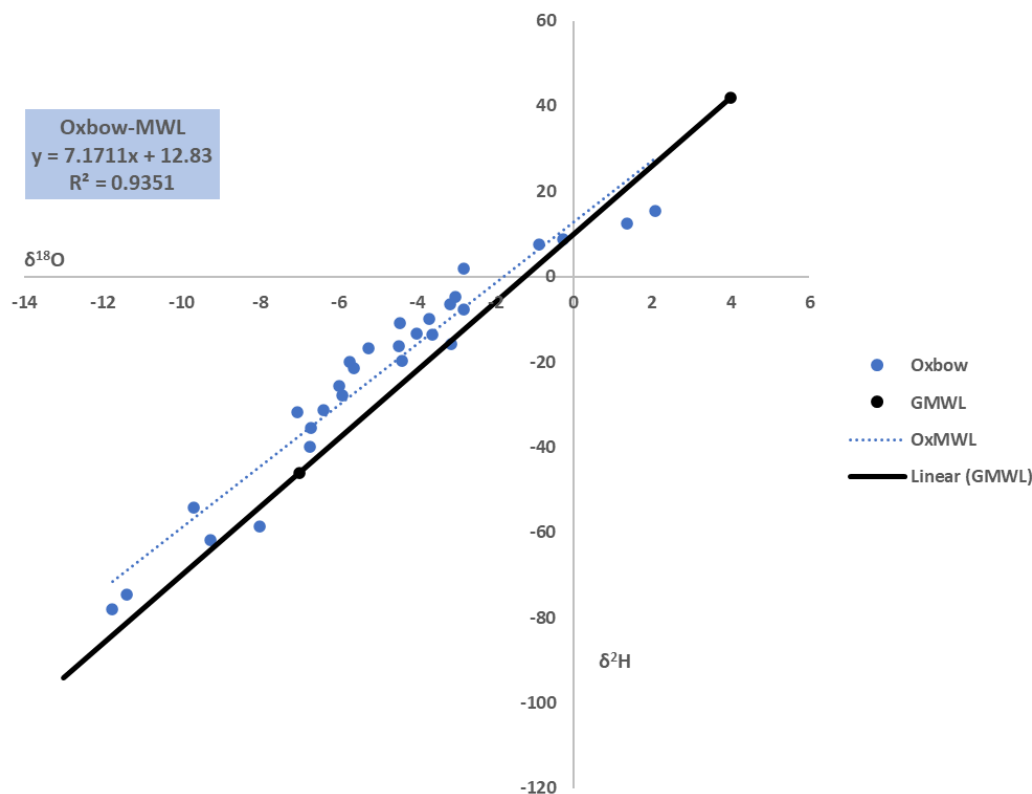


Figure 5.1 Oxbow Local Meteoric Water Line (Ox-LMWL) plotted against the Global Meteoric Water Line (GMWL), illustrating the isotopic characteristics of local precipitation in comparison to global averages.

Oxbow Local Meteoric Water Line (Ox-LMWL):

$$\delta^2H = 7.17\delta^{18}O + 12.83\text{‰} \quad (1)$$

Furthermore, the Maseru GNIP data is shown on Figure 5.2 and used to develop the Maseru-LMWL in the lowlands of Lesotho. The d-excess of 9.30‰ with a slope of +6.8 and correlation of 89%. These characteristics are in the same range of regional isotopic properties found in semi-arid inland areas within South Africa (Durowoju et al., 2019; Leketa et al., 2018) as south southwest of South Phuthiatsana catchment has a semi-arid climate (see Figure 3.6).

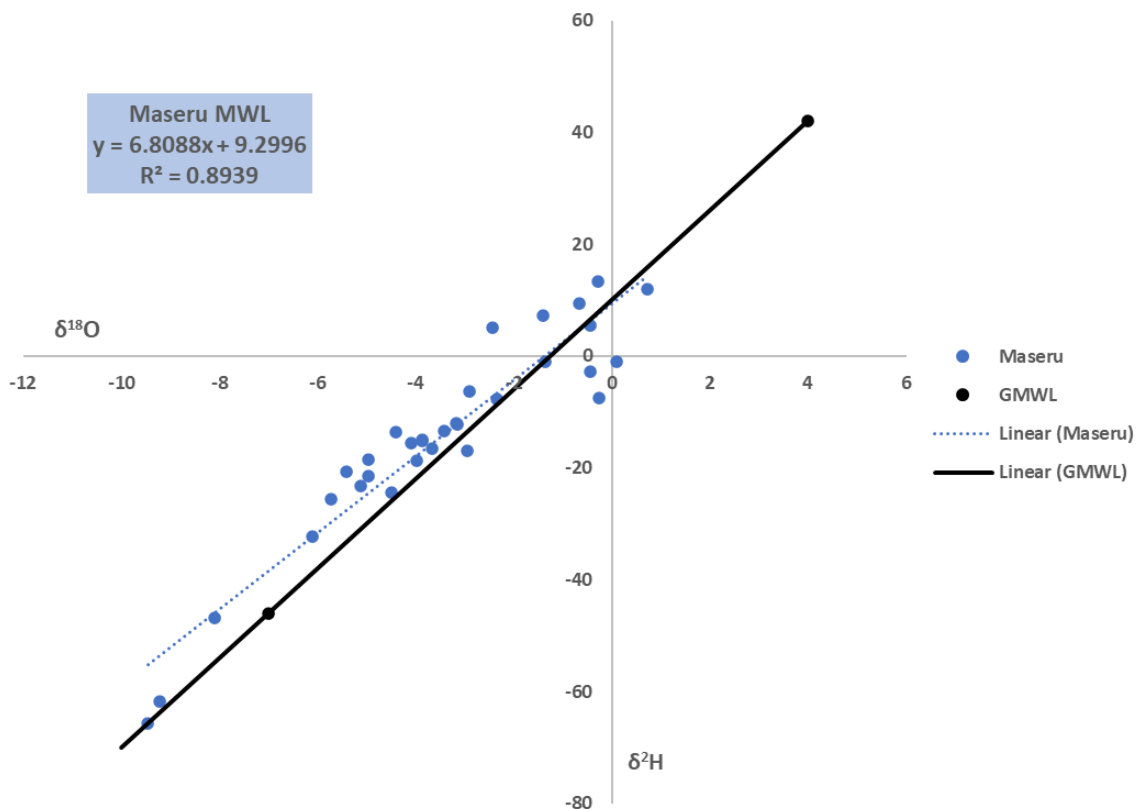


Figure 5.2 Maseru Local Meteoric Water Line (Ms-LMWL) plotted against the Global Meteoric Water Line (GMWL), showing the isotopic composition of precipitation in Maseru relative to global meteoric trends.

Maseru Local Meteoric Water Line:

$$\delta^2H = 6.81\delta^{18}O + 9.30\text{‰} \quad (2)$$

The newly developed local meteoric water lines from the four-year time series form a baseline for the characteristics of isotopes in precipitation for Lesotho. Although these monthly long-term data are used as the baseline, both stations do not fall within the study catchment but rather resemble the properties of the study area on the altitude, temperature and rainfall pattern. This provides a comparable platform in the assessment of catchment hydrology.

Moreover, Figure 5.3 shows three precipitation stations consisting of one daily sampling and two monthly sampling stations distributed spatially at different altitudes in the study area. For all the stations within the South Phuthiatsana catchment (see Figure 4.2), the correlation of data is 95% and has a slope of 7.2. In addition, the daily Abia data has a d-excess of 12.67‰, which is higher than that of the GMWL being 10‰ and this is consistent with the temperate climate (Holko et al., 2023) and semi-arid region isotopic properties (Hao et al., 2019; Pang et al., 2011).

Moreover, the isotope composition of daily rainfall taken from Abia shows a correlation with other stations within the South Phuthiatsana catchment. This suggests that the Abia-LMWL will be used as the reference plot for catchment characterisation because of the representative data collected from April 2022 to January 2024.

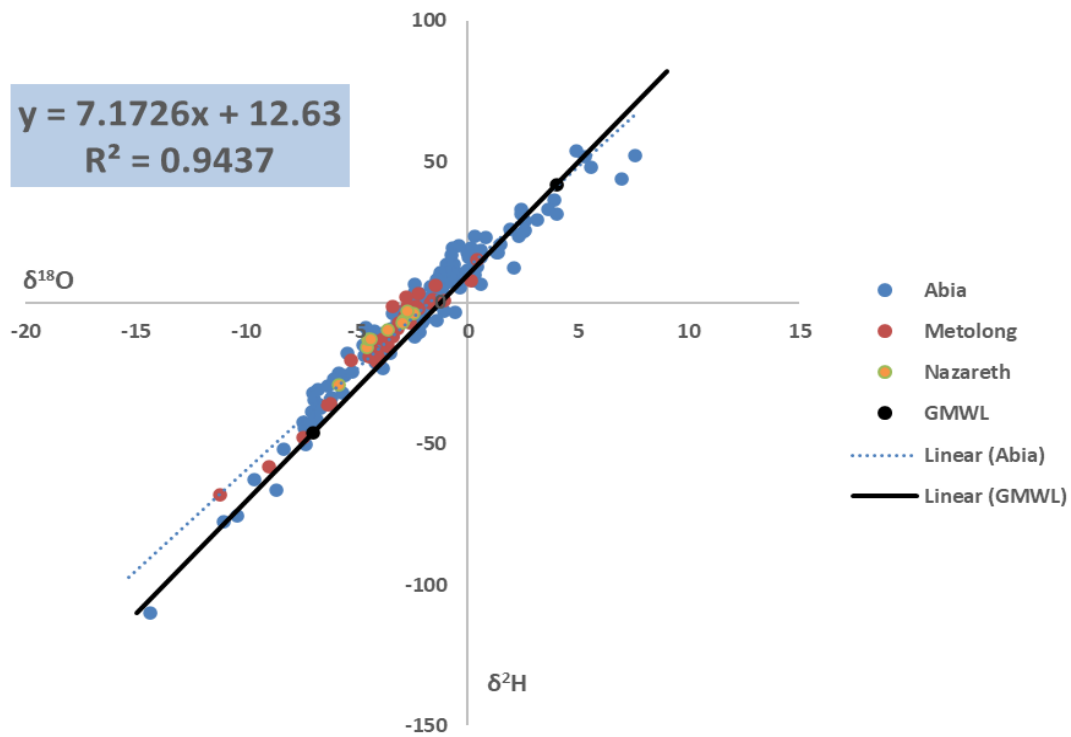


Figure 5.3 Isotopic composition of precipitation collected from three stations at different elevations within the South Phuthiatsana Catchment, compared with the Global Meteoric Water Line (GMWL).

Abia Local Meteoric Water Line:

$$\delta^2H = 7.17\delta^{18}O + 12.63 \quad (3)$$

The Abia-LMWL developed by daily sampling when compared to both Maseru and Oxbow Local Meteoric Water lines, have a positive slope ranging from 6.8‰ to 7.17‰ with the intercepts (d-excess) ranging from 9.30 to 12.83‰.

Furthermore, Lesotho’s Local Meteoric Water Lines developed by available data show an enriched δ^2H signal when compared to the GMWL. This isotopic signal is associated with arid to semi-arid climates (Durowoju et al., 2019; Leketa et al., 2018). In addition, the slopes of Lesotho’s meteoric water lines are below 8 (GMWL), and this also resembles the precipitation characteristics of the semi-arid region (Hao et al., 2019; Pang et al., 2011; Rozanski et al., 1993).

Abia-LMWL has an enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signal with d-excess higher than 10‰ of GMWL like the Oxbow-LMWL while Maseru-LMWL has a lower d-excess of 9.3‰ indicating the sub-cloud evaporation effect (Hao et al., 2019; Leketa and Abiye, 2020). This makes all three Local Meteoric Water Lines of Lesotho a baseline for further studies and duplication in the national catchments of Lesotho, as they represent different geographic locations.

The Global Meteoric Water Line (GMWL) is a pioneer of explaining the relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ and has a slope of 8 with an intercept (d-excess) of 10 (Clark and Fritz, 1997; Craig and Gordon, 1965).

Table 5.1 Summary of Meteoric Water Lines (MWLs), including slope and intercept values for local meteoric water lines in comparison to the Global Meteoric Water Line (GMWL).

Name	Acronym	Equation	D-excess	Reference
Global Meteoric Water Line	GMWL	$\delta^2H = 8\delta^{18}O + 10\text{‰}$	+10‰	(Craig, 1961)
Pretoria Local Meteoric Water Line	PLMWL	$\delta^2H = 6.7\delta^{18}O + 7.2\text{‰}$	+7.2‰	(Leketa et al., 2018)
Johannesburg Local Meteoric Water Line	JLMWL	$\delta^2H = 6.7\delta^{18}O + 10\text{‰}$	+10‰	(Leketa et al., 2018)

Thoyandou Local Meteoric Water Line	TLMWL	$\delta^2H = 7.56\delta^{18}O + 10.64\text{‰}$	+10.64‰	(Durowoju et al., 2019)
Oxbow local Meteoric Water Line	OxLMWL	$\delta^2H = 7.17\delta^{18}O + 12.83\text{‰}$	+12.83‰	Not yet published
Maseru Local Meteoric Water line	MsLMWL	$\delta^2H = 6.81\delta^{18}O + 9.30\text{‰}$	+9.30‰	Not yet published
Abia Local Meteoric Water Line	Abia-LMWL	$\delta^2H = 7.17\delta^{18}O + 12.63\text{‰}$	+12.63‰	Not yet published

Lesotho's (Oxbow, Maseru and Abia) Local Meteoric Water Lines have an enriched $\delta^{18}O$ and δ^2H signal (eclipse A on Figure 5.4) than the GMWL and the arid to semi-arid South African (Pretoria, Johannesburg and Thoyandou) Local Meteoric Water Lines.

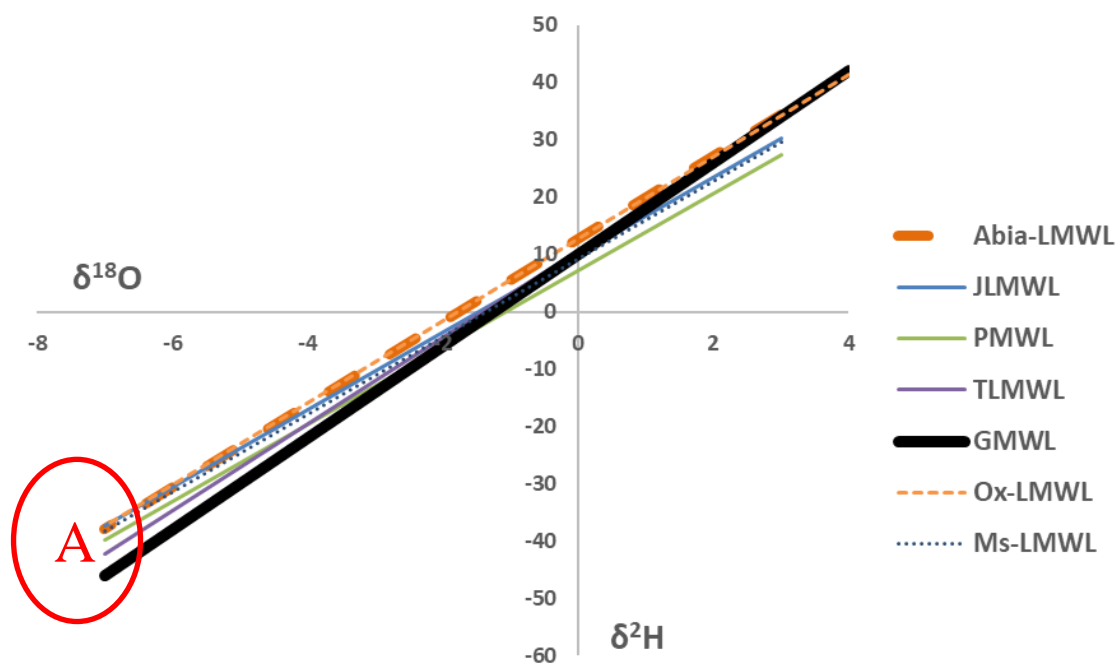


Figure 5.4 Lesotho’s Local Meteoric Water Lines (LMWLs) plotted against Regional Meteoric Water Lines (RMWLs), with a red oval highlighting the influence of an arid vapour source on the isotopic composition of precipitation.

5.1.1.2 Amount Effect

Figure 5.5 below is the daily sampling and shows that the depleted rainfall is associated with a large amount, while the enriched rainfall is associated with a low rainfall amount (Dansgaard, 1964). This indicates that rainfall showers have depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signal therefore high rainfall, whereas low rainfall goes through evaporation hence an enriched signal.

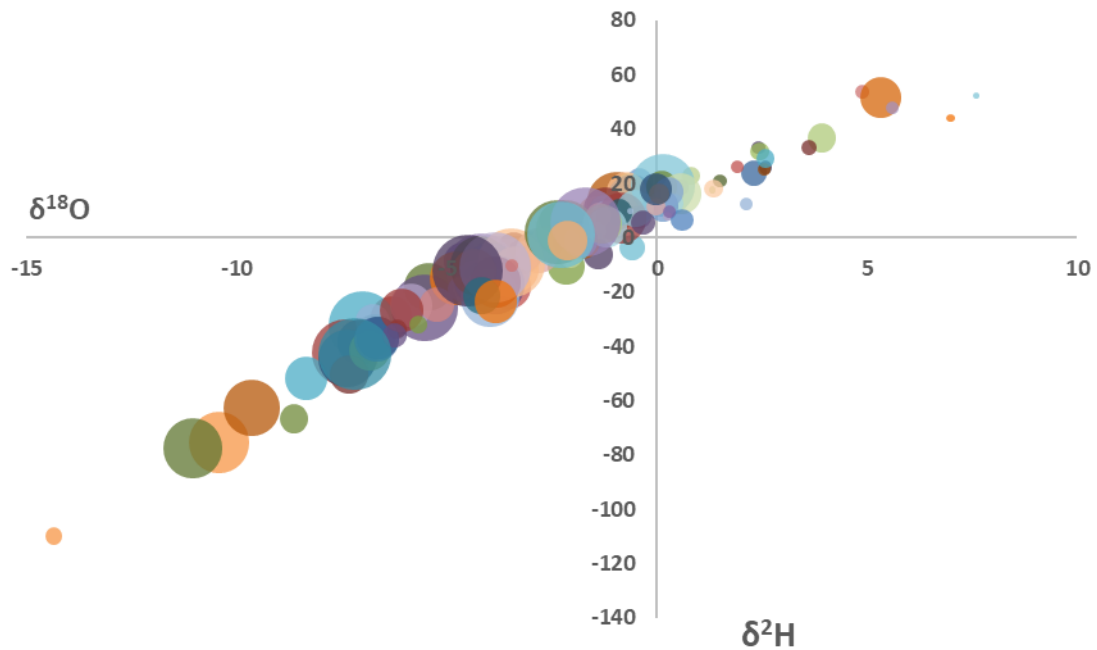


Figure 5.5 Relationship illustrating the amount effect based on daily rainfall isotopic data for Abia precipitation, showing the inverse correlation between rainfall amount and isotopic enrichment.

The correlation between rainfall amount and $\delta^{18}\text{O}$ indicates that from about 0.2mm to 19mm of precipitation, there is a good negative trend but for precipitation higher than 20mm, there is no clear correlation as the graph flattens, as shown in Figure 5.6. This implies that daily cumulative precipitation below 20mm in depth can be isotopically characterised, but precipitation amount above 20mm in depth cannot be isotopically characterised as it becomes isotopically constant. The rainfall amount of 20mm as a cut-off threshold was selected by looking at the data distribution from the graph (Figure 5.6) and reference to previous studies (Leketa and Abiye, 2020).

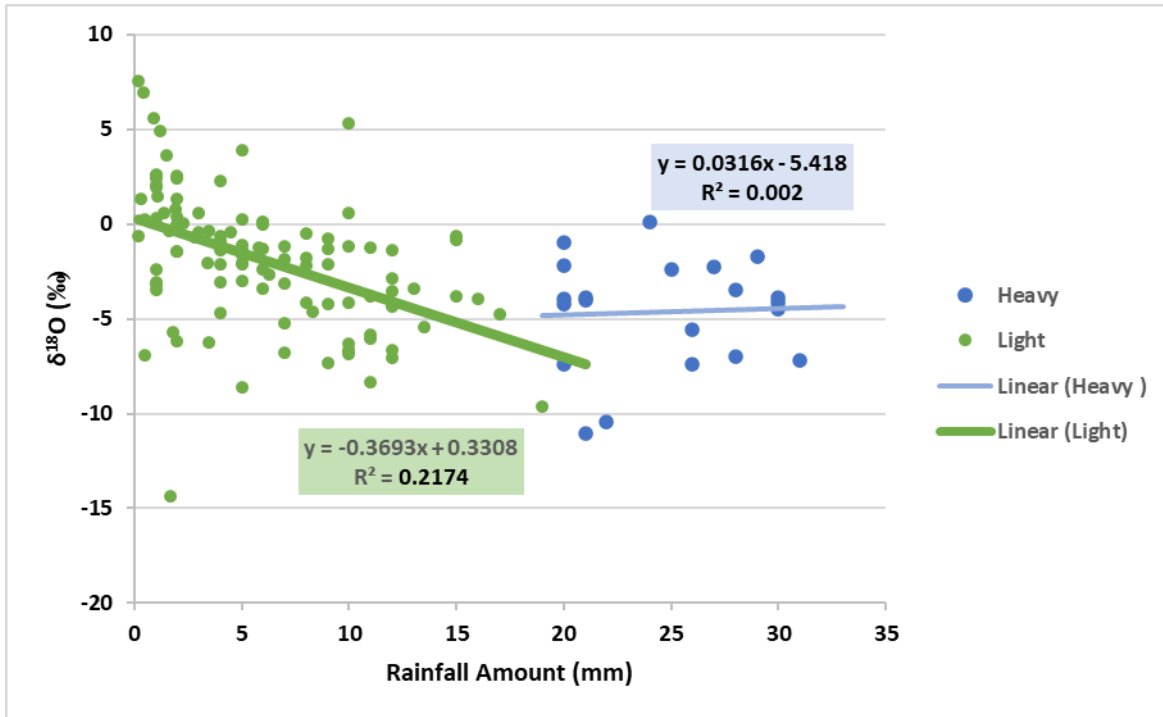


Figure 5.6 Correlation between daily rainfall amounts and $\delta^{18}\text{O}$ values at the Abia precipitation station from April 2022 to January 2024, illustrating isotopic variability over time.

Using a similar threshold of light rainfall (<20mm) and heavy rainfall (>20mm) as Figure 5.6 above. Figure 5.6 shows the slope of +7.1 and d-excess of +12.20‰ for light rainfall, which indicates secondary evaporation in the sub-cloud (Yang et al., 2019). Whereas heavy rainfall has a slope of +8.8 and d-excess of +21.82‰, resembling a decrease in secondary evaporation of precipitation (Yang et al., 2019). The differentiation between the two types of rainfall is controlled by temperature, making light rainfall vulnerable to re-evaporation, which means fractionation occurs under non-equilibrium conditions (Clark and Fritz, 1997; Gat, 1996; Holko et al., 2023; Leketa and Abiye, 2020; Yang et al., 2019).

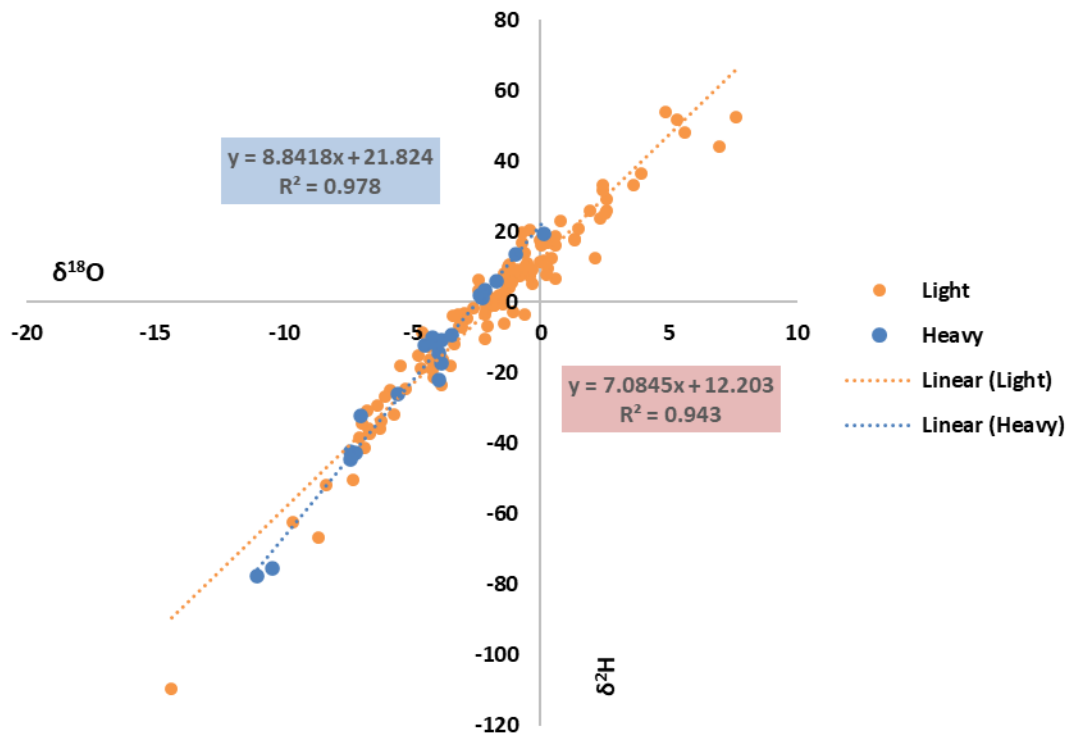


Figure 5.7 Meteoric Water Lines (MWLs) derived from event-based sampling, comparing light rainfall events (<20 mm) and heavy isotopic rainfall events (≥ 20 mm), to assess differences in isotopic signatures associated with rainfall intensity.

Figure 5.8 below shows the monthly cumulative precipitation collected from Oxbow, Maseru, Nazareth and Metolong having a similar negative correlation as the daily samples shown in Figure 5.6 above.

The two stations namely Oxbow and Maseru, show a good correlation between precipitation amount and $\delta^{18}\text{O}$, whereas Nazareth and Metolong stations do not clearly show the correlation of the two variables (Figure 5.8). It is worth noting that the Metolong station is near a small portable water supply reservoir (Metolong dam) which could affect precipitation properties to some extent.

The Maseru station is the closest to the study area and shows a clearer negative correlation between rainfall amount and $\delta^{18}\text{O}$ indicating that the general rainfall intensity is through showers. This is consistent with the summer rainfall received in the lowlands of Lesotho. On the other hand, Oxbow station records higher rainfall amounts when compared to Maseru (Figure 5.8).

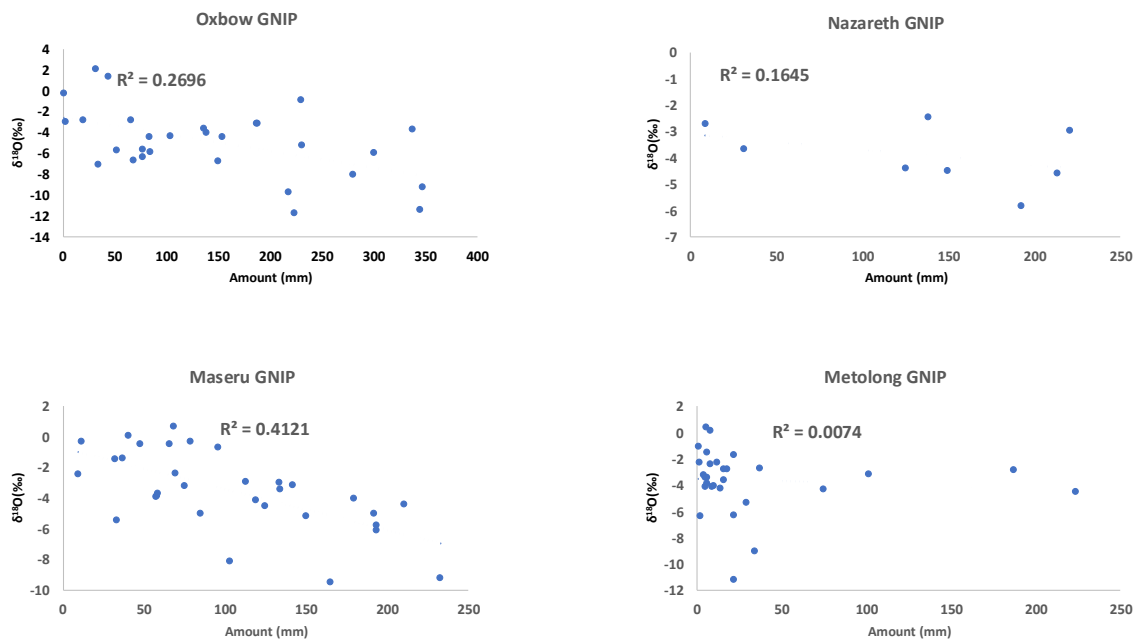


Figure 5.8 Cumulative monthly precipitation from four GNIP stations, including correlation coefficients (R^2), illustrating temporal precipitation patterns and inter-station consistency across the observation period.

Similarly, Figure 5.9 below shows that high cumulative monthly precipitation amount has a depleted signal, whereas a low cumulative precipitation amount has an enriched isotopic signal. The histogram graph (Figure 5.9) show a clear correlation in the hydrological year of 2021/2022 whereby the high precipitation amount during the wet season (October to March) has depleted $\delta^{18}\text{O}$, and low precipitation amount during dry season (April to September) has enriched $\delta^{18}\text{O}$. The data for both Oxbow and Maseru stopped in 2022 while the Metolong and Nazareth GNIP stations data commenced in 2022. It is worth noting that the data is not continuous but has gaps. However, there is a similar V-shape trend of highly enriched $\delta^{18}\text{O}$ at the beginning of a wet season (October) and a highly depleted $\delta^{18}\text{O}$ during the wet season's peak (December to February) then enrichment begins thereafter.

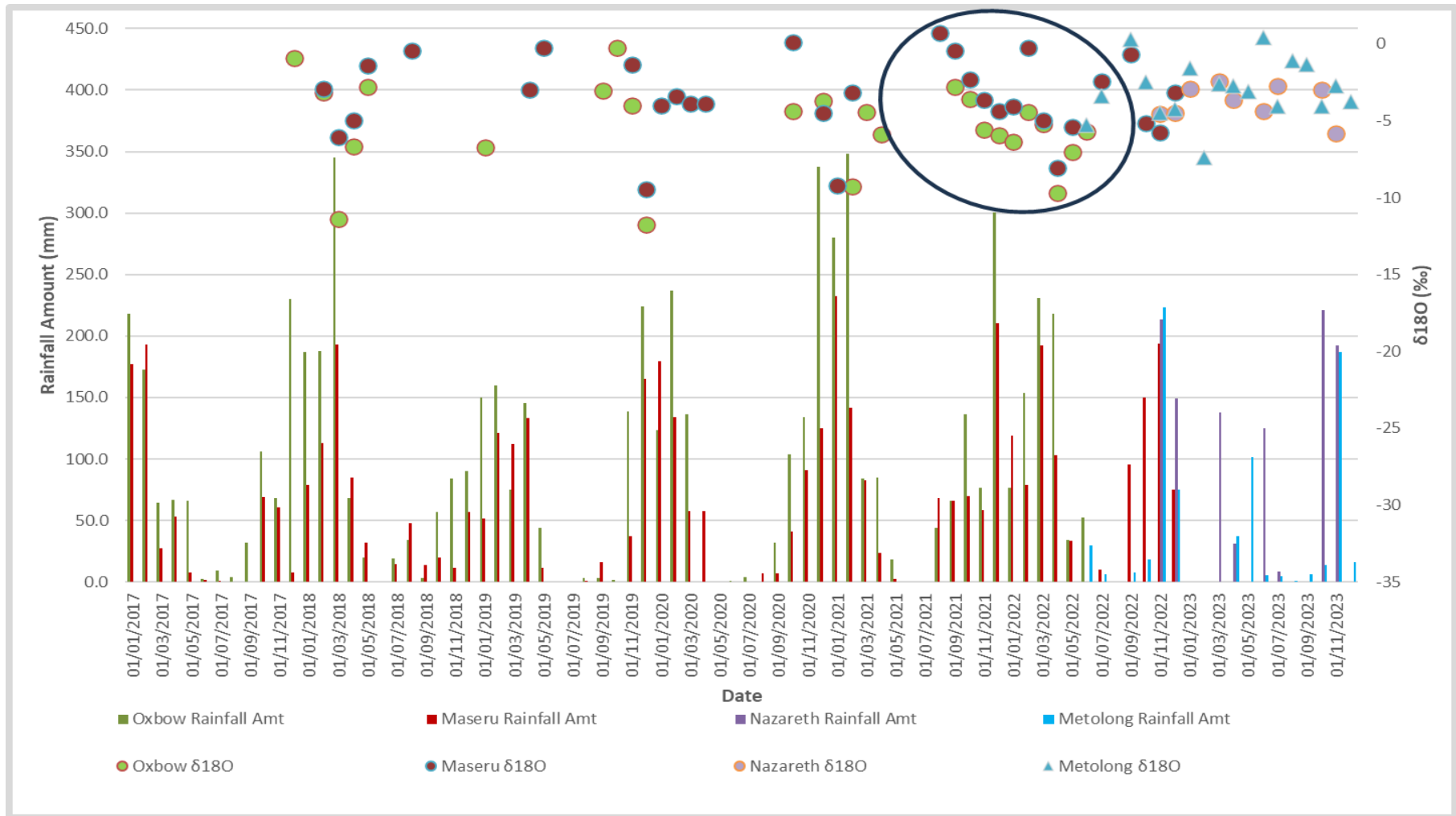


Figure 5.9 Rainfall amount histogram for the four monthly GNIP stations, illustrating the correlation between rainfall amount and isotopic signature. The 2021/2022 data show enriched isotopic values during low winter rainfall and depleted signatures during high summer rainfall. Both the amount effect and seasonal influence are highlighted by a black oval.

5.1.1.3 Altitude Effect

The rugged terrain of Lesotho and the proximity of the precipitation station within the study area made it possible to determine the altitude effect.

Table 5.2 Long-term weighted average isotopic values for precipitation at the Oxbow station, representing the mean composition over the observation period.

Collection period	Elevation (m)	$\delta^{18}\text{O}$ weighted mean
1970-1980	2591	-5.3‰
2018-2022	2649	-6.4‰

Table 5.3 provides information about the different precipitation stations where isotopes were collected at various elevations within Lesotho. The altitude difference is about 1107 m from the highest to the lowest, with a calculated $\delta^{18}\text{O}$ weighted mean ranging from -3.76‰ to -6.14‰.

Table 5.3 Comparison of $\delta^{18}\text{O}$ values in precipitation across different altitudes, illustrating the influence of elevation on isotopic composition within Lesotho.

Station Name	Counts	Daily/monthly	Elevation	calculated weighted average $\delta^{18}\text{O}$	calculated weighted average $\delta^2\text{H}$
Maseru	32	Monthly	1542	-4.45	-13.14
Abia	130	Daily	1601	-3.76	-20.96
Metolong	32	Daily and Monthly	1715	-4.49	-13.89
Nazareth	9	Monthly	2049	-4.11	-13.77
Oxbow	29	Monthly (4-5yrs)	2649	-6.14	-32.14

Figure 5.10 below presents $\delta^{18}\text{O}$ weighted averages versus altitude provided in Table 5.3 above. There is a combination of large and small datasets. Both large datasets such as Abia, Metolong, Maseru, Oxbow and a small dataset of Nazareth appear not to show much bias. Therefore, a combination of large and small datasets is paramount in providing a snapshot of catchment

properties. However, large datasets are vital for informed decisions and to complement work that has been done in the past. The lapse rate (equation below) is used to develop Lesotho's altitude effect. The equation is a product of Figure 5.10 below.

Lesotho's Altitude Effect

$$\delta^2H = -0.0017\delta^{18}O - 1.37 \quad (4)$$

The current study found the altitude effect to be -0.17‰/100m and the $\delta^{18}O$ weighted mean to be -6.4‰ shown in Figure 5.10 below. However, previous research found the altitude effect to be -0.10‰ /100m with $\delta^{18}O$ long-term mean of -5.3‰ for the west-facing catchment from Oxbow to Bloemfontein while the east-facing (Oxbow to Escourt) is -0.13‰ (Abiye et al., 2013).

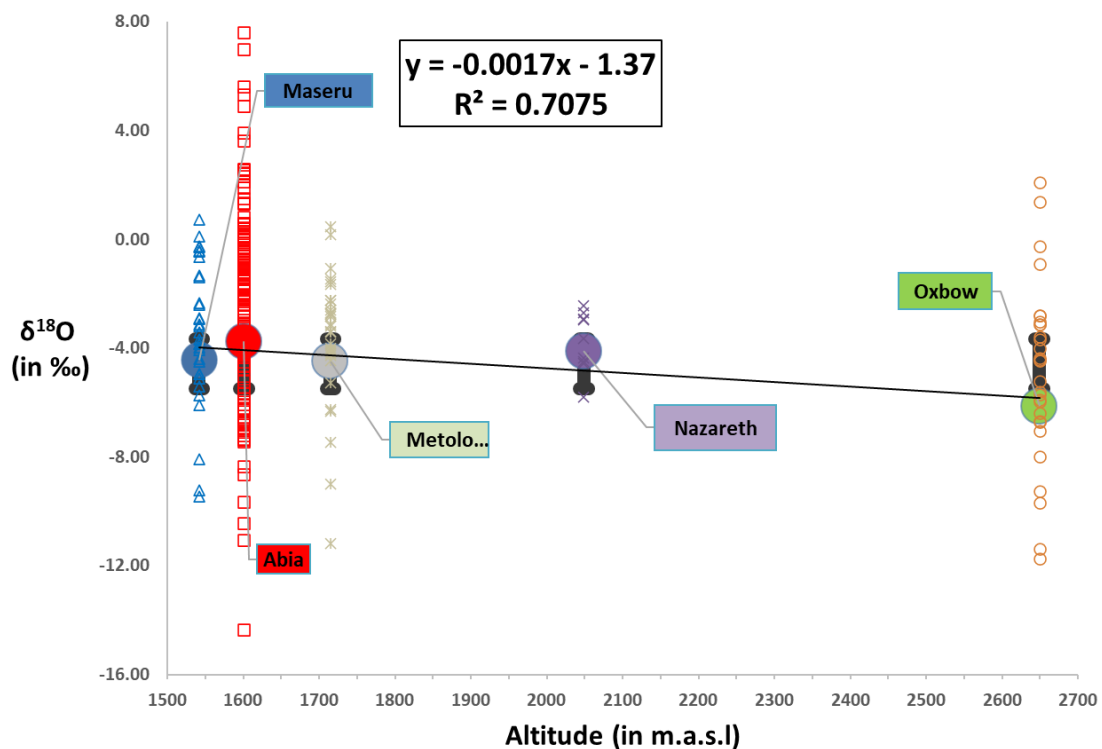


Figure 5.10 Weighted average of $\delta^{18}O$ values plotted against altitude, demonstrating the altitude effect on the isotopic composition of precipitation within Lesotho.

5.1.1.4 Seasonal Effect

The precipitation properties differ with the season because of factors such as temperature, moisture source, discussed in section 2.2 and section 3.6. The winter precipitation is dominated by snow in the highlands and frost in the lowlands and isotope data in Figure 5.11 show an enriched isotopic signal when compared to the depleted summer precipitation.

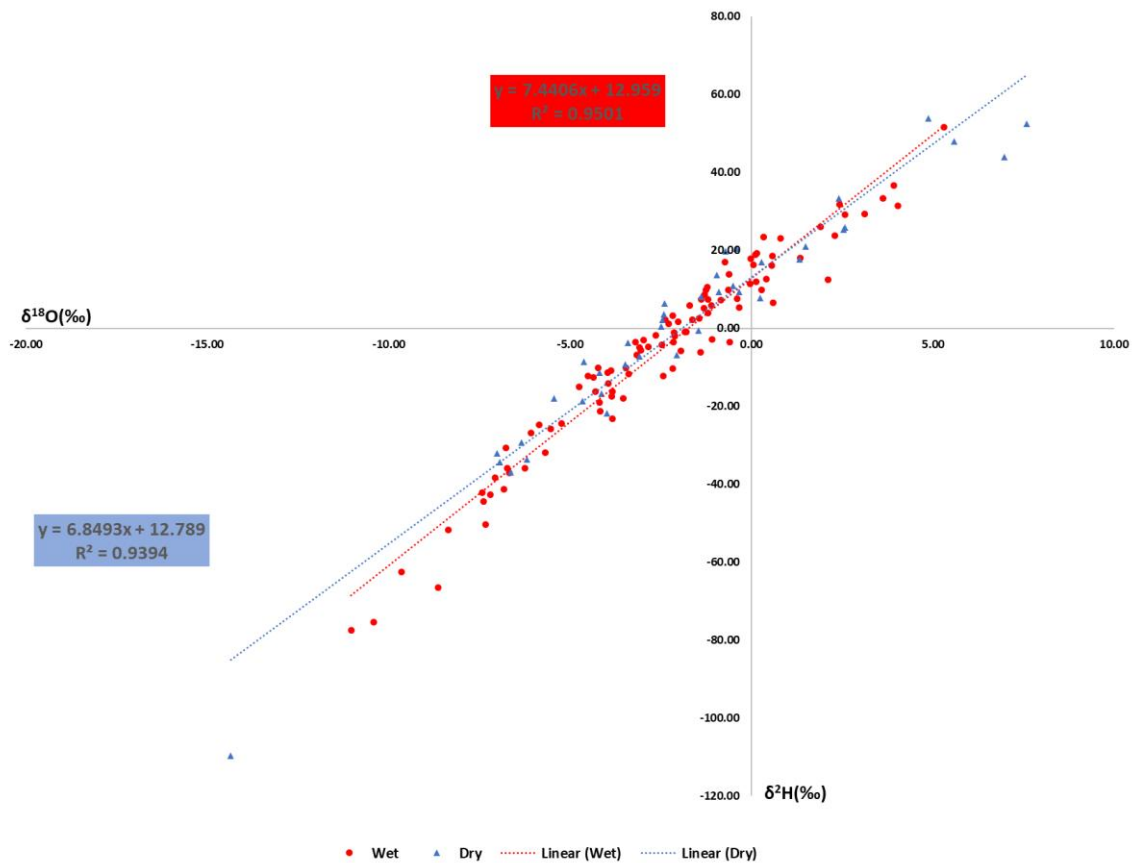


Figure 5.11 Seasonal variation of isotopic composition in precipitation, comparing dry season (April–September) and wet season (October–March) values, highlighting the influence of seasonal climatic conditions on isotope signatures.

The isotopic variation is displayed in Figure 5.12 below shows that winter has a clear trend whereby it starts with a depleted signal and gradually becomes enriched, then starts to be depleted as the summer season approaches. A similar trend is observed for summer precipitation but in the peak (December to February) of the summer season, there is a depleted signal of heavy isotopes. Despite having a depleted signal in summer, the daily precipitation also has a

highly depleted signal in the winter season (May), showing that meteorological conditions such as moisture sources or hurricanes can alter the isotopic composition of precipitation.

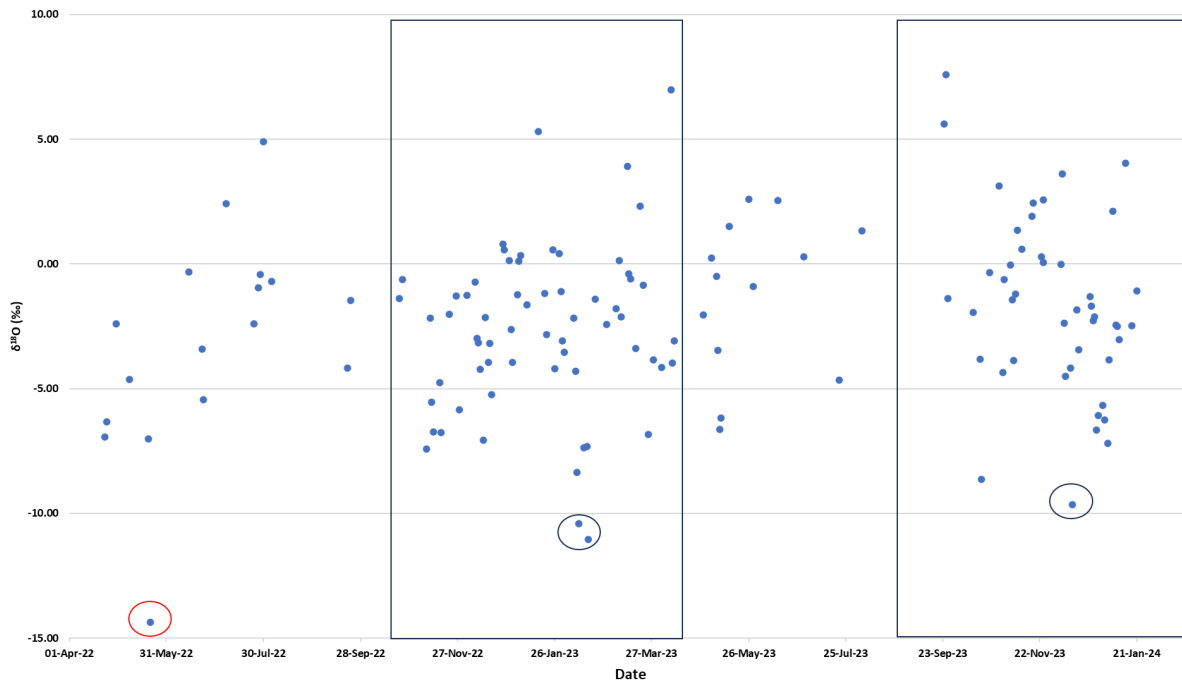


Figure 5.12 Seasonal isotopic variation in daily precipitation shows depleted isotope values mainly during the wet season due to higher rainfall and moisture sources, with an anomalous depleted sample in the dry season indicating different moisture origins or conditions. This pattern reflects seasonal changes in precipitation processes affecting isotopic signatures.

5.1.2 Water Resources Characterisation

5.1.2.1. Local Evaporation Line

Figure 5.13 below is the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ plot for the GNIR station and surface waters within the study area. The slope of the only GNIR samples (4.9) differs from that of all surface water samples (3.7) distributed within the study area. However, the Local Evaporation Line slope ranges from 4 to 6 (Clark and Fritz, 1997).

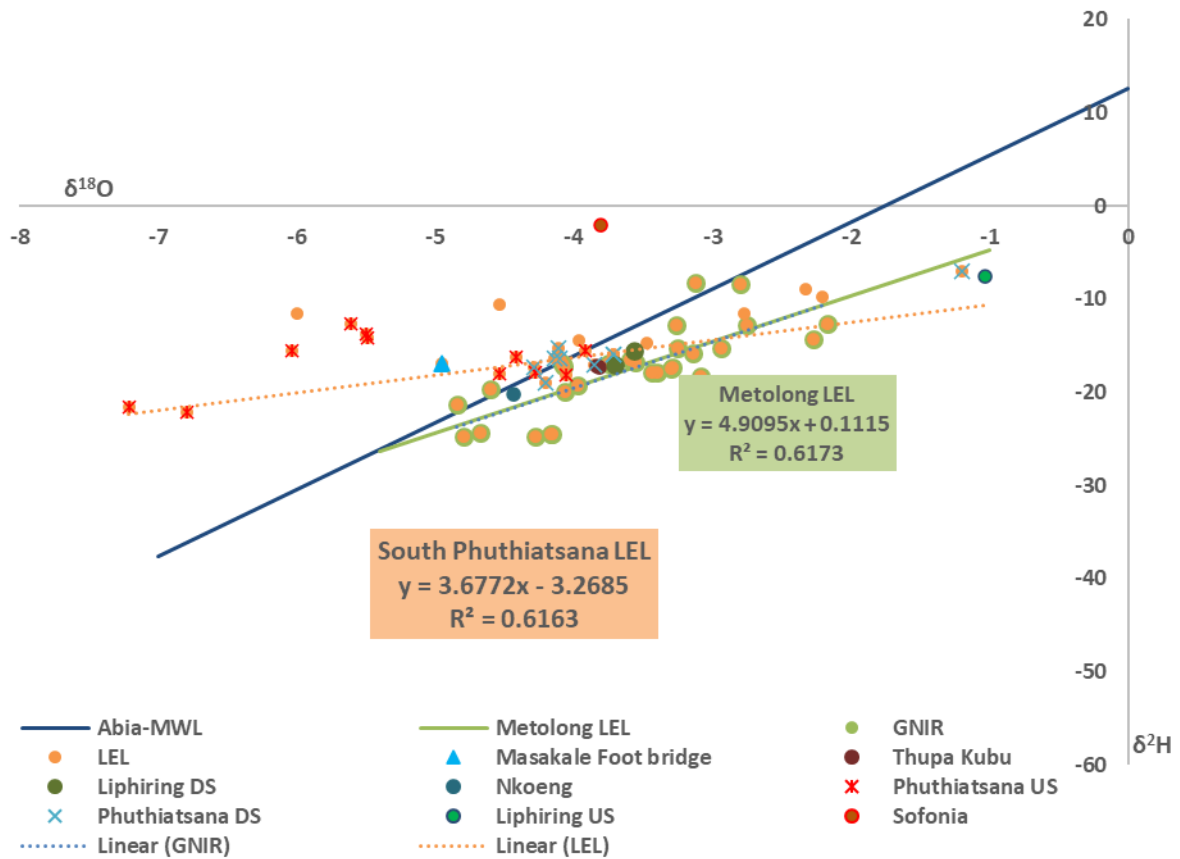


Figure 5.13 Comparison of the South Phuthiatsana Local Evaporation Line and Metolong Local Evaporation Line, based on GNIP and surface water isotope data within the catchment, illustrating evaporation effects on local water bodies downstream of the reservoir.

The regression line from the GNIR data produced the Metolong Local Evaporation Line (Equation 5) below.

Metolong Local Evaporation Line (M-LEL):

$$\delta^2H = 4.91\delta^{18}O + 0.11 \quad 5$$

Despite Metolong-LEL having a desired slope range, the lengthy data that covers more than one hydrological year thus improves data quality. In addition, the interpretation of isotope data will use the M-LEL to explain the contribution of surface water in the catchment. The intersection of LEL and LMWL can provide important information on the recharge properties within the catchment (Kebede, 2004).

Figure 5.14 below shows the distribution of $\delta^{18}\text{O}$ with upstream rivers having different isotopic signals. In the headwaters, the main river shows a range between -4.00‰ to -4.99‰ , whereas the contributing tributary ranges from -5.00‰ to -7.99‰ , which can be associated with precipitation in the higher elevations to sustain the river flows. In addition, the wetlands located upstream of the reservoir have been identified as highlands because they are near the sources. The wetlands downstream of the reservoir are identified as lowlands since they are in the lowlands of the catchment.

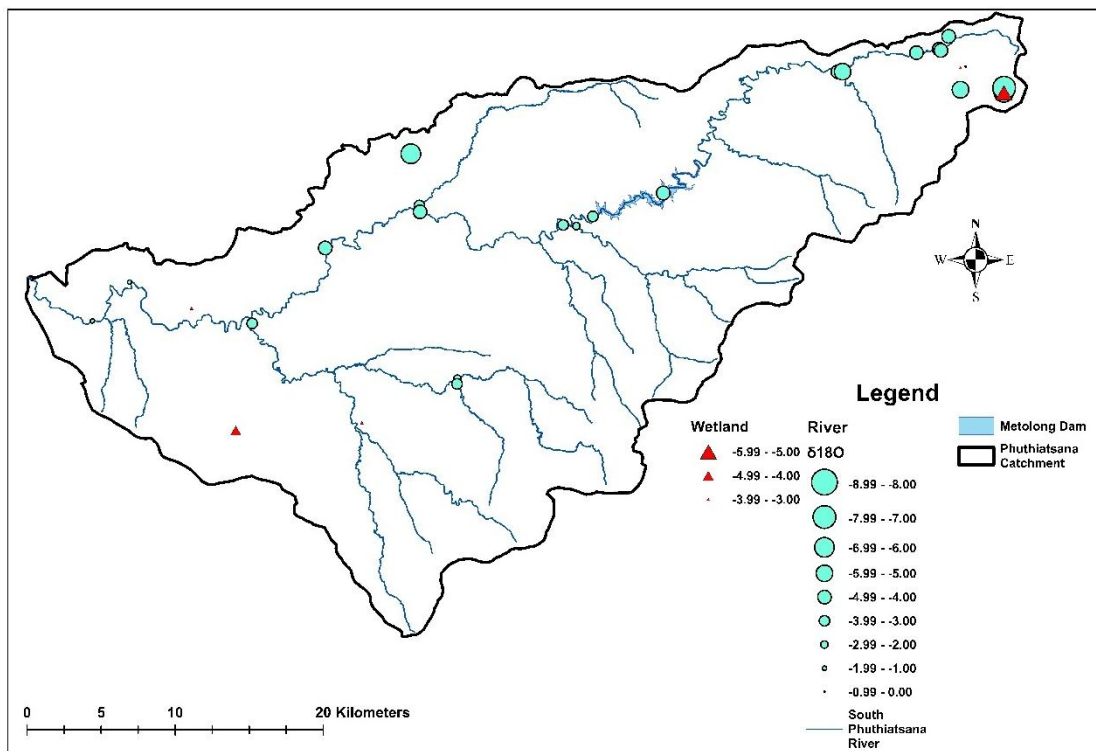


Figure 5.14 Distribution of $\delta^{18}\text{O}$ values in river and wetland samples collected upstream and downstream of the Metolong Dam, highlighting spatial variations in isotopic composition within the catchment's surface water.

Figure 5.15 below shows wetlands in the lowlands being enriched in heavy isotopes due to isotopic fractionation that takes place on an open water body. The wetlands in the highlands are depleted in heavy isotopes due to lower fractionation that takes place in high altitudes.

Moreover, wetlands in the highlands sustain the upstream river, whereas wetlands in the lowlands and together with the downstream river, depend on precipitation as shown in Figure 5.15 below.

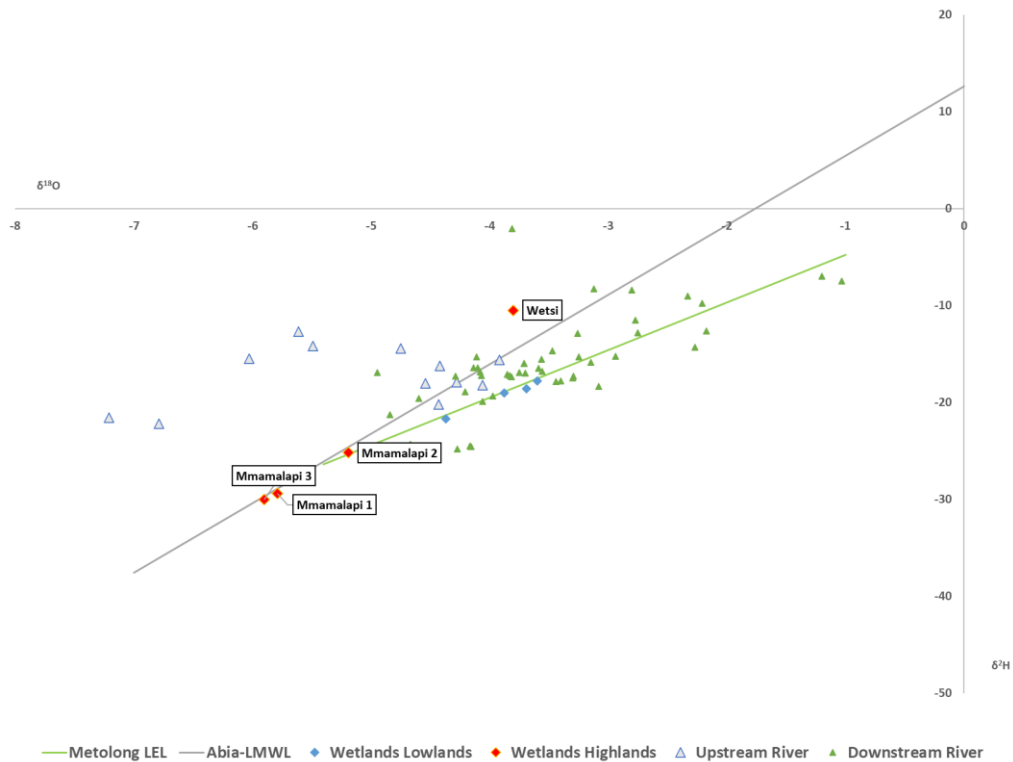


Figure 5.15 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data for wetlands and rivers within the South Phuthiatsana Catchment, illustrating variations in surface water isotopic composition across different aquatic environments.

Although wetlands have been classified using highlands and lowlands based on their geographic location, Mmamalapi is a sponge, while Wetsi is a wetland with vegetation like that in the lowlands. Nevertheless, lowlands wetlands show an evaporation loss as they plot on the LEL. As a result, sponges are more depleted in $\delta^{18}\text{O}$ than wetlands with exposed surface water and different vegetation types shown in Figure 5.16 below.

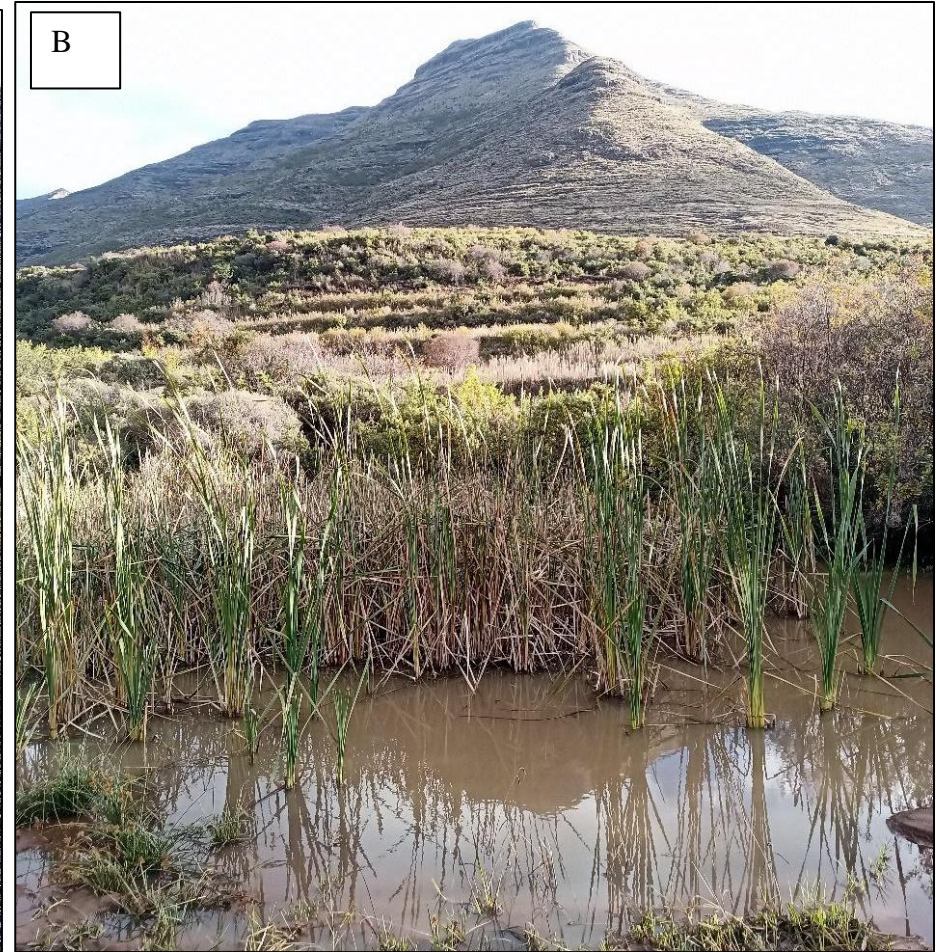


Figure 5.16 Photographs of (A) Mmamalapi Wetland and (B) Wetsi Wetland, showcasing key wetland environments within the South Phuthiatsana Catchment at the highlands/headwaters.

Figure 5.16 below is a localized characterization of the hydrological cycle in the Metolong area using the existing GNIP and GNIR stations. The groundwater through springs and boreholes shows a strong influence of the reservoir as they plot on the Metolong-LEL developed using the GNIR data (Figure 5.16). The borehole plots near the intersection of LMWL and LEL of Metolong and this requires an in-depth of recharge using other isotopic effects.

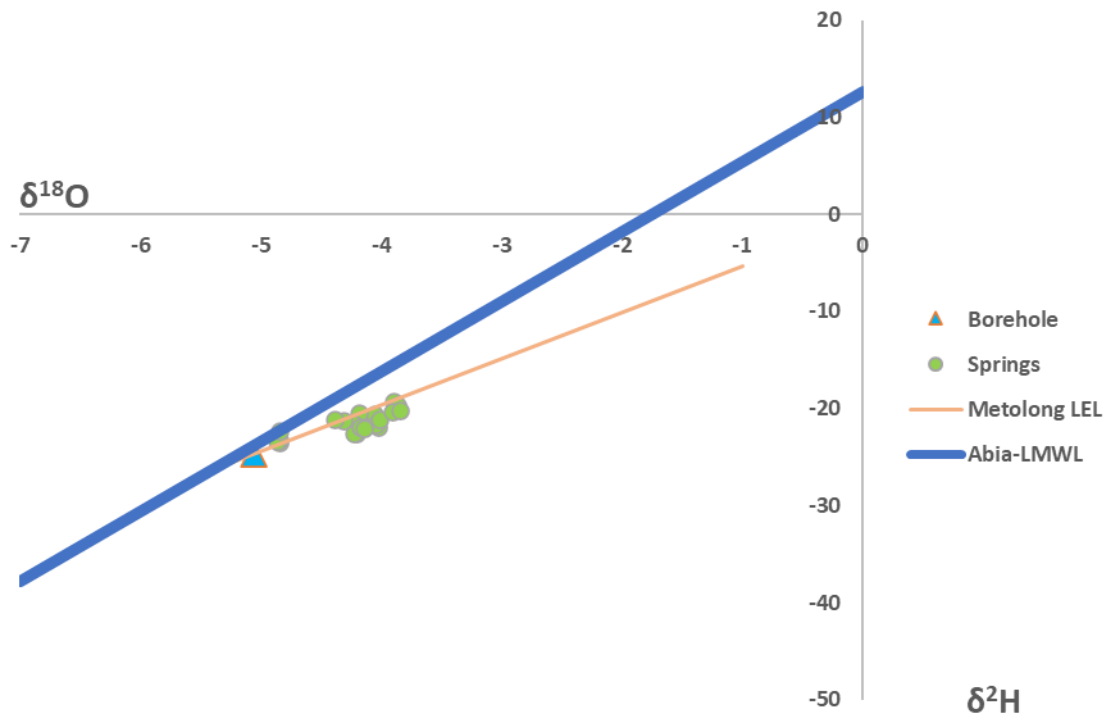


Figure 5.17 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope plots illustrating localized groundwater recharge processes in the Metolong area within the South Phuthiatsana Catchment.

The rest of the springs within the catchment have been analysed using the Abia-LMWL as a reference for local precipitation within the catchment. Figure 5.18 shows that most of the springs have encountered evaporation during the recharge process. Therefore, these roles out the springs near the reservoir to being recharged by Metolong Dam since most springs display a similar isotopic signature.

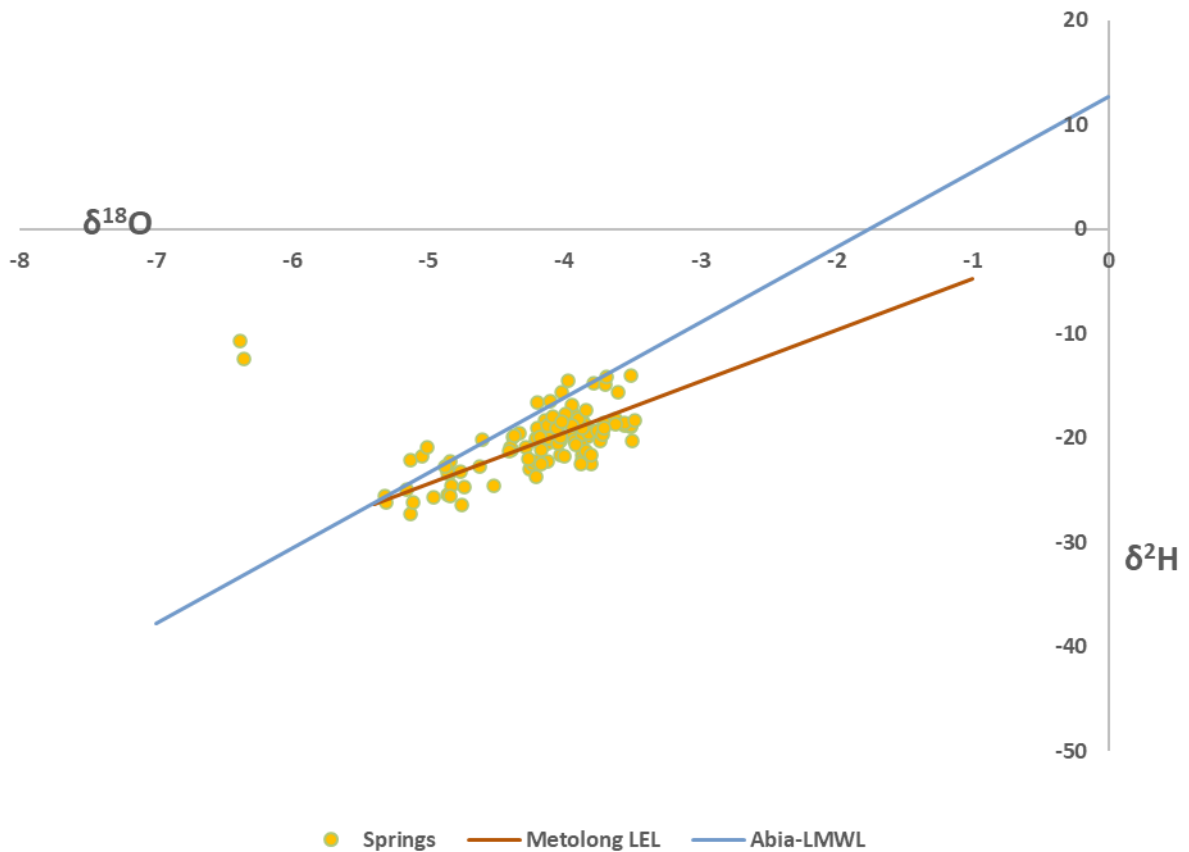


Figure 5.18 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope plots characterising groundwater recharge sources and processes for springs within the study area.

The springs are recharged by precipitation as they plot close to the MWL; however, two springs (Phuleng and Naka 1) are enriched in $\delta^2\text{H}$ but depleted in $\delta^{18}\text{O}$. They are in the highlands in the ephemeral tributary of South Phuthiatsana.

The boreholes shown in Figure 5.19 below, plot in a similar area as upstream rivers in the highlands and above the Abia-LMWL. This data indicates a similar source of boreholes and upstream rivers. Most of the borehole data plots on the left side of the LMWL and this is consistent with low temperature water-rock interaction (Jasechko, 2019). Further analysis using different isotopic effects can provide a better interpretation of groundwater.

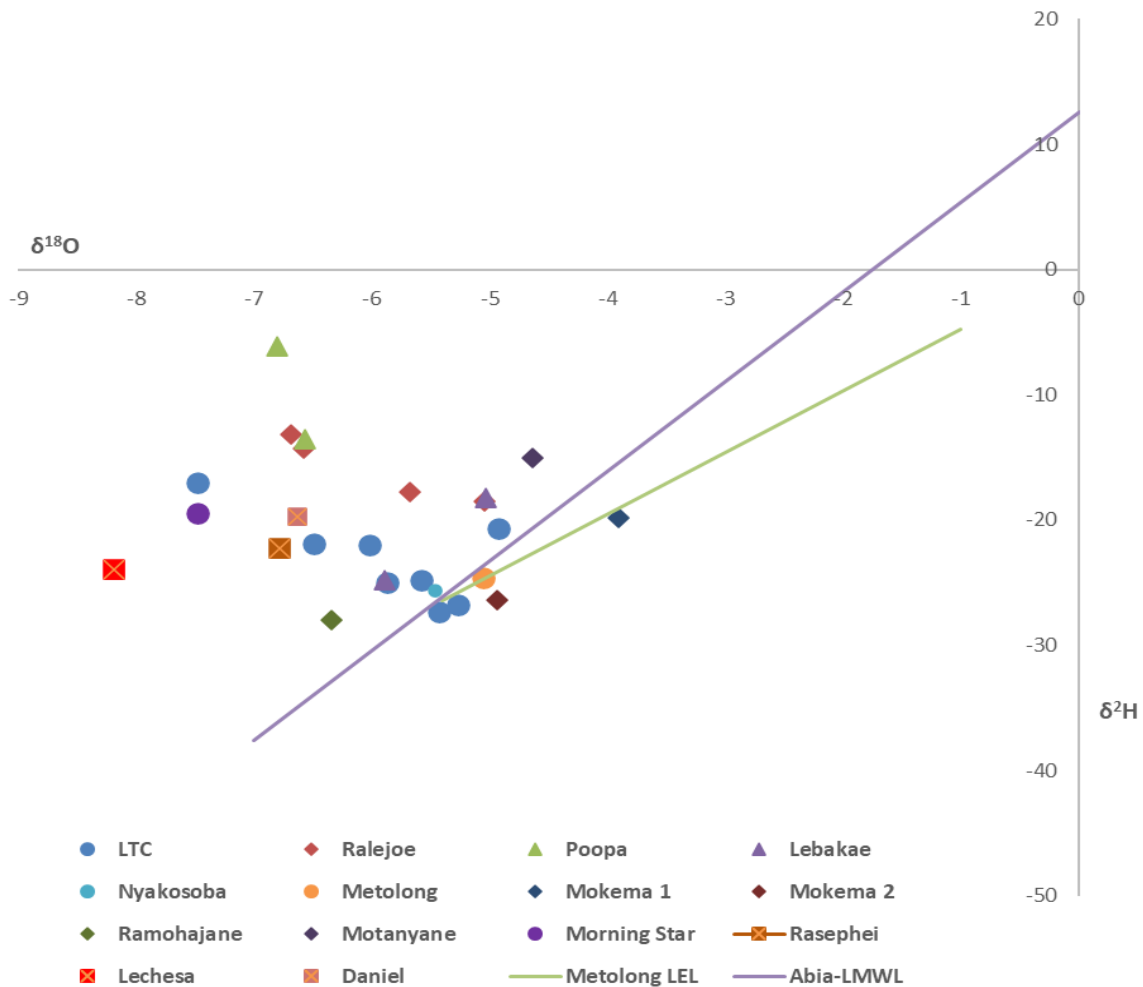


Figure 5.19 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope plots for borehole water samples, indicating signatures consistent with low-temperature water–rock interaction within the South Phuthiatsana Catchment.

The LTC and Ralejoe boreholes have a recurring isotopic sampling and are regularly pumped for domestic water use. These two boreholes show an isotopic variation which could result from different seasons and the response time for groundwater concerning seasonal changes. The season of sample collection can likely affect the isotopic signals depending on the processes governing borehole recharge.

5.1.2.2. Amount Effect.

Figure 5.20 below shows three precipitation stations (Abia, Metolong and Nazareth) within the catchment and adjacent to these stations, a borehole is present. All the boreholes show a

depleted isotopic signal when compared to the weighted mean precipitation amount. This indicates that recharge occurs at a higher altitude or is governed by different rainfall intensities.

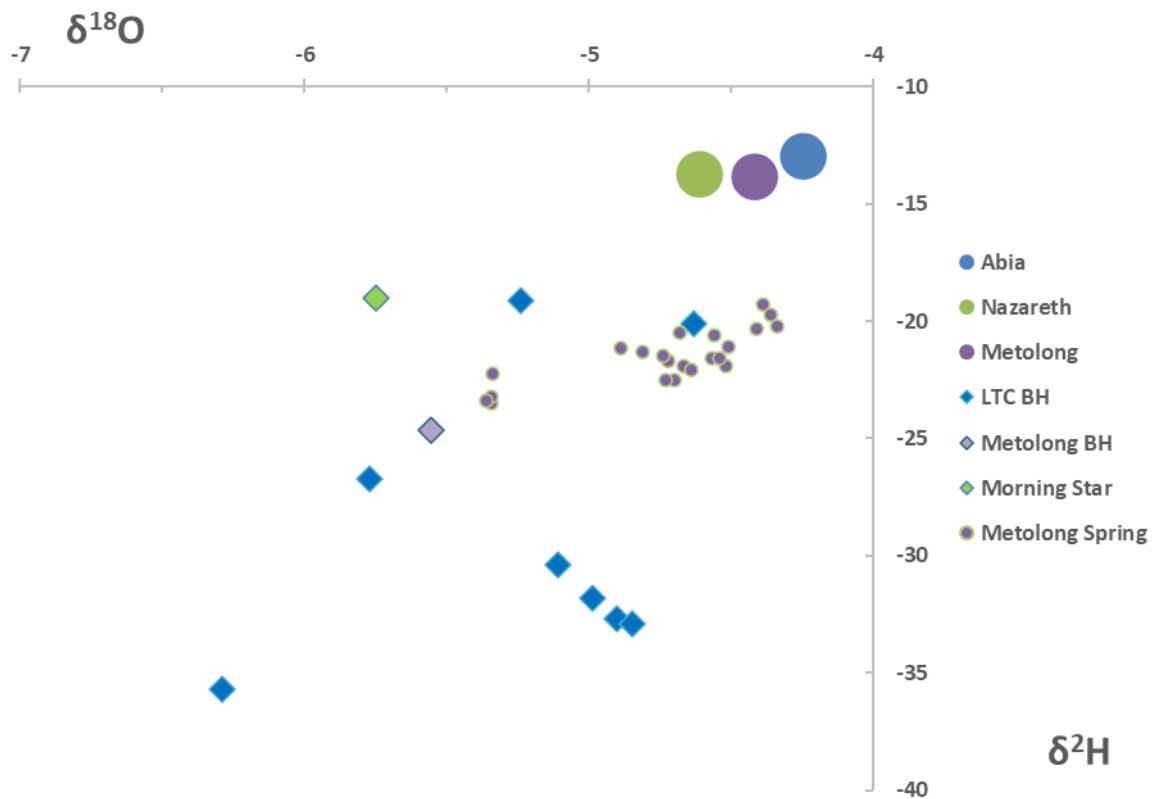


Figure 5.20 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope plots comparing weighted average rainfall with groundwater samples from three adjacent boreholes, illustrating recharge relationships within the South Phuthiatsana Catchment.

Long-term precipitation data adjacent to a borehole has been collected from the Abia precipitation station, which has been used to analyse the recurring LTC borehole. Since the weighted mean precipitation amount showed recharge from a depleted source, Figure 5.21 below indicates the daily amount of precipitation that has been used to determine the isotopic signal of precipitation in the local borehole (Cook, 2020). The LTC borehole is mainly recharged by high rainfall intensity and is characterised by depleted isotopic signals. Therefore, precipitation governs recharge for the LTC borehole if local precipitation is the source of recharge. The Abia Wetland also shows characteristics of recharge by depleted precipitation.

The daily amount effect histogram indicates that heavy rains are depleted, and light rains are enriched with $\delta^{18}\text{O}$. However, borehole isotopes show slightly depleted signals when compared to local precipitation (Figure 5.21).

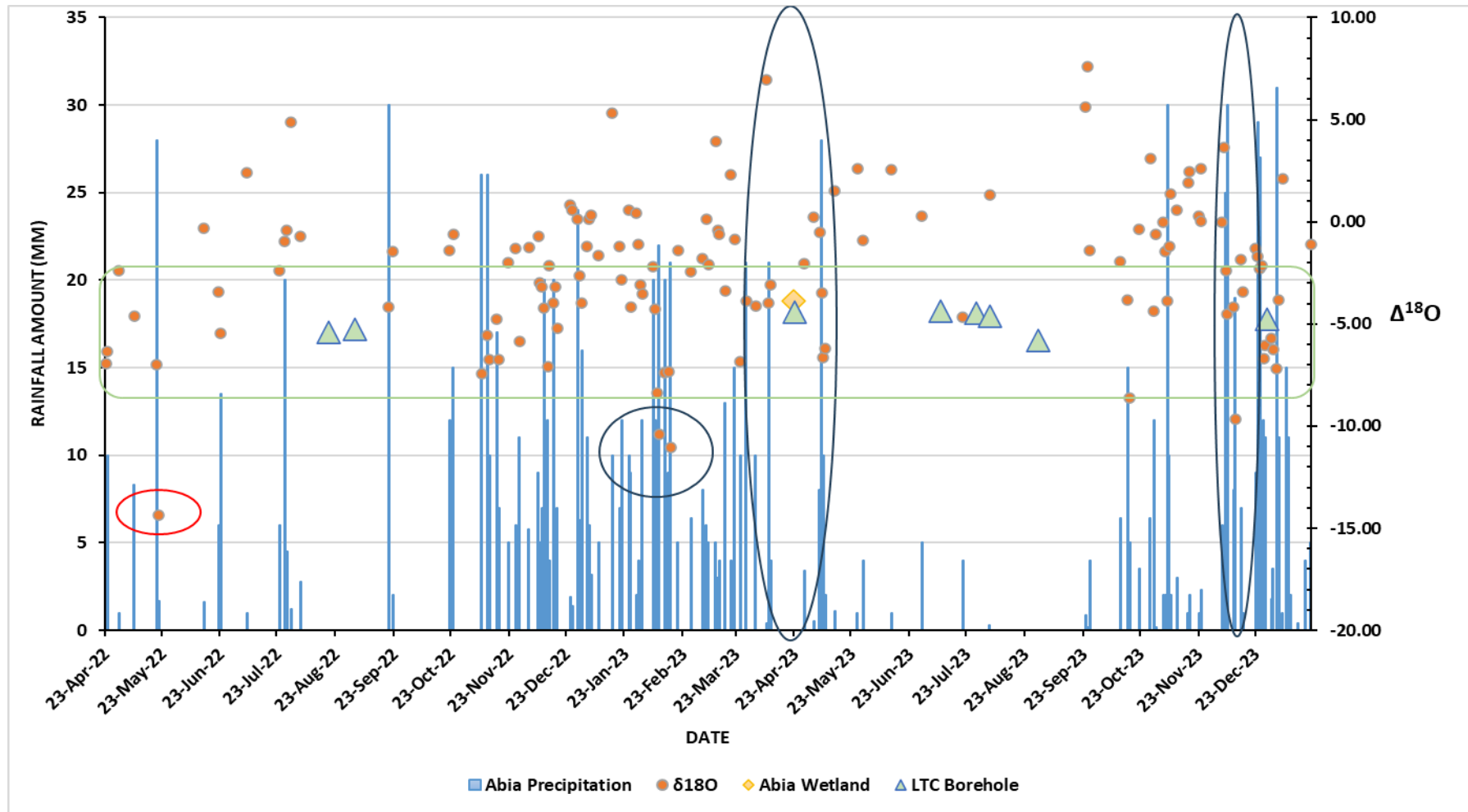


Figure 5.21 Temporal variation of precipitation (blue bars) and oxygen-18 isotopic composition ($\delta^{18}\text{O}$, orange circles) at Abia from April 2022 to December 2023. The primary y-axis on the left indicates daily rainfall amount (mm), while the secondary y-axis on the right represents $\delta^{18}\text{O}$ values (%). Also shown are isotopic values from groundwater sources: Abia Wetland (yellow diamond) and LTC Borehole (blue triangles).

The Metolong and Morning Star boreholes were sampled once, and their precipitation data has gaps. Therefore, there is a need to collect more data to determine the contribution of local precipitation on the borehole.

5.1.2.3. Altitude Effect

Mmamalapi wetlands 1&3 are recharged at a higher elevation, while Mmamalapi 2 has an evaporated signal as shown in Figure 5.22 below. The results for Mmamalapi 2 can be discarded because samples were taken from the wetland sponge eye in a transect, which is expected not to show high variability. Mmamalapi 1&3 are at the base of Mmamalapi peak (3033 masl). Whereas Wetsi wetland has an exposed water body and is located at a lower elevation, still in the headwaters with an evaporated isotopic signal.

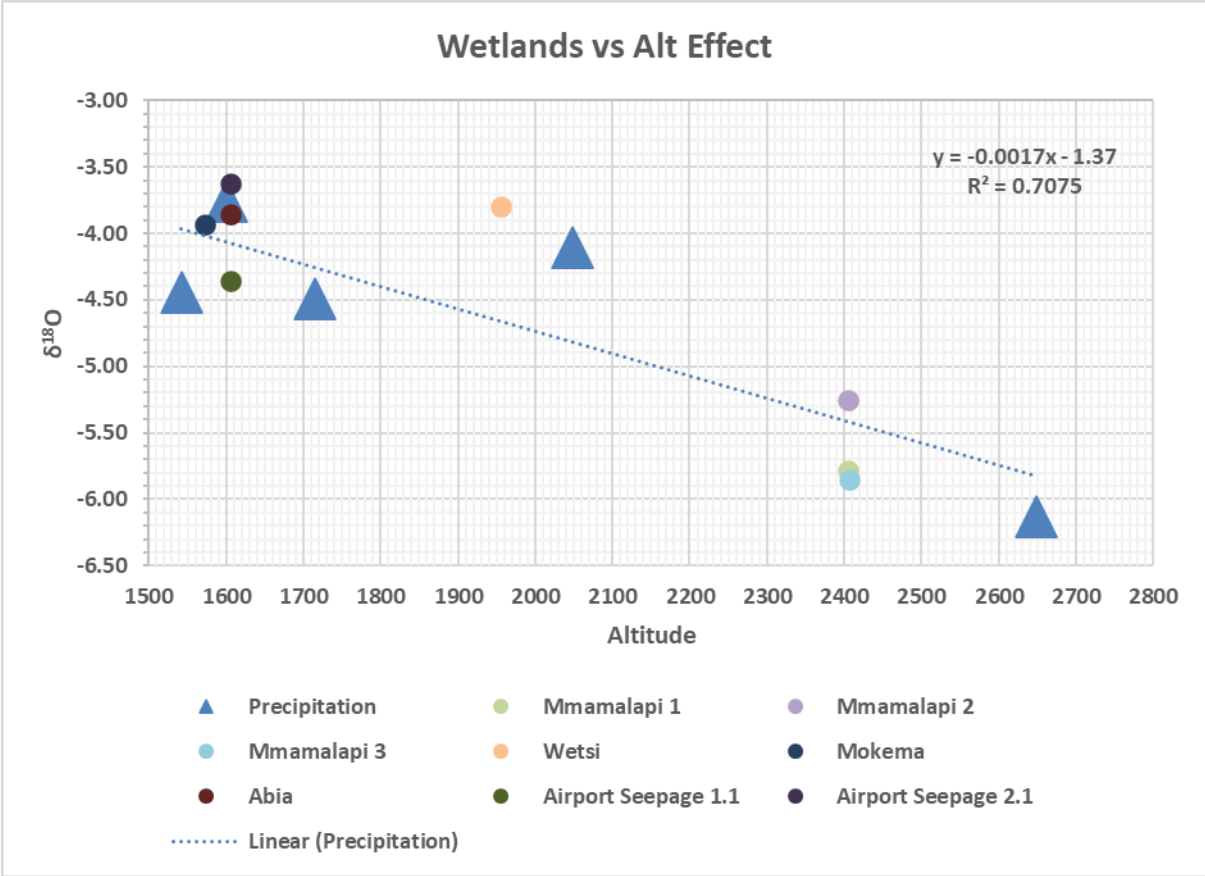


Figure 5.22 Determination of altitude zones contributing to groundwater recharge of wetlands within the South Phuthiatsana Catchment, based on isotopic data analysis.

The Abia wetland shows that recharge is occurring at the same altitude, and this is because the wetland is a result of high precipitation received since 2020. This wetland is recharged by local precipitation and likely to be a patched aquifer. The Airport seepage is also a patched aquifer and is highly influenced by recent precipitation therefore vulnerable to climatic changes (drought and floods).

The Mokema BH 1 is recharged by enriched water and the nearest surface water body is the Mokema wetland, located in the lowlands of the catchment shown in Figure 5.23 below. In addition, there is also a spring and a newly drilled Mokema BH 2. The wetland, spring and borehole 2 are recharged at a higher elevation and the geological map shows a network of dolerite dykes. However, an outcrop of a dolerite dyke is visible, and the spring emerges close to the intersection of these dolerite dykes.

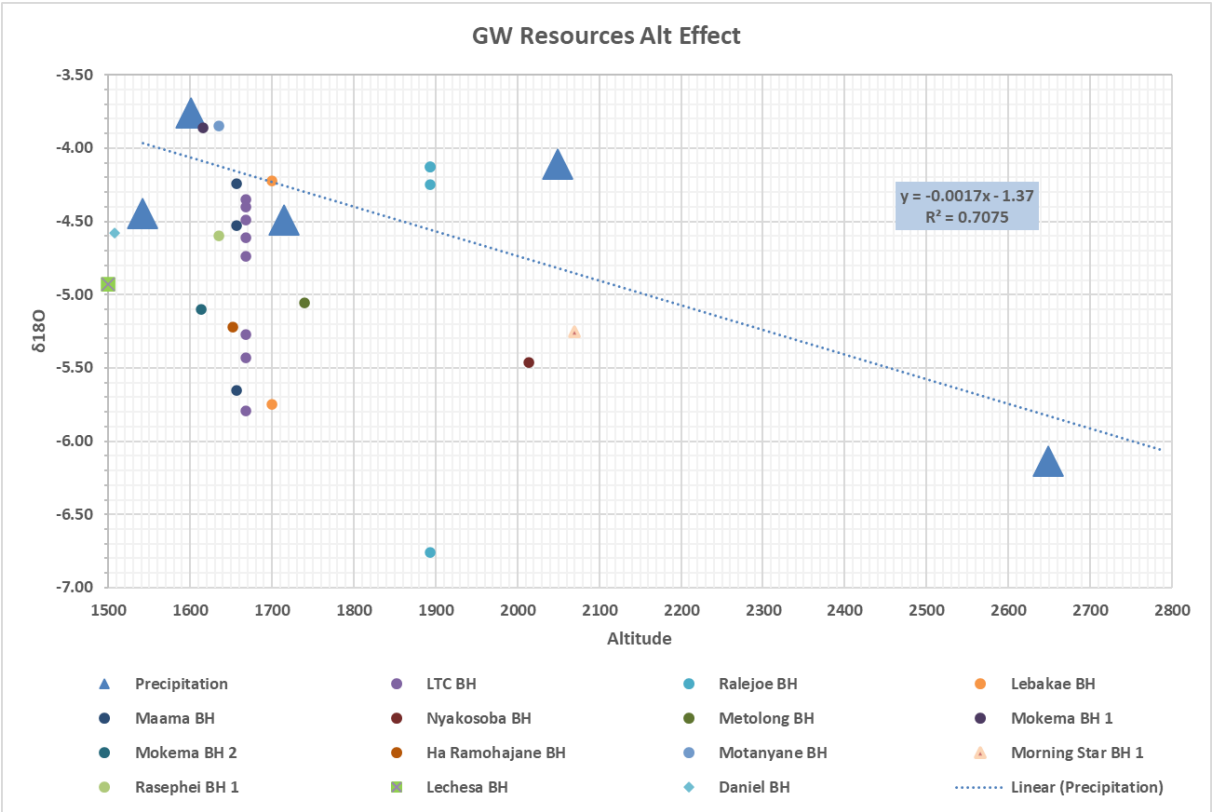


Figure 5.23 Determination of recharge altitudes for boreholes within the South Phuthiatsana Catchment, derived from isotopic signatures.

Figure 5.24 below shows that >50% of the springs have an evaporative isotopic signal and <50% can be assigned to a specific altitude recharge. It should be noted that altitude effect that groundwater recharge is governed by factors mentioned in chapter 2.

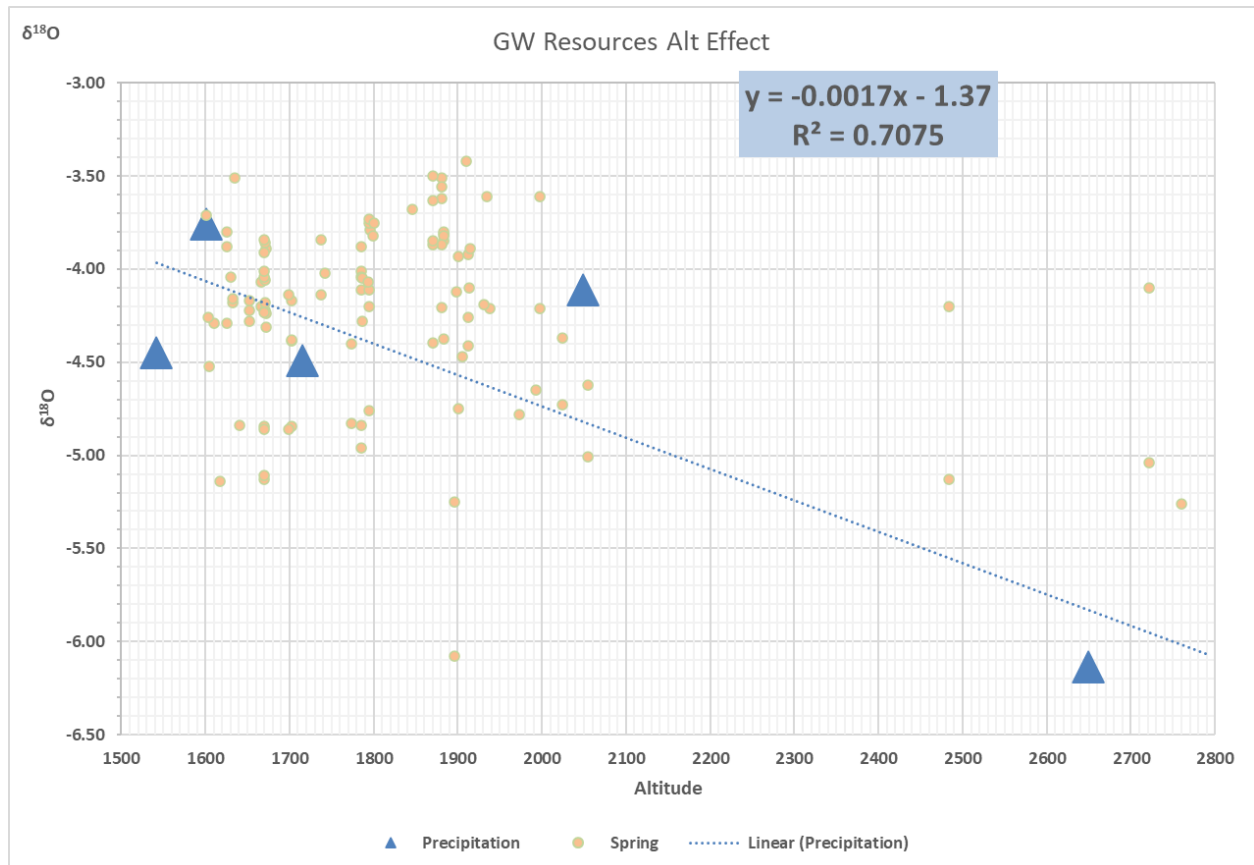


Figure 5.24 Determination of recharge altitudes for springs within the South Phuthiatsana Catchment using isotopic analysis.

5.1.3 Radon

The ^{222}Rn concentrations range from below 50 Bq/m³ to above 350 Bq/m³, with the highest values observed in the upper northwest portion of the catchment, particularly at sampling point 379, which recorded approximately 379 Bq/m³. This area, also represented in the inset map, shows clustering of elevated radon values (e.g., 286 and 216 Bq/m³), suggesting strong groundwater inflow in that segment of the catchment. These elevated readings likely indicate that the river in this region is gaining water from underlying aquifers enriched with radon, reinforcing the presence of active baseflow contributions.

Moderate concentrations (101 to 250 Bq/m³) appear in the central portion of the catchment, marking transitional zones that may represent weaker or more diffuse groundwater discharge, or zones where radon begins to degas as the water mixes with surface flows.

Lower concentrations (typically <100 Bq/m³), such as those observed at sites with ²²²Rn concentrations of 28 Bq/m³, 32 Bq/m³, 49 Bq/m³, and 101Bq/m³, tend to dominate the southern and eastern extents of the catchment. These readings could indicate sections of the river that are more surface-water-dominated, or areas where radon has already degassed after upstream groundwater discharge. Alternatively, they may reflect sections of the river that are losing reaches, where surface water recharges the underlying aquifers rather than receiving input from them.

The presence of Metolong Dam in the northeast, near low-radon areas (Metolong Dam out-let), which may be influenced by stratification, mixing, or minimal groundwater interaction due to reservoir characteristics.

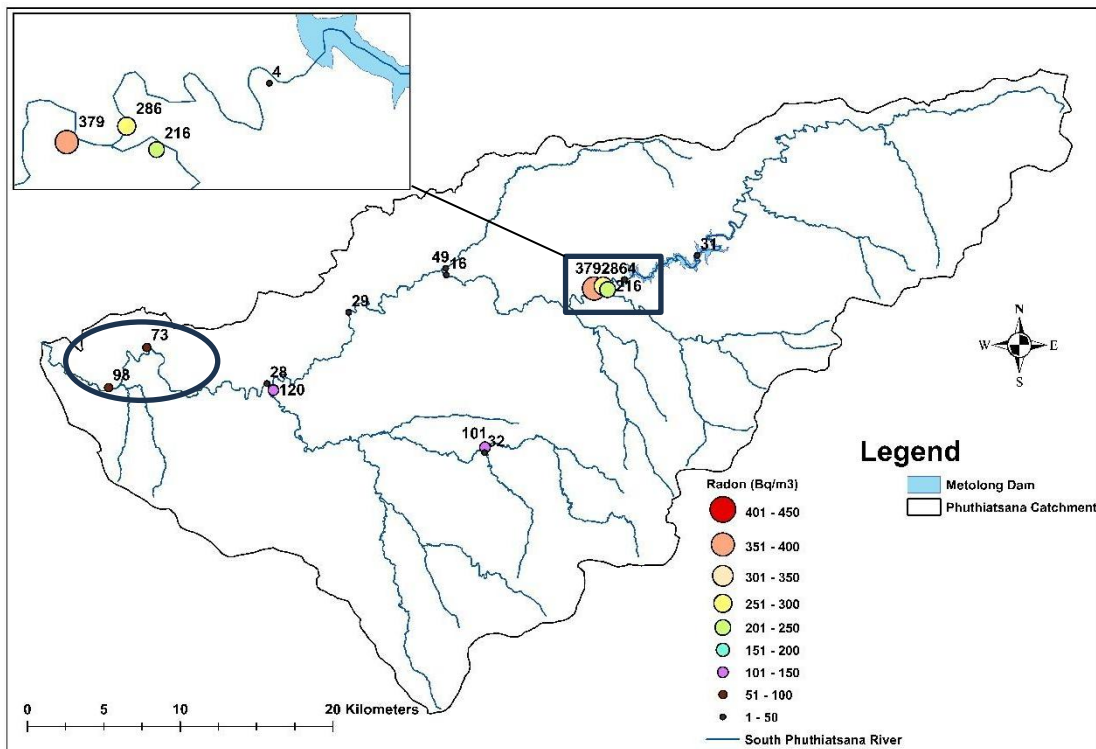


Figure 5.25 Spatial distribution of ^{222}Rn concentrations (Bq/m^3) across South Phuthiatsana Catchment. Elevated concentrations in the northwest indicate zones of groundwater discharge into the river system. Radon levels progressively decrease downstream, reflecting degassing and dilution effects. The inset map show a detailed sampling near Metolong Dam.

The unique distribution of radon can be seen when plotted against geological formations. Figure 5.26 below shows that radon concentration is higher in the Clarens formation (highlighted by a rectangle) followed by the Alluvial deposits (highlighted by an oval) then Burgersdorp formation making Elliot formation being the lowest. No measurements were done in the Molteno formation along the South Phuthiatsana River, therefore not much can be deduced from this geological formation.

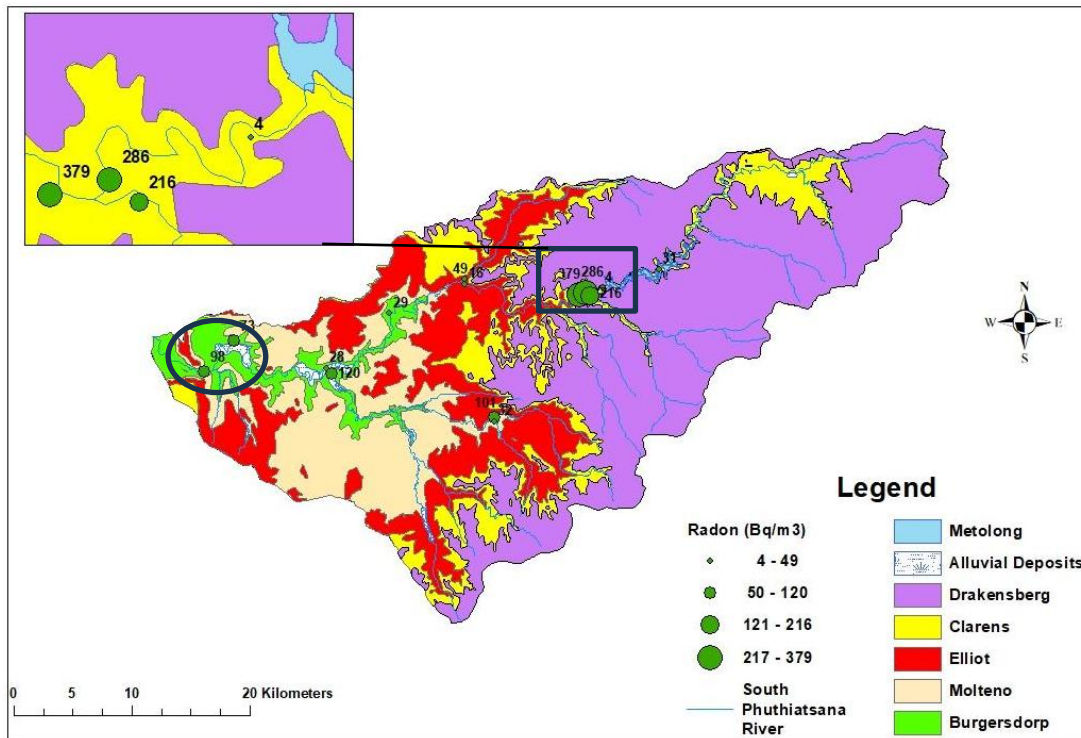


Figure 5.26 Radon concentrations measured in the river plotted against underlying geological formations, illustrating the influence of geology on radon levels within the South Phuthiatsana Catchment.

5.2 Electrical Conductivity (EC)

Figure 5.27 below shows the distribution of EC concentrations within the catchment in rivers. There is a trend in EC distribution in the river network, indicating low EC concentration in the highlands, while higher EC is observed in the lowlands. The same cannot be said about the springs, as they show a random distribution without any pattern. However, EC concentration in groundwater (boreholes and springs) is higher than EC in the rivers.

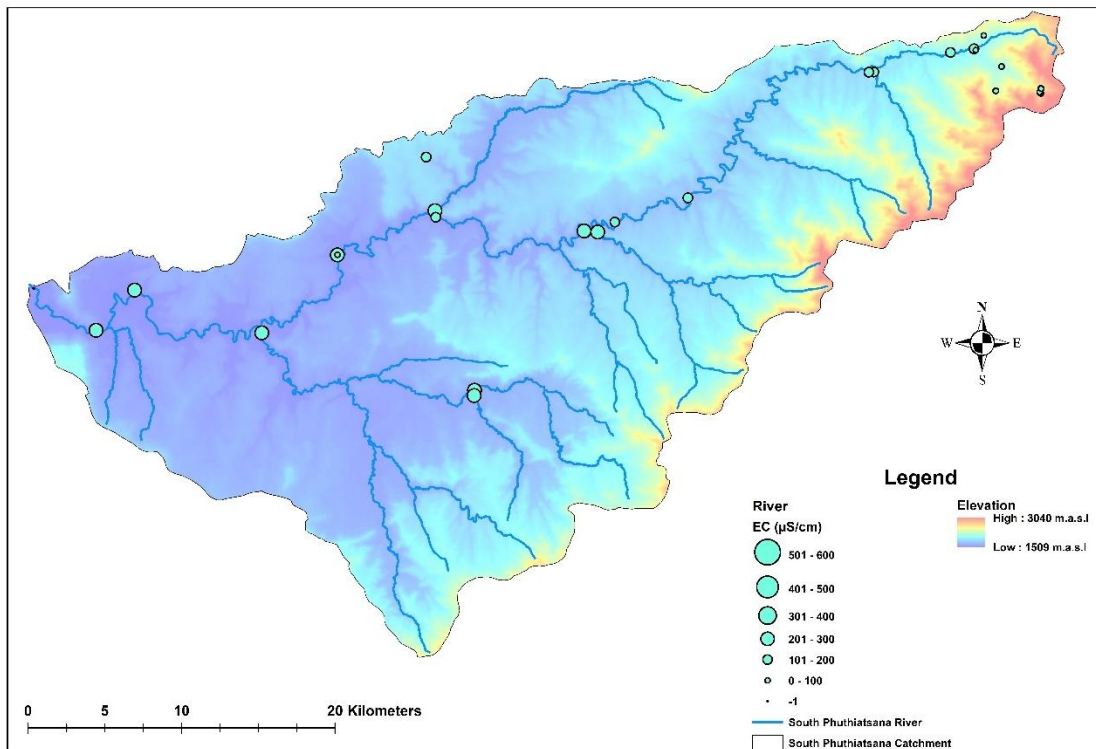


Figure 5.27 Spatial distribution of electrical conductivity (EC) concentrations in river water within the South Phuthiatsana Catchment, indicating variations in dissolved ion content across different locations.

5.2.1 Water Resources Characterisation

The EC distribution in the catchment varies for different water resources, and a trend is observed on the river system. The EC range in a river system is from $40\mu\text{S}/\text{cm}$ in the highlands to $239\mu\text{S}/\text{cm}$ in the lowlands. As shown Figure 5.27 shows low EC concentrations in the highlands, where by wetlands dominate the area. This could suggest wetlands to be fed by rainfall since EC in precipitation is in a range of $0\text{-}75\mu\text{S}/\text{cm}$ measured during sampling.

Furthermore, the irregularity of EC concentrations within the catchment from groundwater resources is shown in Figure 5.28 below. Several factors such as but not limited to the background geology and different land uses could have influenced this distribution. More investigation is needed to conceptualise the drivers of this unique distribution.

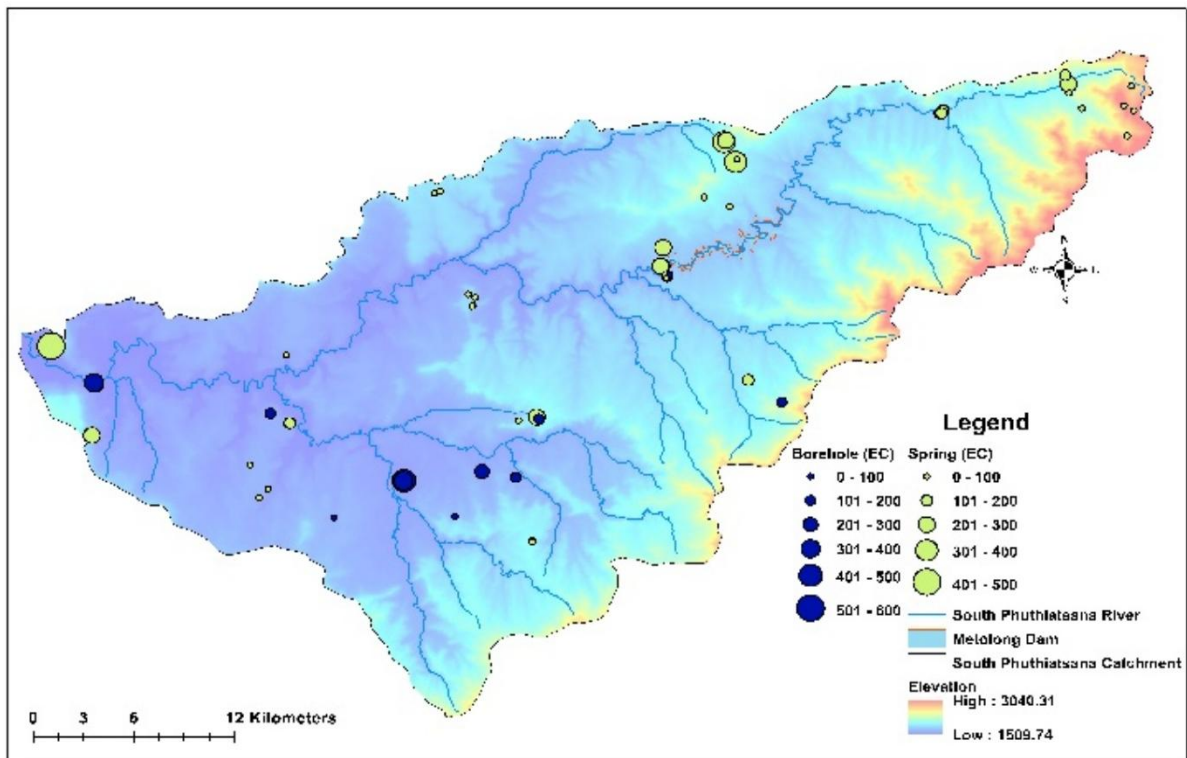


Figure 5.28 Spatial distribution of electrical conductivity (EC) concentrations in groundwater resources within the South Phuthiatsana Catchment, reflecting variations in groundwater quality and mineralisation across the area.

5.3 Baseflow

Table 5.4 below summarises baseflow separation on the hydrograph of the South Phuthiatsana River, indicating that at the Masianokeng gauge station, about 56% is baseflow.

Table 5.4 Long-term flow statistics for the South Phuthiatsana River at Masianokeng, summarising key hydrological parameters that characterise river discharge patterns over time.

Parameter	Minimum	Average	Maximum
Discharge	0.0006	4.5955	352.2483
Baseflow	0.00	1.1458	15.14
BFI Index	0	0.5618	6.89

Figure 5.29 below is the long-term data set from 1972 to 2018 discharge recorded at Masianokeng gauge station, and it shows the river hydrograph. This hydrograph is related to rainfall events causing flash floods and slowly dissipates over time after the flash flood. During the times of low river flows when less precipitation is received, the groundwater, also known as baseflow, sustains the river and makes it perennial.

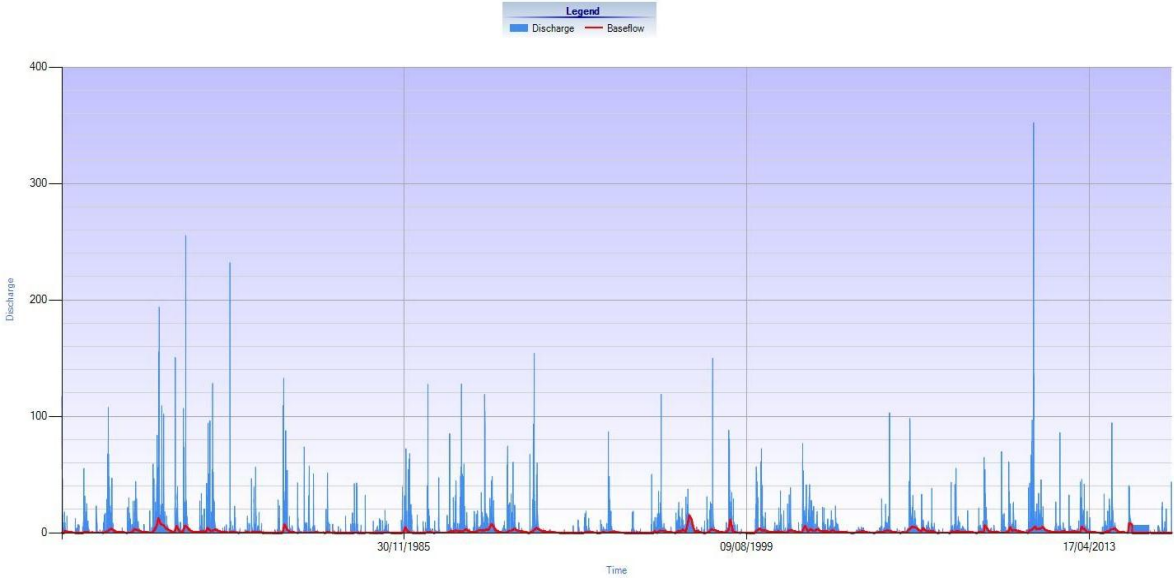


Figure 5.29 Hydrograph of the South Phuthiatsana River at the Masianokeng Gauge Station from 1972 to 2018, illustrating historical variations in river discharge over the observed period.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

6.1 Introduction

The use of multiple parameters to investigate GW-SW interaction has been accomplished. This has been achieved through various methods; (1) Characterisation of rainfall composition. (2) Determination of areas of groundwater recharge. (3) Determination of impacts from different land uses. (4) Determination of water sources sustaining wetlands or sponges in the highlands.

6.2 Characterisation of rainfall composition

The precipitation data collected at different altitudes within Lesotho enabled this characterisation through the development of Lesotho's Local Meteoric Water Lines (Oxbow, Maseru and Abia). Lesotho's precipitation is enriched in heavier isotopes than the GMWL, this phenomenon is consistent with Southern Africa's arid to semi-arid areas (Durowoju et al., 2019; Leketa et al., 2018; Setargie et al., 2021).

Isotope hydrology studies in arid areas are highly influenced by altitude and precipitation depth rainfall (Leketa and Abiye, 2020). Data showed a good correlation between heavy (high amount) rainfall and high altitudes as they had highly depleted $\delta^{18}\text{O}$ for monthly data (Ambach et al., 1967; Diamond, 2022). Similarly, daily data shows a strong correlation for ≤ 20 mm rain depth but rainfall >20 mm does not show any correlation for the Abia station.

The altitude effect of Lesotho shows a strong isotope ($\delta^{18}\text{O}$) variation of -1.7% for every 1000m elevation change for the Western slope (Ambach et al., 1967). This altitude effect is stronger than in the previous study (Abiye et al., 2013) which showed an altitude effect of -1% per 1000m from Oxbow to Bloemfontein.

It must be emphasised that the altitude effect is site-specific. This study focused on Lesotho's precipitation collected from four stations within the Mohokare Catchment, while Oxbow is in the Senqu Catchment. Therefore, the altitude effect must be used with caution as it applies to the Mohokare Catchment and could be improved by collecting data in the Mafeteng district

which has low rainfall. Moreover, other major catchments like Makhaleng and Senqu should have their altitude effect developed.

The long-term datasets (Oxbow and Maseru) and daily (Abia) datasets show a high variation when compared to short-term (Metolong and Nazareth) datasets. These variations can be associated with moisture sources because the winter season is linked to the Atlantic Ocean while the summer moisture source is from the Indian Ocean (Durowoju et al., 2019; Leketa et al., 2018; van Wyk et al., 2011).

6.3 Determination of areas of groundwater recharge and groundwater discharge into the river system

This study used radioactive radon isotope and EC in-situ measurements, as well as stable water isotopes, to pinpoint the interaction between GW-SW. The use of a multiparameter approach enabled the characterisation of catchment flow dynamics.

6.3.1 Radioactive Radon isotope (^{222}Rn)

The noble gas was measured only in surface water, primarily in the main river and its tributaries. To draw informed conclusions from the collected data, land use, geology, and hydrocensus information have been incorporated to support the ^{222}Rn data.

The presence of ^{222}Rn contribution in the main river increased near the Liphiring tributary, which is underlain by the Clarens formation. By examining the geological characteristics in conjunction with hydrocensus data, this noble gas suggests that the area has considerable potential for replenishing the river. This potential arises from groundwater being directly linked to the riverbed or from springs that flow directly into the channels feeding the river.

Downstream of the Metolong dam, the catchment area shows that the measured levels of ^{222}Rn suggest the potential for groundwater to recharge surface water. This region includes alluvial deposits between Likotsi and Abia, where various industries and agricultural fields operate, some using irrigation while others depend on rainfall. Due to its geological features and land

use, this area could enhance groundwater recharge through bank storage during floods or water percolation from irrigated fields.

In summary, first-order rivers sustain the perennial flow of the South Phuthiatsana River. Additionally, two areas have been identified as potential segments of a gaining river, alongside the contributions from tributaries (see Figure 5.25 & Figure 5.26).

6.3.2 Stable water isotopes ($\delta^{18}\text{O}$ or $\delta^2\text{H}$)

Groundwater-surface water (GW-SW) interaction was analysed using stable isotopes through the Metolong-LEL and GIS. Figure 6.1 below shows that the upstream rivers are more depleted as compared to the downstream river below the Metolong dam. Data comparisons indicate that local precipitation and tributaries replenish the rivers. Specifically, first-order rivers are sustained by water from springs and wetlands or sponges in the highlands.

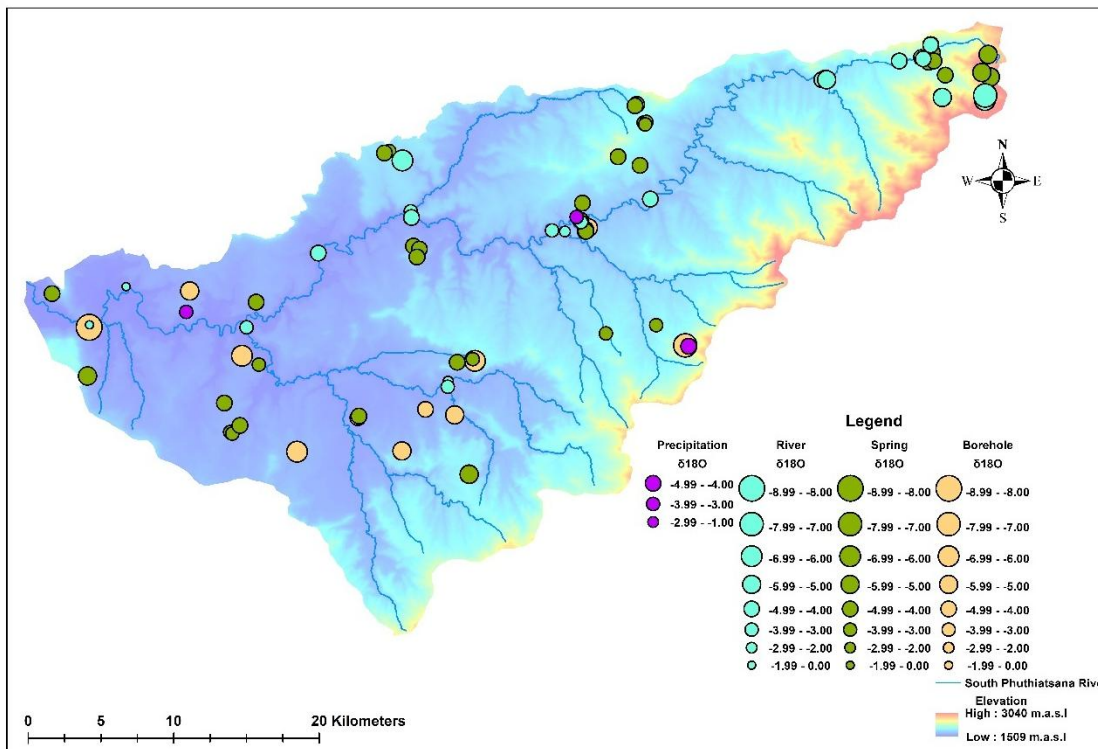


Figure 6.1 Spatial distribution of stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) within the South Phuthiatsana Catchment, overlaid with elevation data, highlighting the influence of topography on isotopic variation in the study area.

The boreholes are highly depleted in $\delta^{18}\text{O}$ and are approximately 80 meters deep, suggesting no direct link to surface water. Dual isotope plots indicate low-temperature rock-water interactions, likely due to Lesotho's winter temperatures dropping below freezing.

Upstream of the Metolong Dam, rivers are depleted in $\delta^{18}\text{O}$ values due to smaller surface areas, faster flow rates, and cooler temperatures, which reduce evaporation. In contrast, downstream rivers are more enriched in $\delta^{18}\text{O}$ because of larger volumes, greater cross-sectional areas, and slower velocity. The South Phuthiatsana River may either lose water to the surrounding landscape or become disconnected from groundwater, depending on its riverbed characteristics and the underlying geology.

6.4 Determination of impacts from different land uses and GW-SW interaction on the water quality

Land use and water demand within the catchment area vary significantly (Maliehe, 2012). Most activities are concentrated along or in proximity to the river, raising concerns about water quality. The EC of the river exhibits an increasing trend from the highlands to the lowlands. Considering the changes in land use, it is likely that various activities contribute to the rise in EC downstream, as illustrated in Figure 5.27.

Meanwhile, Figure 5.28 shows that the EC distribution in groundwater (including springs and boreholes) is heterogeneous and does not correlate with specific land uses. Furthermore, this study has proven that wetlands in the highlands sustain upstream rivers to maintain flow.

6.5 Determination of water sources sustaining wetlands or sponges in the highlands

Wetlands, particularly those in highland areas, show a depleted isotopic signal, as illustrated in Figure 6.2 below. The isotopic composition of precipitation was compared with that of wetlands and springs, revealing that both feature isotopic signatures typical of higher altitudes. This indicates that wetlands are fed by precipitation from higher altitudes, which emerges at lower elevations as springs or wetlands.

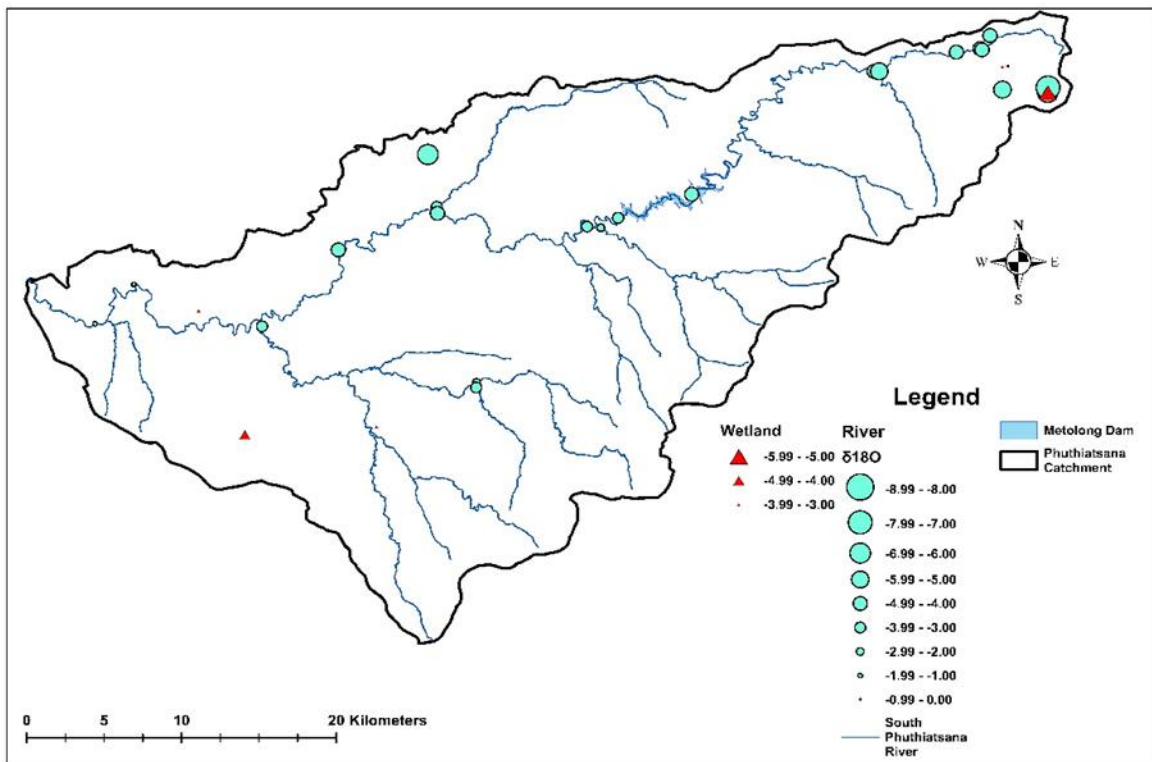


Figure 6.2 Relationship between wetlands and rivers within the South Phuthiatsana Catchment, illustrating hydrological connectivity and potential surface water interactions.

6.6 Conceptual Model

The study examined the interaction between GW-SW using stable water isotopes, radioactive radon gas, electrical conductivity, geological data, GIS, land use analysis, and a literature review. This multi-parameter approach led to a conceptual model that enhances understanding of the flow dynamics in the South Phuthiatsana catchment.

The conceptual model is based on the local geology of the Karoo Supergroup, which includes three main groups as outlined in section 3.2 Geological Setting. The Karoo Supergroup features a variety of depositional environments, leading to distinct lithological units like sandstone, shale, mudstone, and basalt. These units are categorised into formations and subgroups, including the Dwyka, Ecca, Beaufort, and Stormberg Groups, each with different hydraulic characteristics. Additionally, volcanic rocks, particularly the Drakensberg Basalts, often lie above the sedimentary sequences (Woodford and Chevallier, 2002). This stratigraphic and

lithological diversity affects aquifer properties and groundwater flow within the supergroup (Schmitz and Rooyani, 1987) as discussed in section 3.3 Geohydrology.

The Figure 6.3 below is the conceptual model developed from the literature review of local (Davies, 2003; Fobo, 2009; Maliehe, 2012; Mots'ets'e et al., 2017; Schmitz and Rooyani, 1987) and transboundary (Bordy et al., 2017; Botha et al., 1998, 2019; Eilers et al., 2015; Neveling, 2006; Woodford and Chevallier, 2002) studies in the Karoo as the basis for the cross-section. The additional data is collected through water resources and precipitation data at different altitudes within the South Phuthiatsana Catchment in Lesotho using a multiparameter approach at different scales in the catchment.

The precipitation data from stable isotopes showed variations due to altitude and geography. Meanwhile, in-situ parameters like EC remained consistent. Different isotopic effects effectively characterise and classify water resources.

The springs and wetlands showed a relationship with localised recharge, possibly an enriched precipitation that has undergone evaporation before recharging the groundwater. On the contrary, boreholes have shown a possibility of recharge occurring at higher altitudes or a more depleted precipitation.

Figure 6.3 is a cross-section of the conceptual model showing various formations and their hydraulic properties. Wetlands rely on groundwater and precipitation, functioning as discharge points for patched aquifers, especially in the highlands. The wetlands retain water during a rainy season and gradually release water to sustain river flow as baseflow.

Moreover, springs, on the other hand, resemble similar characteristics of shallow recharge and points of discharge both in the highlands and lowlands. Based on the geological characteristics of the Karoo, water within the matrix does not produce yielding boreholes or springs but rather along secondary porosity as a result of dykes, faults and folds (Botha et al., 1998; Davies, 2003; Woodford and Chevallier, 2002).

Therefore, the conceptual model presents the shallow flow that produces springs and wetlands. However, no evidence confirms deep or regional flow and vertical flow from one formation to another.

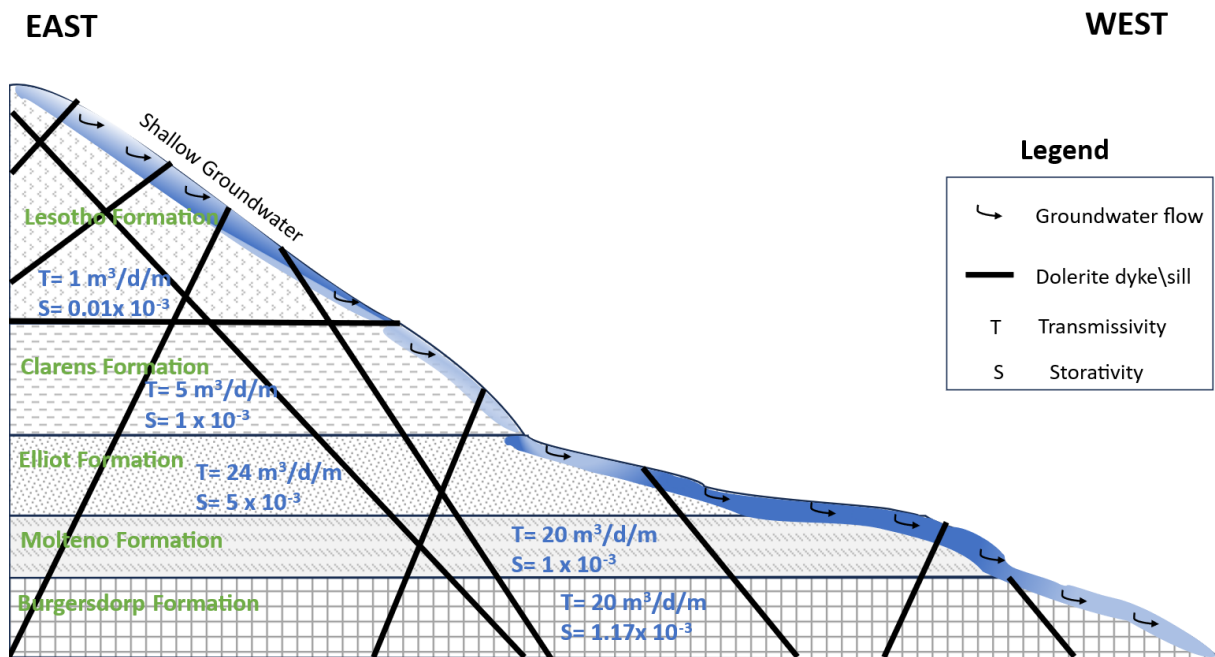


Figure 6.3 Conceptual model of the South Phuthiatsana Catchment illustrating groundwater flow dynamics. Shallow groundwater emerges as wetlands or springs in the highlands (Lesotho Formation) and as springs in the lowlands (Clarens, Elliot, Molteno, and Burgersdorp Formations). The model also highlights the presence of dolerite dykes, which act as barriers or conduits to groundwater flow, influencing localised recharge and discharge zones. Transmissivity and storativity values are incorporated for each geological formation, offering insights into aquifer properties and their role in subsurface water movement and storage across the catchment.

The hydraulic properties of the Karoo Supergroup in Figure 6.3 above reflects its complex lithological and structural characteristics, ranging from productive sandstone aquifers to impermeable shale aquitards. These variations underscore the importance of site-specific hydrogeological assessments for sustainable groundwater utilisation. As water scarcity becomes an increasing concern in southern Africa, understanding the Karoo's hydraulic properties is vital for effective resource management and environmental conservation.

It is worth noting that the transmissivity (T) and Storativity (S) provided in this study is based on previous studies done and the estimated result from borehole pumping tests, not laboratory experiments (Davies, 2003). Therefore, these values must be used with caution.

In conclusion, the evidence from the analysis made during this study does not strongly support regional flow but rather a localised flow.

6.7 Contributions of the Study

The study addressed gaps found in previous isotope hydrology studies (Abiye et al., 2013; Fitchett et al., 2024; Mots'ets'e et al., 2017) by developing Lesotho's Local Meteoric Water Lines, improving the altitude effect and improving knowledge about wetlands recharge mechanisms (Stichler and Herrmann, 1983). The study has echoed the importance of treating GW-SW as a single source in line with previous studies (Barthel, 2014; Hunt et al., 2005; Winter et al., 1998). It also intends to inform practitioners and policymakers through its scientific results in line with (Lewandowski et al., 2020). The study emphasised the importance of GW-SW interaction in maintaining water resources, understanding the approaches and dissemination of scientific results.

6.8 Challenges on sampling and groundwater management

The cultural activities, particularly the initiation school processes, restricted sampling consistency. This is because, during winter when there are low flows, activities happen along the river, making certain areas inaccessible. Whereas in summer, which has high flows in the river, the rituals take place in the highlands. Given the two scenarios, there were instances where the rivers were not accessible during summer because the specific community considers the area to be their highlands or secluded from the community to perform cultural practices. Spring sampling was also a challenge because some of them are for rituals and there are restrictions regarding accessing them.

In addition to the cultural limitations, the terrain and remoteness of sampling sites made it difficult to do a consistent sampling. However, data collected throughout the study area was

compensated for by the long-term data collected by the Department of Water Affairs to mitigate the challenges encountered during sampling.

Hydrogeological exploration in the Karoo Supergroup is complicated by its lithological variability and structural complexity. Predicting groundwater availability and flow requires detailed geological mapping and geophysical investigations to identify productive units and fracture systems (Woodford and Chevallier, 2002). Additionally, the potential impacts of anthropogenic activities, such as shale gas exploration in the Karoo Basin, pose significant risks to groundwater quality and quantity (Botha et al., 2019). Careful monitoring and management strategies are essential to protect these valuable water resources.

6.9 Future possibilities

Isotope hydrology studies in the future will use this study to assess water resources on a catchment or national scale. The government can adopt a combination of conventional methods and isotope hydrology to assess catchment hydrology to mitigate data gaps.

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APPENDICES