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**Water quality, health risk assessment, and treatment options for groundwater in Matsa,
Mamvuka, and Manyii villages, Limpopo Province**

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by

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DECLARATION

This dissertation constitutes my master research work under the Department of Chemical Engineering in the Faculty of Engineering, Built Environment and Information Technology at the University of Pretoria from April 2024 to April 2025, under the supervision of Professor S.A. Iwarere, Professor M.O. Daramola, and Professor J.N. Edokpayi.

I declare that:

- (i) This dissertation, except where otherwise indicated is my original work
- (ii) The written expressions are in my own words, and where other written sources have been quoted, then:
 - (a) Their words have been re-written, but the general information attributed to them has been referenced;
 - (b) where their exact words have been used, their writing has been placed inside quotation marks and referenced

Ondwela Venetia Tshikombeni

PUBLICATIONS AND CONFERENCES

Conference Presentations

1. Tshikombeni, O.V., Edokpayi, J.N., Daramola, M.O., and Iwarere, S.A. 2024. Characterisation of groundwater quality and its associated health risks: case study of Matsa village. 1st Annual Symposium for the Department of Chemical Engineering, University of Pretoria, South Africa, 9 December 2024.

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ABSTRACT

Water sources in rural areas are mostly contaminated by different pollutants such as pathogens, heavy metals, and chemicals. The communities of Matsa, Mamvuka, and Manyii have been without a municipal treated water source. Therefore, they depend on spring water to meet their basic water demand. This study addresses the water quality issues associated with the consumption of contaminated water in these villages due to the lack of existing research assessing the water quality of the spring water utilised. The study evaluated the physicochemical and microbiological quality of groundwater in Matsa, Mamvuka, and Manyii villages, Limpopo Province, South Africa. A water quality assessment was carried out on 48 samples, and the method of interviews using a questionnaire was used to determine the communities' practices of water collection and storage. The questionnaire was distributed to 15 households in the Matsa, Mamvuka, and Manyii villages, with 5 people from each village being interviewed, and adults over 18 years were randomly selected for an interview questionnaire.

The physicochemical parameters were measured using the 7-in-1 water quality meter (Hanna Instruments), and turbidity was measured using the turbidimeter (Thermo Scientific Eutech TN-100). Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and Discrete Analyser were used to analyse heavy metals and anions, whereas the membrane filtration method was used for microbial analysis. Various water treatment methods, including chlorine tablets, boiling, plasma technology, ceramic filters, and bleach, were applied to determine the most effective water treatment for the three villages. Ecological Structure Activity Relationships (ECOSAR) was used to test the ecological risks posed by the various water treatment methods on the environment. Statistical analysis was performed using Microsoft Excel to test the significance of the influence of seasons on physicochemical, heavy metal, and anion parameters, as well as treatment methods. PCA and Box and Whisker were used to describe the distributions of metals and ions across the sampling sites.

Most of the physicochemical parameters' concentrations in drinking water samples were within the regulatory standards limits of South African National Standards 241 and the World Health Organisation, except for S10 (Manyii spring), which exceeded the ≤ 5 as it recorded 10.75 and 51.5 NTU for the dry and wet seasons. Some heavy metals, such as Fe and Al, exceeded the SANS regulations in both seasons. For the dry season, Fe was above the limit at S3 (2.03 mg/L), while Al exceeded at S2 (0.34mg/L). In the wet season, these metals exceeded the limits at S3 (4.3mg/L) and S10 (2.095 mg/L) for Fe. Meanwhile, Al exceeded at points S6 to S12 with concentrations of 0.315, 0.785, 0.415, 0.855, 0.345, and 0.45 mg/L, respectively. According to SANS 241, these metals should not exceed the values of 2 and 0.3 for Fe and Al, respectively. Moreover, As (0.046 mg/L at S2, and 0.027 mg/L at S12 during the dry season,) Mn (0.15 mg/L and 0.31 mg/L at S7 during both seasons),

and Ni (0.102 mg/L at S6 during the dry season) exceeded the SANS 241 values of $\leq 0.01, 0.1$, and 0.07 mg/L, respectively.

Average highest *E. coli* detected from Matsa (1312.5 CFU/ 100 mL), Mamvuka S1 (330 CFU/ 100 mL), Mamvuka S2 (1327.5 CFU/ 100 mL) and Manyii (2340 CFU/ 100 mL) during the wet season exceeded levels detected in the dry season (892.5, 340, 350 and 542.5 CFU/ 100m L) respectively; whereas, for Total coliform, the levels detected in the wet season did not have a specific trend as compared to the levels of *E. coli*. However, the average highest recorded level among all sampling points was found to be in S5 (9547.5 CFU/ 100 mL) for the dry season, and in S10 (13125 CFU/ 100 mL) for the wet season. Furthermore, the microbial results showed that 100% of the sampling points were contaminated with *E. coli* and Total coliforms.

The water treatment methods employed showed no statistical difference from one another. It was therefore concluded that the water purification methods tested are all effective and can all treat water, as there is no statistical evidence that one method outperforms the other. However, toxicological results showed that bleach and Plasma may pose high risks to the environment and aquatic animals; therefore, the use of other methods (chlorine tablets, ceramic filters, and boiling) is recommended to avoid contaminating the environment.

The calculated sum Water Quality Index of the sampled water showed that the heavy metals play a role in contributing to low water quality in these communities. The dry and wet seasons WQI sum range within the poor water quality class (160.17 and 121.84). The carcinogenic effects using the Hazard Index (As) through ingestion and dermal pathways ($4.80e+00$ and $1.26e+00$) and Carcinogenic Risk (As $2.16e-03$ and $5.66e-04$) and (Ni $2.08e-02$ and $5.45e-03$) for children and adults during the dry season showed that the usage of springwater could present significant health risks, as the indices were above the recommended value by the United States Environmental Protection Agency (USEPA).

The questionnaire results showed that the residents from the three study areas lack access to potable water, as 46.68% of the respondents responded that they use spring water, whereas 26.66% buy from those with boreholes, and the other 26.66% depend on their private borehole. These communities have been without potable drinking water for over 10 years. Furthermore, during the summer season, most households practice harvesting rainwater in the study areas. Water in these communities is used for all domestic needs, and stored in covered drums or tanks, mostly for less than a week before another collection. Meanwhile, storage practices are good, but most of the residents are not aware of the associated health risks of consuming contaminated water, with only a few associating untreated water with illnesses such as cholera and diarrhea.

Based on the results from the water quality analysis, as well as the questionnaire, this study recommends the need for municipalities to invest in providing potable drinking water for the study areas and suitable water treatment methods to treat water before consumption. This can be done through the provision of tankers, maintaining the available municipal pipes, and drilling boreholes. Residents from these communities should practice treating water before consumption to minimise health risks, and this can be done by using chlorine tablets, bleach, and boiling methods, as they can easily be employed in rural areas.

Keywords: Contaminants; Groundwater; Health risks; Pollutants; Water sources.

LIST OF ABBREVIATIONS

- BDL: Below Detection Limit
- CR: Carcinogenic Risks
- CDI: Chronic Daily Intake
- CFU: Colony Forming Units
- DNA: Deoxyribonucleic
- DWS: Department of Water Affairs
- ECOSAR: Ecological Structure Activity Relationships
- E. coli*: Escherichia coli
- HI: Hazard Index
- HQ: Hazard Quotient
- HHRA: Human Health Risk Assessment
- LOQ: Limit of Quantification
- PET: Polyethylene Terephthalate
- PCA: Principal Component Analysis
- QMRA: Quantitative Microbial Risk Assessment
- RfD: Reference Dose
- SANS 241: South African National Standards
- SF: Slope Factor
- SDG: Sustainable Development Goals
- USEPA: United States Environmental Protection Agency
- WQI: Water Quality Index
- WHO: World Health Organization

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CHAPTER 1: INTRODUCTION

1.1 Background and purpose of the study

“Water is a basic human need; thus, they have the right to access safe and quality water” (Abegaz & Midekssa, 2021). The rise in human population contributes to increased demand for clean and safe water in Africa and globally (Adeola & Forbes, 2021). Water shortages and access to safe water are a global problem (Memon et al., 2021), and this is mainly due to an increased population and water contamination from natural and anthropogenic activities (Ahmed et al., 2020; Edokpayi et al., 2020). Even though in various places people have access to water, the water available is rarely safe for human consumption and insufficient to meet the people's basic needs (Edokpayi et al., 2018a); therefore, the United Nations have set the Sustainable Development Goals (UNSGDs) to providing sustainable access to clean and sufficient quantity of water for all by 2030 (Terefe et al., 2024).

Over the past 20 years, the world has recorded progress in improving access to potable drinking water and hygiene through the United Nations Sustainable Development Goals (SDGs) (WHO/UNICEF, 2015). This progress, however, is still an issue as approximately 703 million people globally still lack access to potable drinking water (WHO/UNICEF, 2023). In addition, this has led to numerous people depending on untreated water from various sources. Furthermore, it has been reported by Enitan-Folami et al. (2020) that the use of untreated water sources is associated with the deaths of millions of underage children. It has also been noted that > 80% of waterborne illnesses result from consuming contaminated water (Abubakar, 2018a, b). The United Nations has adopted the 2030 SDGs to improve people's welfare by aiming to end waterborne disease epidemics (Goal 3) and ensure equal access to potable water (Goal 6), even though it is a challenge to achieve these goals in rural areas due to weak physical infrastructure and institutional support system (Stewart et al., 2023).

It is essential to have access to clean and safe water to avoid the spread of waterborne diseases (Schoeman et al., 2017). However, any water source is open to contamination, and the water sources are under threat due to high pollution loads, making water less acceptable for consumption. Typical sources that inject pollutants into water bodies include acid mine drainage, animal grazing, agricultural run-off, and littering (Ogoko, 2019). The accessibility to safe water sources does not guarantee the quality of water consumed (Luvhimbi et al., 2022). The World Health Organisation (WHO) also confirms that the shortage or lack of water seriously impacts human survival (WHO, 2017).

Less developed countries, especially in Sub-Saharan Africa, have the lowest accessibility to safe drinking water (Dos Santos et al., 2017), and therefore, people rely more on groundwater than surface water since surface water is heavily polluted (Potgieter et al., 2020). Baguma et al. (2017) reported that approximately two-thirds of the South African population depends on groundwater for domestic uses, with 65% being in rural areas. Most communities depending on groundwater are unaware of the quality of water they consume, as they mostly assume it is clean (Edokpayi et al., 2018a). In such cases, rural areas are the most impacted, and residents are forced to collect water from various water sources such as rivers, streams, springs, private and communal boreholes, and wells to meet their domestic needs (Edokpayi et al., 2018a).

The provision of potable drinking water in South Africa is poor, typically for rural and peri-urban communities (Masindi and Foteinis, 2021). The domestic use of contaminated water in rural areas is common due to a lack of access to safe and clean drinking water (Olasoji et al., 2019). In South Africa, surface water is the main water supply source. However, groundwater is mostly used, as reported by Tladi et al. (2023) that 80% of rural areas within the Northwest and the KwaZulu-Natal provinces use groundwater, together with 50% of these people residing in the rural areas of the Eastern Cape. Rural areas are often exposed to elevated levels of environmental pollution since the groundwater supplied is mostly untreated (Mangesi & Mngeni, 2024). Increased threats to groundwater quality result from increased population, agricultural intensification, climate change, and the development of industries (Kumar, 2019). Groundwater pollution has become a harmful threat affecting human health, social well-being, and economic development (Wakode et al., 2018). In the absence of public water supply systems and the government's failure to meet people's demands in rural areas, society finds alternative solutions such as using underground water resources, which are sometimes the only possible drinking water supply (Hirata et al., 2019). However, groundwater is vulnerable to pollution, affecting its quality, physicochemical characteristics, and has negative impacts on aquatic animals and human beings (Mangesi & Mngeni, 2024).

Ihsan and Derosya (2024) reported that even though people have access to clean and safe drinking water according to the South African constitution, millions still lack a potable water supply. Residents from these communities usually consume water without any form of treatment (Ihsan & Derosya, 2024). Nevertheless, these sources are mostly polluted by faecal matter or *E. coli* (UNICEF, Indonesia, 2022). Enitan-Folami et al. (2019) and Taonameso et al. (2018) reported that in rural areas of South Africa, groundwater pollution is associated with animal farming and onsite sanitation systems. These onsite sanitation systems include the use of the “bush method”, which also can cause groundwater contamination; however, people are unaware of this issue (Classen and Lewis, 2017).

From a global perspective, most people depend on groundwater daily, and it has proven to be a reliable water source for meeting people's demands in the South African rural areas (Mutileni et al., 2023). In rural areas, it is a common practice to collect water from rivers, springs, taps, and other sources, and store it, provided they do not have a piped water supply in their homes (Edokpayi et al., 2018a). According to Luvhimbi et al. (2022), most South African communities have access to municipal water; however, the water is piped into households in urban rather than rural areas. They further reported that in rural areas, water is supplied through street pipes, and residents still need to collect water from the source to the point of use. Furthermore, water disturbances are mostly experienced in rural areas, hence the need for long-term storage. Water is stored in different containers such as buckets, drums, jerry cans, etc. (Luvhimbi et al., 2022). They further reported that during water collection from sources, contamination during transportation, handling, storage, and poor hygiene practices usually result in and cause diseases.

This is the case with some of the rural areas in Limpopo Province, such as Matsa, Mamvuka, and Manyii villages. For the past years, the communities of Matsa, Mamvuka, and Manyii have been without clean and safe drinking water. The lack of water forced the community to come up with a plan to access clean water. During the rainfall season, residents rely on rainfall harvesting for drinking, and some buy water from those with private boreholes. Water scarcity in these areas is a huge challenge since the villagers have little or no water and require water for domestic needs such as drinking, cooking, bathing, and laundry.

The South African National Standards (SANS 241) and the WHO have established limits for healthy drinking water. These limits must not be exceeded for the water to be considered safe for consumption. Although, due to water scarcity, groundwater is traditionally taken as a safe and dependable source of drinking, this is mostly not the case since it is easily exposed to pollution from both natural processes and anthropogenic activities (Masindi and Foteinis, 2021). Primarily, groundwater contamination is due to natural organic substances, mainly humic substances, which are difficult to remove using conventional methods (filtration, sedimentation, and aeration) (Mangesi & Mngeni, 2024).

According to Manga et al. (2020), groundwater can be contaminated by various pollutants, including pesticides, fertilisers, bacteria, viruses, coliform, pharmaceuticals, metals, and oxyanions. The water quality of Matsa, Mamvuka, and Manyii villages could be affected due to these pollutants, as the residents from these communities consume untreated brownish water from the springs. Water scarcity in these areas results in several waterborne illnesses, as it is a risk to drink untreated water. Although the residents use traditional methods such as boiling and bleaching to purify water, it is still not safe enough for consumption, as these methods are not accurate enough to kill biological contaminants.

WHO (2023) reported that in 2022, approximately 1.7 billion people globally consumed water from drinking water sources contaminated with faeces, and this poses a great risk to drinking water safety. A major health concern for contaminated water use is the microbial and physicochemical quality of water, mainly due to anthropogenic activities (Edokpayi et al., 2021).

In rural areas, groundwater resources are usually located near pit toilets, landfills, or dumpsites (Luvhimbi et al., 2022). Some groundwater resources are poorly managed due to their undisclosed nature, and it takes time to notice when it is polluted and contaminated. Therefore, it's difficult to restore its quality by stopping pollution from the source, as the contamination could persist even after the source has been stopped or removed (Edokpayi et al., 2018b). Most of the groundwater resources in rural areas are often untreated, and Edokpayi et al. (2018b) reported the difficulties of groundwater purification. Conversely, the use of unknown groundwater quality puts consumers at risk and causes waterborne diseases (Zhao et al., 2022).

It was further reported that the consumption of contaminated water causes diseases such as Cholera, Diarrhoea, Hepatitis A, Polio, Typhoid, stomach ulcers, Guinea and ringworm infections, Giardiasis, and Dysentery, with an estimate that about 1 million people die from diarrhoea every year (WHO, 2023). In addition, at Matsa, Mamvuka, and Manyii villages, there are various animals in the bushes, meaning people are consuming the same water that animals are polluting; thus, the water is unsafe for consumption and poses a high risk for waterborne illnesses that could lead to a high rate of deaths. Therefore, it is important to provide accessible as well as safe, and quality drinking water for the public.

Several studies have addressed the water quality challenges (Potgieter et al., 2020; Manga et al., 2020; and Lin et al., 2022). Therefore, preventing water pollution needs productive and continuous monitoring of microbiological, physical, and chemical parameters to identify the possible risks associated with the consumption of groundwater. Health risk assessment of pathogens at Matsa, Mamvuka, and Manyii villages will provide information to health statisticians, communities, and the public. As stated by WHO (2023), more people are dying each year because of poor-quality drinking water consumption. Therefore, it is essential to study the importance of clean and safe drinking water. Although several studies on water quality challenges have been conducted, there is still a need for further investigations, solutions to the problem, and recommendations. This helps to minimise the problems and prevent future pollution. This study's purpose is to understand the health risks associated with the consumption of poor-quality water and provide solutions to ensure that the drinking water at Matsa, Mamvuka, and Manyii villages meets the necessary limits set by SANS 241 and WHO by providing sustainable and reliable treatment options.

1.2 Problem statement

Access to quality and available water for human consumption is a serious global problem, with an increase in contamination levels of several pollutants, heavy metals, and microbial pollutants. The situation at the Matsa, Mamvuka, and Manyii villages causes a serious threat to public health as it causes waterborne diseases and has an impact on the high death rate. Studies by Mutileni et al. (2023) and Machona et al. (2025) reported elevated *E. coli* and Total Coliforms present in groundwater. Mutileni et al. (2023) also reported the cancer risks for the trace metals found in the sampled water and concluded that the consumption of water is unsafe, as it can cause cancer. These studies support that the consumption of contaminated water with heavy metals and microbial pollutants is a threat to the public, hence the need for treatment. The use of traditional water treatment strategies (boiling and the use of chemical disinfectants) is often ineffective in removing these contaminants. Therefore, it is essential to assess and implement innovative strategies for safe and sustainable drinking water sources for this community. Tyhali & Forbes (2023) reported that chlorination is the most used and effective method for water purification. This study aims to assess the groundwater quality in the Matsa, Mamvuka, and Manyii villages by conducting an extensive health risk assessment of the available water sources and evaluating suitable treatment options to improve their quality.

1.3 Research Questions

This project seeks to answer the following research questions:

1. What are the possible contaminants available in groundwater sources in the Matsa, Mamvuka, and Manyii villages?
2. What are the health risks associated with the identified contaminants in (1)?
3. What are the potential and feasible treatment options to remove these contaminants from the water sources?
4. How do seasonal variations affect the physicochemical and microbial parameters of water quality?

1.4 Main objective and Specific objectives

Aim: Assess the groundwater quality in the Matsa, Mamvuka, and Manyii villages by conducting an extensive health risk assessment of the available water sources and evaluating suitable treatment options to improve their quality.

Specific objectives of the study:

1. Assessment of the groundwater quality in Matsa, Mamvuka, and Manyii villages by measuring physical, chemical, and biological parameters to determine its suitability for human consumption
2. Identification and evaluation of the associated health risks using Chronic Daily Intake, Hazard Quotient, Hazard Index, Cancer Risk, and Quantitative Microbial Risk Assessment
3. Investigate alternative treatment options for the contaminated groundwater sources in Matsa, Mamvuka, and Manyii villages
4. Evaluating seasonal variations in physicochemical and microbial water quality parameters to assess the impact of dry and wet seasons on the groundwater quality

1.5 Study outline

This dissertation consists of the following:

Chapter 1: Study background and motivation

This chapter explained the background to the identified problem, the study aim, objectives, research questions, and the problem statement.

Chapter 2: Literature Review

A comprehensive literature review on water importance, sources of groundwater contamination, factors affecting water quality, health effects of consuming contaminated water, water treatment methods, WQI, HHRA, and QMRA.

Chapter 3: Methods and Materials

This chapter explains the study area, methods of data collection, and analysis.

Chapter 4: Results and Discussion

The physicochemical parameters, water treatment methods employed, WQI, HHRA, and QMRA results, and detailed discussions are presented in this chapter.

Chapter 5: Conclusions and Recommendations

This chapter presents the synthesis of the key findings and gives recommendations and possible future research to be conducted.

References and Appendices

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Groundwater is an important natural resource benefiting mankind globally (Ravindra et al., 2022), and its contamination is considered a major threat to human health (Raza et al., 2017). Abanyie et al. (2023) reported that most water quality issues include nitrates, chlorides, arsenic, organic compounds, Total Dissolved Solids (TDS), microbiological, and fluoride. They further reported that groundwater resources are considered unhealthy for consumption due to the generation of wastewater, agricultural effluents, waste disposals, and livestock feedlots. Groundwater is a major source of nitrate and is often untreated. These nitrates include animal waste, the use of fertilisers, and waste disposal (Adimalla & Qian, 2019). The quality of groundwater correlates with human health risks, and the usage of polluted water has negative health effects (Fu et al., 2021). The physical, chemical, and biological parameters of water are used to represent its quality, protecting human health, and most of these parameters are influenced by both natural and anthropogenic activities such as groundwater interaction with the local lithology, agricultural activities, and improper exploitation methods for groundwater resources (Gugulothu et al., 2022a).

Several studies have reported on the associated health risks of consuming contaminated water (Edokpayi et al., 2017, 2018, a, b; Raza et al., 2017 & Zhang et al., 2023). These reports point out the need for characterising water sources and human health risks to communities in rural areas that are resource-limited and socio-economically challenged (Stewart et al., 2023). The proximity of groundwater to dumpsites and animal droppings littered around them may also degrade groundwater quality, hence the need to monitor and assess its quality. On the other hand, the decline in groundwater is witnessed during the dry season due to climate change (Le Duy et al., 2021). The use of agrochemicals for an extended period affects the quality of groundwater due to increased ions and poor flushing concentrations (Elumalai et al., 2020).

2.2 Sources of groundwater contamination

2.2.1 Naturally occurring sources

Groundwater contamination can occur in dual ways: natural sources, such as floods, excessive amounts of minerals in aquifers, and rainfall leachates; and anthropogenic activities such as municipal and industrial waste (Sarkar et al., 2022). The groundwater quality depends mainly on the geological formation of the area; however, anthropogenic activities also play a role (Kiwanuka et al., 2023). The quality of groundwater differs with locations, seasonal variations, types of soil and rocks, and the surface through which it moves (Patil et al., 2020). The naturally occurring contaminants are found

in rocks and sediments where the groundwater flows through the sediments, and metals like Manganese (Mn) and Iron (Fe), dissolved, may be high in concentration levels as they have similar atomic valence state (Sharma et al., 2021). In addition, rainfall plays a crucial role in contaminating groundwater resources (Santos et al., 2023). Conditions such as climate, hydrogeological environment, land use, wastewater products, absence or presence of water quality monitoring, and groundwater location affect the water quality (Latchmore et al., 2020). Rainfall affects water quality and increases turbidity and microbial contamination (Santos et al., 2023). Seasonal variations, including rainfall intensity, temperature changes, and atmospheric humidity, are other natural factors that directly and indirectly affect the groundwater quality (Ober & Karwot, 2021). These are the main sources that affect the groundwater chemical composition during the evaporation process in the dry season and the infiltration of rainfall water during the wet season (Zhang et al., 2021a).

Other natural sources affecting groundwater quality include the weathering of rocks under the ground and sediments, and natural disasters such as floods, landslides, earthquakes (Raza et al., 2017), lithology, and geochemical processes (Elumalai et al., 2020). Natural occurring processes such as tsunamis, earthquakes, and weathering affect the groundwater quality by leaching anionic and cationic chemicals such as fluorides, sulphates, heavy metals, and metalloids (Li et al., 2018).

2.2.2 Anthropogenic activities

Anthropogenic activities are reported as the main factors in determining the nature of groundwater through atmospheric contamination and the utilisation of farming chemicals (Krishna et al., 2019). Pollution occurs through anthropogenic activities (point and non-point sources) is a huge concern for groundwater contamination. Point sources include municipal, industrial, and domestic waste, whereas non-point sources include runoff from agricultural practices or runoff from hard surfaces, including roads (Raza et al., 2017). Anthropogenic activities can alter the natural composition of groundwater through chemical disposal and injecting waste directly into groundwater (Abanyie et al., 2023). Limpopo is one of the poorest provinces with water resources, and this is due to extensive pollution. Several villages in Limpopo Province face water quality issues due to high calcium (Ca), magnesium (Mg), and nitrate in private boreholes, and these minerals are caused by the washing of clothes in the neighbourhood boreholes and agricultural practices, resulting in salty water (Maluleke et al., 2025).

Much use of fertilisers for agricultural purposes increases the risks of groundwater pollution, which results in anthropogenic and environmental harm (Maluleke et al., 2025). High levels of Ca and Mg are not good for household appliances, and they cause corrosion and hardness in water (United States Geological Survey, 2022). The practice of anthropogenic activities results in a decline in groundwater levels (Sinha and Rai, 2021) and pollution. The availability and quality of water are affected by

anthropogenic activities and socio-economic development (Uddin et al., 2018). High nitrogen concentrations are due to agricultural activities (Shakya et al., 2019). Gugulothu et al. (2022b) reported that man-made activities are the main causes of poor groundwater quality in arid and semi-arid regions globally.

2.3 Factors Affecting Groundwater Quality

2.3.1 Physicochemical parameters

Water quality is defined by physical, chemical, and microbiological characteristics. Five important physicochemical parameters include temperature, pH, total dissolved solids, electrical conductivity, and turbidity (Bwire et al., 2020).

2.3.1.1 Temperature

Temperature is an important factor that influences the overall water quality (physical, chemical, and biological) characteristics; however, no set standard limit is recommended for drinking water (WHO, 2017), and any temperature change in the groundwater disturbs the water ecosystem balance and affects the climatic variations (Bantin et al., 2020). Further, temperature affects water aging, and therefore microbial contaminants can grow in the water at normal or slightly higher temperatures and reduce the water quality (Boadi et al., 2020).

2.3.1.2 pH

pH indicates the acidity and alkalinity of water (Popoola et al., 2019). Popoola et al. (2019) also reported the side effects of consuming water with low pH to be acidosis, which can cause eye and skin irritation, and mucous membrane cell injury. Further, Khan and colleagues (2020) reported that metal corrosion in household apparatus is a major issue for low pH.

2.3.1.3 Total Dissolved Solids

Total Dissolved Solids is the presence of dissolved solids in water, and it shows the behaviour of salinity in groundwater. High TDS influences total hardness, taste, and corrosive properties (Ojekunle et al., 2020). According to Ilori et al. (2019), TDS shows the capability of water to break down organic and inorganic minerals such as sulphates, chlorides, phosphates, and others. The presence of these minerals in water creates an undesirable odour, taste, and colour appearance. Ilori and colleagues (2019) and Lalumbe and Kanyerere (2022) reported that the side effects of consuming water with high TDS concentration cause constipation or laxative effects, and heart or kidney problems.

2.3.1.4 Electrical Conductivity

EC measures the water capacity to pass the electrical current. It shows the total number of dissolved acids and salinity present in water (Ojekunle et al., 2020). The EC of water is primarily determined by the concentration of inorganic ions (chlorides, fluorides, alkalis, sulphides, carbonates, etc.) in the aquifers (Al-Khashman et al., 2017). It gives information about the mineralisation of water and differs with the levels of the dissolved salts and is usually affected by the water's temperature (Bantin et al. 2020). The use of water with elevated levels of EC can cause cardiovascular and kidney diseases (Boadi et al., 2020).

2.3.1.5 Turbidity

Turbidity is an important parameter for water quality that defines the presence of suspended solids such as clay, silt, and organic and inorganic matter, as well as algae and organic dyes in water, causing a muddy appearance in water bodies (Boadi et al., 2020). Turbidity is due to the presence of colloidal and fine dispersions and measures the cloudiness of the water (WHO, 2017). Elevated concentrations of turbidity in water change its taste, and the water may cause health problems as this water may be a breeding space for pathogens, which may cause a breakout of waterborne diseases, including Cholera and Diarrhea (Boadi et al., 2020).

2.3.2 Heavy Metals

Contamination of groundwater by heavy metals is a serious issue in residential, industrial, and agricultural regions (Raza et al., 2017). Heavy metals in groundwater occur as a result of ultramafic and basaltic rocks present in the water (Benitez, 2018). In general, drinking water contains various heavy metals such as As, Cd, Cr, Cu, Al, Fe, Sb, Se, Hg, Pb, Ni, and Zn; and they pose serious threats to human health and the environment due to insufficient and excessive exposure (Mitra et al., 2022). Hasan et al. (2023) reported that Cd, Cu, Zn, Mn, and Fe in water are a result of using fertilisers and fungicides during agricultural activities, and this affects the water quality. The presence of Cu, Zn, and Cd in water results in low pH (Edokpayi et al., 2018b).

2.3.2.1 Arsenic (As)

As is normally associated with toxic results; however, it is tasteless, odourless, and colourless, and it is, therefore, difficult to perceive its effects (Monteiro De Oliveira et al., 2021). Although the release of As to the environment naturally occurs from sediment to groundwater, digging wells, and the use of chlorine for sanitation also play a role in releasing As and other metals into the groundwater (Monteiro De Oliveira et al., 2021). The presence of As in groundwater can occur naturally through volcanic activities, weathering of volcanic rocks, and microbial and anthropogenic activities such as

As-based pesticides. The presence and release of this metal in groundwater highly depend on climate and physicochemical factors of soil and water interactions (Moneiro De Oliveira et al., 2021). Additionally, Munyangane et al. (2017) reported high levels of Arsenic to be found in groundwater globally. The use of groundwater that is highly contaminated with As is the main exposure for humans to it; however, there are other sources, such as dermal (Zhang et al., 2019). As is primarily absorbed through oral consumption and inhalation, and dermal exposure (Moneiro De Oliveira et al., 2021).

It is reported by Monteiro De Oliveira and colleagues (2021) that the toxicity of As is dependent on the exposure type and duration. “The direct ingestion of contaminated groundwater, and indirect exposure (consumption of food grown with contaminated water) are the main forms of exposure to As” (Rahman et al., 2018). High exposure to As causes non-cancerous and cancerous skin lesions such as basal cell carcinoma and squamous cell carcinoma (Moneiro De Oliveira et al., 2021). Zhao et al (2022) also reported that As is considered a carcinogenic contaminant, and it causes various cancers such as skin, liver, bladder, lung, and kidney. According to Chakraborti et al. (2017), exposure to As by women affects the reproductive and developmental processes of the unborn baby, as it affects mostly the placenta.

2.3.2.2 Nickel (Ni)

Ni is a common metal found in food and drinking water from human and natural sources. Further, the direct ingestion of Ni can cause severe human health-related effects (Salehi et al., 2024). Ni is carcinogenic and widely distributed in groundwater; therefore, its prolonged exposure can lead to heart problems, allergies, lung fibrosis, kidney problems, and respiratory tract cancer (Raza et al., 2017). Further, high intake of Ni causes allergic reactions, reduction of lung functioning, chronic bronchitis, and nasal sinuses (Pradhan et al., 2023). Ni enters the groundwater through leaching and the dissolution of Ni ore-bearing rocks, which are in contact with the underground flow of water (Pradhan et al., 2023). According to Pradhan et al. (2023), mining of metals, burning of fossil fuel, smelting, disposing of waste by municipalities and industries, and the use of fertilisers and manure are the main contributors to the contamination of groundwater with Ni. Moreover, they reported that acid rain can mobilise the amount of Ni in the soil and increase its concentration in groundwater.

2.3.2.3 Mercury (Hg)

Hg is normally present in groundwater at concentrations <0.005 mg/L, and mineral deposits in water increase their concentration (WHO, 2017). According to Ewool et al. Hg is a toxic metal that is hazardous and known as a “persistent bioaccumulative toxin”. When this metal exceeds its regulated limit, it can get biological accumulation through the food chain, harming the children’s nervous, immune systems, cardiovascular systems, and neurotransmitter production, and decreasing

hormones. The toxicity of Hg causes renal disturbances, and neurological damage such as ataxia, weakness in muscles, numbness in limbs, and disturbs speech, chewing, and swallowing (Chen, 2020). The sources of Hg in the groundwater can be through volcanic emissions, forest fires, and degassing from Hg-containing rocks and sediments (Ermolin et al., 2018). The Hg released is gaseous and transported into the atmosphere, and therefore can enter the aquifer during groundwater recharge (Aleku et al., 2024). Human activities such as industrial processes and the burning of fossil fuels are the major contributors of Hg to the environment. Moreover, once Hg is released into the environment, it can travel distances before its deposition on land and water surfaces, which can therefore contaminate other areas without a direct source of human emissions (Beckers & Rinklebe, 2017).

2.3.2.4 Zinc (Zn)

Zn is an important metal that acts as a catalyst during enzyme activity and regulates gene expression. It is naturally present in food and drinking water in the form of salts (Mutileni et al., 2023). At a concentration of 4 mg/L, Zn imparts an unpleasant taste to water, and water with a high concentration of Zn becomes greasy when boiling (WHO, 2017). Ullah et al. (2022) reported that Zn is known to protect humans against fast muscle and skin aging due to its antioxidant properties; and it is due to by-products of steel or coal-fired power plants, and combustion waste material. Moreover, Zn helps in the healing process of an injury (Mutileni et al., 2023). Exposure to high levels of Zn can cause gastrointestinal effects, headaches, and impaired immune functions. It further causes diseases such as stomach cramps, nausea, anemia, damage to the pancreas, and reduction of high-density lipoprotein (HDL) cholesterol (WHO, 2023).

2.3.2.5 Cadmium (Cd)

Cd is a rare metal that occurs naturally in soil, minerals such as sulphates and chlorides, as well as in water (Durowoju et al., 2020). The occurrence of this metal is normally due to activities taking place in industries. Further, exposure to high concentrations of Cd could disturb essential mechanisms in the body and, therefore, result in either short or long-term disorders (Zhao et al., 2022). Cd is a heavy metal without any physiological function in the human body, and its excessive intake or contamination in groundwater can cause various cancers, including lung and breast cancers, cardiac failure, kidney failure, metabolic disorder, and cerebral infarction (Nordberg et al., 2018).

2.3.2.6 Copper (Cu)

Cu is an important element for human health, and is usually considered non-toxic; however, its prolonged exposure can cause health problems. Cu is also important because it helps with the build-up of enzymes in the human body (Raza et al., 2017). Excessive intake of Cu causes severe mucosal irritation, corrosion, capillary damage, renal and hepatic damage, and central nervous system irritation that leads to depression, and alters the water's taste (WHO, 2023). Moreover, high levels of Cu cause stains on clothes and sanitary wares. It also causes an undesirable taste to water at higher levels and changes its colour, and further causes cardiovascular problems (WHO, 2017).

2.3.2.7 Chromium (Cr)

The presence of Cr in groundwater is found naturally in a pair of isotopic forms: trivalent, Cr (iii), and hexavalent, Cr (vi) (Mpouras et al., 2021). The natural sources of Cr in groundwater include weathering, erosion, and mineral dissolution (Perraki et al., 2021), and human activities include leakages, poor storage, and industrial waste disposal (Rashi et al., 2021). Contamination of groundwater with Cr is harmful because of its genotoxicity, bioaccessibility, leaching, and carcinogenicity (Zhang et al., 2021b). Leachates from landfills and dumpsites due to heavy rainfall and the disposal of metals result in high levels of Cr (Edokpayi et al., 2018b). A specified amount of Cr is needed in the human body; however, the consumption of high Cr causes gastrointestinal cancer, undesirable taste, and nausea in human beings (WHO, 2017), liver and kidney dysfunctioning, nose lining irritation, nose ulcers, and breathing problems like asthma and coughing (Rashid et al., 2021). Further, Lin et al. (2022) reported that high Cr causes DNA damage in human beings if the level of Cr is > 0.05 mg/L.

2.3.2.8 Selenium (Se)

Selenium is an important element to humans at a low concentration; however, it becomes toxic if taken in high amounts. This metal is present in groundwater in four forms such as Selenium (Se^0), Selenide (Se^{2-}), Selenite (Se_3^{2-}), and Selenate (Se_4^{2-}) (Gupta et al., 2022). In groundwater, Se occurs because of weathering and leaching of rocks, oxidation of soluble salts in soil, volcanic eruptions, selenium-bearing rocks, agricultural drainage, and discharge of wastewater containing selenium-based minerals (Guo et al., 2023). Industrial and agricultural activities are the common human sources of Se in groundwater, and Se toxicity threatens water systems. In groundwater, Se is mostly detected at low levels, and research has shown that high levels of Se in drinking water cause low blood glutathione peroxidase (Ruj et al., 2022).

2.3.2.9 Antimony (Sb)

The natural sources of Sb are water, soil, and rocks; and this metal has two major ores, which are Jamesonite ($Pb_4FeSb_6S_{14}$) and Stibnite (Sb_2S_3), and its contamination is considered a threat globally (Pradhan et al., 2023). Sb is mostly used for industrial applications, including antimony oxides being utilised as flame retardants in plastics, lead acid batteries, Polyethylene Terephthalate (PET), pump sealants, and medications (Nishad & Bhaskarapillai, 2021). The Sb groundwater contamination occurs due to the weathering of rocks containing Sb and anthropogenic activities. Mining, smelting of wastewater, combustion of fossil fuel, and using products containing Sb also play a huge role in groundwater contamination with Sb (Tao et al., 2021). Further, the health effects of Sb are like those of arsenic, as its excessive intake causes cancer, skin problems, and neurological disorders (Hao et al., 2020).

2.3.2.10 Manganese (Mn)

Mn occurs naturally in groundwater; however, anthropogenic activities increase its concentrations. Mn in drinking water is mainly due to Mn-bearing minerals, including managnite, rhodonite, and bixbyite. The presence of this metal in groundwater is mainly due to various factors such as temperature, porosity, humidity, and acidity of soil and rocks (Zhang et al., 2020). Regardless of its common occurrence in groundwater, the risks linked with this metal are mostly unknown. Mn is a needed nutrient for the human body due to its ability to bind and regulate several enzymes within the body; however, it can be neurotoxic if ingested in excess amounts (Sharma et al., 2021); and its prolonged exposure can lead to neurodegenerative disorder and affect children's cognitive ability (Kullar et al., 2019) and damages the reproductive system (Bodrud-Doza et al., 2020). According to WHO (2017) Mn level of < 0.05 mg/L has no effects; however, levels between 0.20 and 0.15 mg/L cause critical stains and taste problems.

2.3.2.11 Lead (Pb)

Pb is known as a harmful element that harms the biological system. This metal induces neurological, respiratory, urinary, and cardiovascular disorders due to changes in the human body's immune system and inflammatory mechanisms (Kannan et al., 2021). Pb can cause fetal tissue damage, anxiety, fever, nerve damage, abdominal pains, high blood pressure, lung, kidney, and liver damage, stomach cancer, and anemia (Saleh et al., 2018). In addition, high levels of Pb can cause miscarriage, delayed development, and low weight during birth (Raza et al., 2017). Exposure to high levels of Pb can also cause kidney and brain damage, specifically in males (Ahamed et al., 2019), whereas <0.05 mg/L causes a slight risk of behavioral changes and neurological impairment in the fetus and young children developing their brain tissues (WHO, 2017). Further, according to Saleh et al (2018), exposure to Pb

causes high blood pressure in older and middle-aged groups. Pb's occurrence in groundwater results from anthropogenic activities such as household painting, vehicle exhaust, and industrial waste. WHO (2023) has reported that Pb is primarily used in the production of lead batteries, solder, and alloys.

2.3.2.12 Iron (Fe)

Fe is the foremost important element in the Earth's surface, and groundwater is easily contaminated with it. The presence of iron in groundwater is due to the discharge of wastewater with Fe into the water resources, Fe-rich minerals including hematite, goethite, and weathering of Fe-containing sedimentary rocks (Zhang et al., 2020). The presence of Fe in groundwater at an elevated concentration makes the water unsuitable for drinking since its presence in water gives the water a reddish colour, high turbidity, metallic taste, and bad odour (Sukmilin & Sangsirimongkolying, 2021). High levels of Fe in water (>0.3 mg/L) affect taste in humans and cause stains on white clothes if used for laundry purposes (Edokpayi et al., 2018b). High intake of Fe causes a severe disease that can destroy various human body organ's 'hemochromatosis'. It further causes fatigue, weight loss, and joint pains (Ahmed et al., 2020). Fe is an important element for normal physiology in the human body, and acts as a catalyst; however, its excessive intake causes health problems such as cancer, liver and heart diseases, and diabetes (Raza et al., 2017). Edokpayi et al. (2018b) conducted a study in Muledane village, Thohoyandou, which reported high levels of Fe due to the leaching of Fe from sewer pipes and other non-point sources such as metal disposing, municipal landfills, and storm runoff.

2.3.2.13 Aluminium (Al)

Drinking water is one of the primary sources of Al exposure to humans, as Al is more bioavailable in water (Farhat & Ali, 2020). This metal can easily be absorbed from drinking water by the gastrointestinal tract (Farhat & Ali, 2020). They further reported that when the pH of the groundwater increases or decreases, the solubility of Al increases considerably. In addition, they reported that acid rain decreases the water pH and thus results in Al mobilisation from the environment, causing a rise in human exposure to Al. High levels of Al in groundwater can cause impairment in bone metabolism, renal failure, anemia, cholestasis, and neurological disorders such as Alzheimer's disease, dialysis dementia, Parkinson's disease, and multiple sclerosis (Ahamed et al., 2019). A high level of Aluminium impacts the taste of water and affects its aesthetic properties (Mutileni et al., 2023).

2.4 Methods of evaluating heavy metals in groundwater

2.4.1 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)

ICP-OES is mostly used to analyse metals and metalloids due to its ability to provide precise and multi-elemental detection. This technique is vital for environmental monitoring as it can detect the toxicity of heavy metals like Pb, Hg, and Cd in soil, water, and air samples; as these metals can cause hazardous environmental and health effects, and their regulation by WHO and Environmental Protection Agency (EPA) requires the use ICP-OES (Bhalodia and Desai, 2025). They further reported that ICP-OES is known to be environmentally friendly as it generates low chemical waste and consumes less reagent volume, which reduces both costs and environmental effects. This instrument has several benefits, including its ability to handle multifaceted matrices and adapt to various sample types ranging from biological to industrial discharges. The instrument's ability to perform multi-component analysis in a single run reduces chemical effects intensity and its sustainability (Muller et al., 2017).

ICP-OES operates by heating a sample in a hot plasma (7000-10,000 K), and this excites the atoms. When the excited electrons return to their normal state, they give off light at a specified wavelength that is unique to each element. By measuring the light's brightness, the amount of each element in the sample can be determined (Morrison et al., 2020). This instrument operates around three main components: a system to introduce samples, the plasma source, and the optical spectrometer. With the sample introduction stage, samples are introduced in a liquid form and ensured for their suitability for nebulisation (Muller et al., 2017). Secondly, plasma is sustained using a radio-frequency field that operates at 27 MHz. In this stage, Argon is utilised to form and maintain plasma. It is therefore at this stage that the atoms are excited as the sample passes through the plasma. At the last stage, as atoms return to their ground state, they release energy in the form of light. The light formed is collected and separated into various wavelengths by a spectrometer (Billiard et al., 2020).

Limitations of ICP-OES (Bhalodia & Desai, 2025)

- These instruments are expensive for purchase and maintenance, including their consumables such as Argon, leading to less accessibility to smaller laboratories
- ICP-OES has limited detection limits for particular elements, unlike other instruments like Inductively Coupled Plasma- Mass Spectrometry (ICP-MS)
- It has complex sample preparation as solid samples need digestion before analysis, which is time-consuming
- This instrument consumes more amounts of argon gas and electricity, therefore contributing to higher costs and environmental impact

2.5 Effects of Anions on Water

2.5.1 Nitrate

Nitrate is originally from different geogenic and non-geological activities and is highly percolated into aquifer systems (Kaliyappan et al., 2022). Nitrate is identified as the major pollutant of groundwater sources due to extensive irrigation (Elumalai et al., 2020). Herein, the pollutants released from various land-use activities are carried out by water which filters through the soil, combines with tiny rocks, and weathered materials before they reach the saturated zone (Busico et al., 2017).

Low precipitation, infiltration of leachates from waste disposals, and high evaporation influence water salinity and increase nitrate toxicity in groundwater (Panneerselvam et al., 2023). Nitrate in water can also occur through the nitrogen cycle and because of human activities (Popoola et al., 2019). Nitrate is one of the most well-known groundwater pollutants, a threat to human health, and it can easily percolate through the soil to the groundwater. Hence, various studies (Elumalai et al., 2020; Iqbal et al., 2023; Karunanidhi et al., 2024) have reported high nitrate concentration in groundwater. The heavy use of nitrogenous fertilisers degrades the groundwater quality as it causes nitrate contamination in agricultural areas (Edokpayi et al., 2018a). Nitrate formation in water bodies is also through the oxidation of ammonium and nitrogen compounds found in wastewater. According to Soceanu and colleagues (2021), high concentrations of nitrate levels in groundwater are due to the washing of naturally occurring nitrate in surface soil and fertilisers by rainwater.

An increase in nitrate content in groundwater is a common and growing concern globally. Nitrate-containing groundwater discharge to water bodies can cause eutrophication, influencing excessive algal bloom, which leads to the depletion of dissolved oxygen in water, plant growth, and degradation of aquatic ecosystems and water resources, and harms socio-economic spheres (Edokpayi et al., 2017; Romanelli et al., 2020). In addition, this causes odour to the water and affects its aesthetic value (Iqbal et al., 2023). Ward et al. (2018) outlined that diseases such as colorectal cancer and congenital disabilities are a result of exposure to high concentration levels of nitrate. The consumption of groundwater with high concentrations of nitrate can reduce oxygen-carrying capacity, which results in health problems such as methemoglobinemia (baby-blue syndrome), especially for infants less than six months old (Karunanidhi et al., 2024), and could cause mucous membrane irritation in adults (Edokpayi et al., 2018b), neural tube defects, miscarriage, leukemia, typhoid disorders, and cancers (Ward et al., 2018).

Yu et al. (2020) reported that high intake of nitrate causes thyroid dysfunction and gastrointestinal cancer. A study by Gao et al. (2020) has shown that the large nitrate intake by women affects their offspring as it causes defects in babies. Ingesting nitrate in drinking water also causes “Sclerosis, non-

Hodgkin lymphoma, and thyroid gland hypertrophy, hypertension, severe diabetes, and genotoxic effects on the chromosomal level (Karunanidhi et al. 2024)”.

2.5.2 Fluoride

The presence of Fluoride in groundwater originates from the leaching of minerals under certain physical and chemical conditions (Wang et al., 2021). The commonly known minerals are fluorite and fluorapatite (Subba Rao et al., 2017), and a high concentration of Fluoride is found in most provinces in South Africa (Bretzler et al., 2017). Fluoride has two impacts: it can cause health effects if it is insufficient, and excessive. Fluoride is normally vital for human health and the formation of teeth’s protective layer; however, its insufficiency or excessive amounts can cause harmful effects. Fluoride concentrations within the WHO, DWS, and SANS set limit (1.5 mg/L) are important for the prevention of dental caries (Raza et al., 2017). Exposure to consuming water with elevated concentrations of Fluoride causes fluorosis, ranging from mild dental mottling to a crippling skeletal form (Subba Rao et al., 2020). Further, high concentrations of Fluoride in groundwater cause bone softening, deformation problems, back and joint pain, and spinal problems (Onipe te al., 2020). Approximately, 220 million people worldwide depend on groundwater with Fluoride concentration above the WHO-recommended value of 1.5 mg/L (Zhang et al., 2023).

2.5.3 Sulphate

Sulphate naturally occurs in water because of leaching from a sheetrock and other mineral deposits. Industrial and domestic waste often increases its concentration (WHO, 2017). The presence of Sulphate in groundwater is mainly due to metallic sulphides and rocks crossed by the water (Mutileni et al., 2023). Sulphate is considered a non-toxic anion; however, its high concentration causes diseases such as gastrointestinal irritation and dehydration. Diseases such as diarrhoea are associated with the use of water contaminated with elevated concentrations of Sulphate (Mutileni et al., 2023). The presence of sulphate in drinking water is mostly characterised by taste, especially when the concentration is > 250 mg/L (WHO, 2017), resulting in an unpleasant taste for consumption. Further, the consumption of groundwater with high levels of sulphate can cause respiratory problems in human beings (Park et al., 2018).

2.5.4 Phosphate

Phosphate is one of the primary elements that are essential for the growth of plants; therefore, phosphatic fertilisers release various forms of phosphates such as H_2PO_4^- , HPO_4^{2-} , and PO_4^{3-} into the soil (Rout et al., 2017). These phosphates are soluble and excessive; therefore, the phosphate amount not absorbed by the plants contaminates the groundwater through point sources (industrial discharges,

wastewater treatment effluents) and non-point sources (agricultural runoff, weathering of phosphate rocks, erosion, and sedimentation) (Rout et al., 2017). The presence of Phosphate in groundwater is due to leaching and runoff from phosphate fertiliser fields when used in high amounts (Raza et al., 2017). Vorland et al. (2017) reported that excessive use of phosphate can cause kidney damage and Osteoporosis. An accumulation of phosphate in water bodies leads to the growth of algae and cyanobacteria that affect human health (Pradhan et al., 2023). Further, excessive intake of phosphate can impact the balance of macro and micronutrients in the human body, and this can cause kidney diseases and cardiovascular problems (Bird& Eskin, 2021).

2.5.5 Chloride

Chloride is a fundamental ion present in almost all natural groundwater resources because of its stability. Natural and anthropogenic sources are chloride sources in groundwater, such as agricultural run-off, inorganic fertilisers, and animal feedstock. An elevated concentration of chloride in water changes its taste (Maluleke et al., 2025) and can cause kidney stones (Kumar et al., 2024). Chloride is mainly obtained through the dissolution of hydrochloric salts such as sodium chloride (Mutileni et al., 2023), and groundwater sources primarily acquire larger amounts of chloride than surface water sources. This ion plays a huge role in the human body during the metabolism process as it breaks down the structures (Kiwanuka et al., 2023). It further destroys the metallic pipes and is an indicator of pollution (Kiwanuka et al., 2023; & Mkadmi et al., 2018).

2.6 Method of evaluating anions in groundwater

2.6.1 Discrete Analyser

The Discrete analyser runs using a direct read measuring component consisting of a dual-beam and high-resolution digital detector. This instrument has a robotic sampling arm with a syringe powered by a motor that mixes small amounts of samples and reagents into tiny test tubes (cuvettes). Within these tubes, samples and reagents are incubated at 37°C for a certain period (Dikobe et al., 2024). The incubation period is computed to quicken the chemical reaction and minimise the time needed to reach the endpoint of colorimetric absorbance. After the incubation process, a liquot is transferred onto a glass tube, measuring absorbance and maximising the signal-to-noise ratio for better analytical performances (Dikobe et al., 2024).

Limitations of using the method (Dikobe et al., 2024)

- The instrument is unsuitable for high suspended solids without prior filtration

2.7 Microbial contamination

Groundwater has a good microbial quality in its natural state; therefore, it is mostly preferred as the source of drinking water supply because it looks clean and is acceptable to many people as it is free from odor and sometimes has a pleasant taste (Edokpayi et al., 2018a); however, groundwater looking clean does not mean it is free from contamination. Untreated water sources are most likely to be exposed to microbial contamination (Santos et al., 2023). The groundwater quality and microbial safety are determined by fecal and total coliform in drinking water, as they indicate the presence of diseases that cause diseases and pathogens (Raza et al., 2017). WHO and SANS 241 set the standard limit for the quality of water acceptable for human consumption, which of the standards no coliform bacteria should be detected. (Santos et al., 2023). Microbial-contaminated water is one of the major causes of intestinal dysfunction, making it crucial to monitor the microbial quality of water for human consumption (Uprety, 2020). Spring water sources are more vulnerable to microbial contamination compared to other sources (Agrizzi et al., 2018).

Luvhimbi et al. (2022) reported that the presence of microbial contaminants in water from the water source to the point of use results from using dirty water collection containers and poor storage. Agensi et al. (2019) further reported that the water purification methods employed in households, water storage type, number of days the water is stored, lack of knowledge, and poor hygiene are linked to the level of contaminants in households. Total coliform and *E. coli* are bacteria that settle in the lower intestine of warm-blooded animals, and the detection of *E. coli* in drinking water indicates the existence of pathogens. *E. coli* and Total coliform above the recommended limits cause diseases such as dysentery, cholera, etc (Ibrahim, 2019).

2.8 Method of determining microbial contaminants in groundwater

2.8.1 Membrane Filtration

Kemper et al. (2023) reported that International Standards Organisation 9308-1:2014 (ISO) outlined the membrane filtration and colony count procedure that employs Chromogenic Coliform Agar (CCA) specific for coliforms and *E. coli*. This approach involves incubating coliform at 36°C to promote its growth. Nevertheless, this temperature mostly results in low selectivity, leading to non-specific bacterial growth in samples with more microbial content (Jozic et al., 2018). Jozic et al. (2018) conducted a study that assessed the modification of the ISO 9308-1:2014 by introducing an increased incubation temperature of 44°C. This study's modification showed sufficient sensitivity and efficacy as higher temperatures inhibited the growth of non-specific coliforms and promoted the method's selectivity.

Limitations of the method (Kemper et al., 2023)

- Low sensitivity of CCA at the incubation temperature allows the growth of non-specific coliform
- High microbial content in water interferes with the results
- Overgrowth of non-specific coliforms can affect the enumeration of coliforms and *E. coli*

2.9 Health effects of consuming contaminated water

Waterborne diseases are transmitted through water contaminated by bacteria, viruses, and parasites, which are eliminated through the faeces of an infected individual or animals (Santos et al., 2023). The most common route to transmit the disease is through the oral route, where pathogens are ingested with water, pass through the gastrointestinal tract, and are expelled through faeces (Rios-Tobon et al., 2017). Many South African villagers continue to use untreated water for domestic use and are at risk of being contaminated with the effects of diseases such as diarrhoea (Edokpayi et al., 2018b).

According to WHO (2023), about 88% of diarrheal diseases result from consuming contaminated water. Furthermore, the pollutants and water disinfection by-products are linked with long-term health problems for people in developing and developed countries (Sirvasta et al., 2020). The WHO report shows that due to waterborne diseases (cancer, typhoid, hepatitis, cholera, diarrhoea, etc), many children below the age of five in developing countries are affected by drinking polluted water since the mixture of various biological contaminants causes multiple infectious diseases. In South Africa, diarrhoea is one of the causes of death among many young children. The health risks associated with consuming contaminated water are not only related to infectious diseases, but also heavy metals and ions such as fluoride, Arsenic, Lead, Cadmium, Mercury, and Nitrate (Edokpayi et al., 2018a). Excessive consumption of water with these metals can lead to cancer, dental and skeletal fluorosis, memory lapses, renal failure, etc. (Lin et al., 2022).

Diseases, including vomiting, headaches, dizziness, short breath, muscle weakening, skin rashes, and urinary tract burning sensation, are a result of consuming pesticide-contaminated water (Lin et al., 2022). Groundwater contamination by heavy metals is a serious threat to human health as it results in carcinogenic effects and toxicity (Shakerkhatibi et al., 2019). The consumption of contaminated water causes several diseases, leading to carcinogenic and non-carcinogenic risks to the human body (Shukla & Saxena, 2021). The consumption of this water leads to serious problems for humans and other living organisms.

2.10 Water purification methods

Many people in urban areas are becoming educated about the consumption of contaminated water and its consequences; however, in rural areas, there is always a risk of using untreated water. People from rural areas have adopted household water purification strategies since they cannot afford the conventional ones, including storage and settlement, boiling and filtration, bleaching, chlorination, sunlight exposure (Ihsan & Derosya, 2024), and chlorination (Tyhali & Forbes, 2023). The majority of people from rural areas rely mostly on boiling water using wood as the primary source of fuel. However, this method plays a role in causing indoor pollution, which can cause respiratory concerns within the household (Raju et al., 2020). Some of the water treatment plants adopt chlorination due to their capability to reduce high levels of disinfection by-products such as haloacetic acids (HAA) and Trihalomethanes (THMs) (Tyhali & Forbes, 2023). However, various disinfection products can show mutagenic and carcinogenic effects on human and animal organisms (Ihsan & Derosya, 2024). Tyhali & Forbes (2023) reported that chlorination is the most used water purification strategy based on various literature.

2.10.1 Chlorine Tablets

The use of chlorine tablets is common in disinfecting raw water; however, it is recommended to use these tablets in pipes instead of storage tanks, as this is done to ensure effective pathogen killing. This is due to the ability of chlorine tablets to settle at the bottom of storage tanks after reacting with organic materials. (Ihsan & Devsya, 2024). Chlorine is quick to kill microorganisms, which are the primary source of waterborne diseases. This method is useful in treating huge amounts of drinking water. The use of chlorine tablets has one huge advantage: it leaves a small amount of chlorine in water, which continues to protect water from contamination. This residual aids with the introduction of new pathogens in water (Nambi Kathu, 2025). Kumar (2021) further reports that the use of chlorine tablets is cheap, reliable, and easy to handle, and can provide residual disinfecting effects for extended periods. However, excessive amounts of it cause an unpleasant and bitter taste.

2.10.2 Plasma Technology

Plasma technology is an emerging and effective water treatment method amongst other Advanced Oxidation Processes (AOPs), which addresses water treatment challenges (Zeghioud et al., 2020). This technology is non-thermal and operates at room temperature and atmospheric pressure, which makes it easier to be eco-friendly and cost-effective. It also reacts with various species such as Ozone, hydrogen peroxide, hydroxyl radicals, and others, of which all interact with water molecules to break down pollutants (Lervolini et al., 2019). Moreover, Zeighioud et al. (2020) reported that, unlike other AOPs, plasma technology does not require UV lamps to produce reactive species, and it also emits

light and creates shockwaves during the treatment process. This technology has then proven to be effective in removing toxic substances and microorganisms from water.

2.10.3 Ceramic Filter

According to Yusuf et al. (2023), a ceramic filter is a simplified water purification method that can be easily employed at a household level. They further point out that this method does not require electricity or any machine to operate, hence it can easily be utilised in rural areas. Aliyu et al. (2019) mentioned that the ceramic filter is made from clay and sawdust, and these materials are available in rural areas. Ceramic filters are effective in eliminating microorganisms, making them one of the best options to remove bacteria and viruses, and they can also be used to cool water through the evaporation process (Ihsan & Devsya, 2024). Ceramic filters are efficient in removing turbidity by 83 to 99%, 90% of Fe, and can also remove bacteria from water by 98 to 100%. Therefore, this purification method makes water safe for drinking (Yusuf et al., 2023).

2.10.4 Boiling

The tradition of boiling water is amongst the simplest, oldest, and most effective methods to treat drinking water (Malan & Sharma, 2023). Boiling drinking water at 100 °C for over a minute effectively destroys over 99.99% of waterborne bacteria such as Cholerae, Salmonella typhi, and Hepatitis A present in water (Liu et al., 2020). From a global perspective, UNICEF recognises the boiling method as an important step for the household water treatment framework, most especially in areas lacking main treatment infrastructures. The boiling method removes different hazardous elements such as Fe, turbidity, taste, odour, and bacteria. This method ensures water is safe from microorganisms (Nambi Kathu, 2025). According to Nair et al. (2023), boiling is an effective method, but it poses serious health risks due to indoor pollution, greenhouse gas emissions, and smoke. It was further reported that boiling water is prone to recontamination as it is normally cooled in open containers, which allow access of more microorganisms (Gartner et al., 2021)

2.10.5 Bleach (Sodium Hypochlorite)

Bleach is also known as liquid chlorine, which is used as a disinfectant during the water purification process. Bleach is used to purify drinking water, and it targets bacteria, including *E. coli* and cyanotoxins present in water as a result of fecal contamination (Mokoena et al., 2021). Bleach is recommended for the treatment of water due to its costs and ability to kill waterborne pathogens; however, its dose should not exceed the recommended amount as it can impart health effects to water consumers (Sibisi et al., 2020). It is recommended by Srivasta et al (2020) that before using bleach

to purify water, consumers should adjust the pH of water using activated carbon filters to eliminate by-products and improve odour and taste

2.11 Water Quality Index (WQI)

The Water Quality Index is a crucial model for assessing and classifying water, and several studies have primarily focused on WQI as a modeling framework for evaluating groundwater suitability for consumption and irrigation purposes (Udeshani et al., 2020). WQI presents huge quantities of water quality data into a single number. This model is a useful estimation method for groundwater quality. It is considered the best tool to examine the parameters of water quality, such as pH, temperature, Electrical Conductivity, and Total Dissolved Solids. The safety of water consumption is linked to human health and obtaining safe potable water (Li et al., 2025). The water quality assessment reflects the safety level of drinking water (Zhou, 2024). WQI is mostly assessed by considering numerous water quality parameters and their weights. This involves “constructing a water quality indicator system, computing the indicator risk coefficient, calculating the indicator sub-index, and transforming WQI and its weight to obtain the indices of drinking water quality” (Li et al., 2025). WQI standards are divided into five classes: Excellent water quality (<50), Good water quality (50-100), Poor water quality (100-200), very poor water quality (200-300), and unsuitable for drinking (>300) (Madilonga et al., 2021) (see Table 3.2).

2.12 Human Health Risk Assessment (HHRA)

Groundwater quality is closely linked to human health; therefore, excessive intake of heavy metal concentrations in groundwater can pose severe health risks to humans (Durowoju et al., 2020). The United States Environmental Protection Agency explains HHRA as the process for nature and probability estimation of severe health effects in human beings who could be exposed to metals present in a contaminated environment (USEPA, 2004). This model involves the identification of potential risk sources to introduce risk factors into the environment, estimating the number of risk factors that encounter humans, and quantifying the health effects of exposure (Durowoju et al., 2020). Four steps are involved in the fulfillment of the HHRA, and these include hazard identification, dose-response assessment, exposure assessment, and risk characterisation (Madilonga et al., 2021). According to Madilonga et al. (2021), direct ingestion is regarded as the primary exposure to chemical contaminants in drinking water.

The HHRA model evaluates the possibilities of severe health effects by considering exposure pathways such as direct ingestion, dermal contact, and inhalation. This model assesses certain contaminants in water, specifically heavy metals, and their impacts on human health (Latif et al., 2025). The HHRA model utilises the USEPA guidelines to evaluate parameters such as Hazard

Quotient (HQ), Hazard Index (HI), Chronic Daily Intake (CDI), and Carcinogenic Risks (CR). Further, these computations are employed to evaluate the pollutant intake rate in the human body via the oral consumption of drinking water (Badeenezhad et al., 2023).

2.13 Quantitative Microbial Risk Assessment (QMRA)

QMRA is a statistical model that is used to give a quantitative estimation of health risks associated with pathogens in the water systems (Pettersen et al., 2021). Ryan et al. (2022) further reported that QMRA evaluates the public health risks (infection and illness) following exposure to doses of available pathogens. They further reported the limitation of this model as its ability to rely on primary data collection and assumptions from existing literature. Moreover, it was reported by Ryan et al. (2022) that this tool helps with mapping out the pathways by which the pathogens enter water and are transferred to drinking water sources, allowing risk factors to be identified. The outcome of QMRA allows the monitoring of concentrations of pathogens and keeping their load at safe levels (Amatobi & Agunwamba, 2022). WHO (2023) emphasises the mitigation methods of microbial hazards in the water supply; thus, the QMRA model is considered the best tool to identify these hazards, analyse their vulnerabilities, and estimate their associated health risks. This tool mainly focuses on understanding the microbial outbreaks and health effects of the new pathogens (Amatobi & Agunwamba, 2022).

2.14 Guidelines for drinking water quality for SANS 241 and WHO

The World Health Organisation and South African National Standards 241 have set out the drinking water quality standards limits (Table 2.1).

Table 2.1: Recommended standard limits of WHO and SANS 241 for safe drinking water.

Parameters	WHO	SANS 241
Temperature (°C)	-	-
Conductivity (at 25 °C)	-	≤1700
Total Dissolved Solids (mg/l)	-	≤1200
Turbidity (NTU)	≤5	≤5
pH (at 25 °C)	≥6.5 to ≤8.5	≥5 to ≤9.7
Nitrate	≤50	≤11
Nitrite	≤3	≤0.9
Sulphate	-	≤250
Phosphate	-	-
Fluoride	≤1.5	≤1.5
Chloride	≤250	≤300
Zinc	-	≤5
Arsenic	≤0.01	≤0.01
Cadmium	≤0.003	≤0.003
Chromium	≤0.05	≤0.05
Copper	≤2	≤2
Iron	-	≤2
Lead	≤0.01	≤0.01
Manganese	-	≤0.1
Mercury	≤0.006	≤0.006
Nickel	≤0.07	≤0.07
Aluminium	-	≤0.3
Antimony	≤0.02	≤0.02
Selenium	≤0.04	≤0.04
<i>E. coli</i> or Faecal Coliform) (CFU/100 mL)	Not Detected	Not Detected
Total Coliforms (CFU/100 mL)	-	≤10

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of the study areas

The study was conducted in three villages spanning Matsa, Mamvuka, and Manyii, situated at Nzhelele in the Vhembe district within the Limpopo Province. Vhembe district comprises four local municipalities, namely: Collins Chabane, Makhado, Musina, and Thulamela, and these villages are in the Makhado municipality. The study areas are in the Savannah biome, which has low-veld bushveld vegetation. They have wet and hot summers and dry and cool winters and receive high rainfall in the summer seasons (September to March). Figure 3.1 below illustrates the map of the study area and sampling points in the Vhembe District. Table 3.1 includes attributes, geographic locations, sampling depth, and activities practiced in each village.

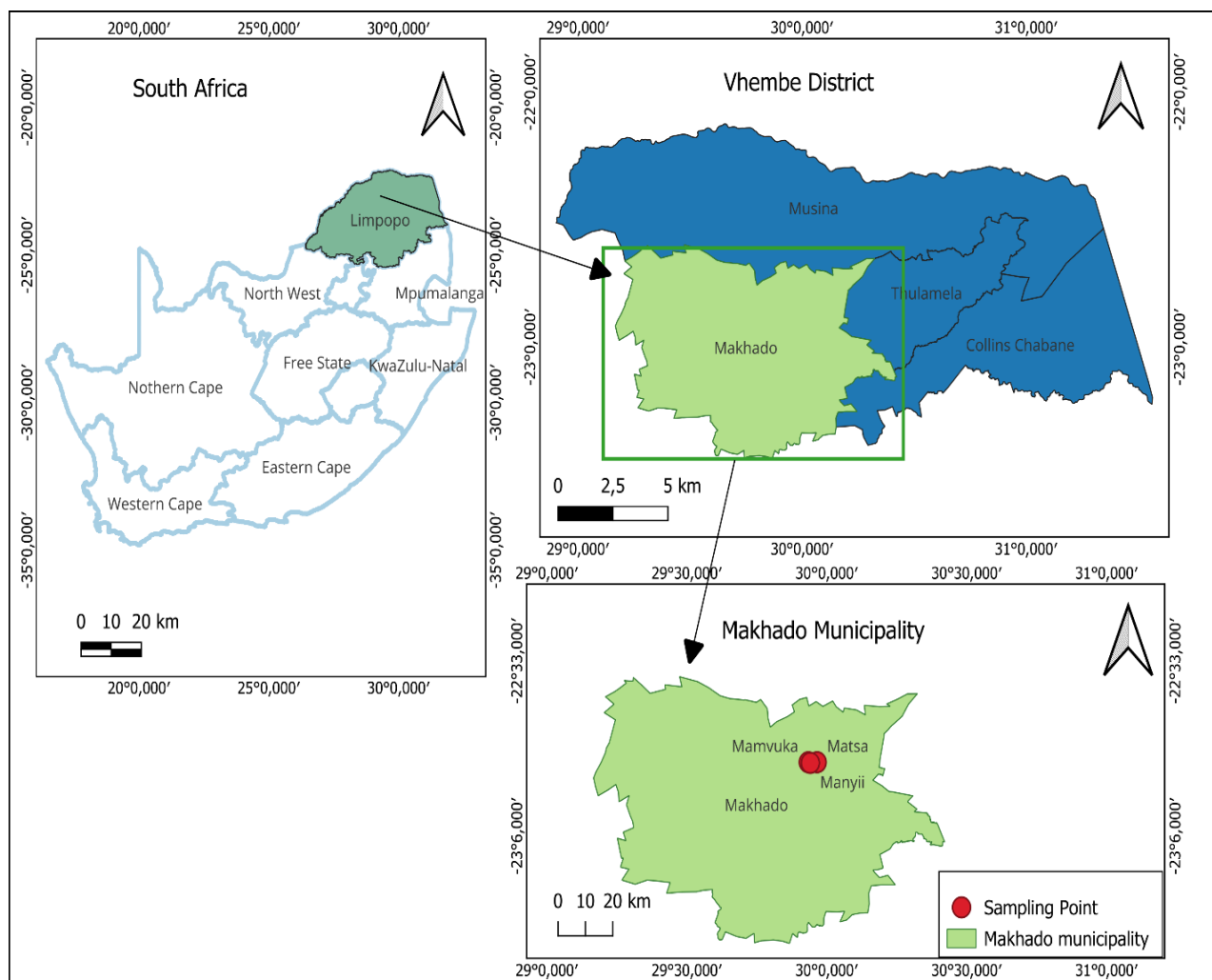


Figure 3.1: Map of the study area and sampling points in the Vhembe District

Table 3.1: Demographic, land use, climate information, and sampling depth of the study areas (Census, 2011)

Attributes	Matsa	Mamvuka	Manyii
Latitude and Longitude	22°87'15''S, 29°96'57'' E	22° 86' 42'' S, 29° 93' 46'' E	22° 87' 16'' S, 29° 94' 33'' E
Average temperature (°C)	31°C	31°C	31°C
Population size	2670	2877	1954
Activities practiced	Agriculture	Agriculture	Agriculture
Sampling depth	Approximately 30 cm	Approximately 30 cm	Approximately 30 cm

3.2 Sampling Methods

3.2.1 Sample Collection and Preservation

Sampling was conducted four times in 2024 based on two seasons (wet and dry), and water samples were collected from the springs and households in Matsa, Mamvuka, and Manyii villages. The dry season sampling was carried out between July to August 2024, while the wet season sampling was collected in September and November 2024. The samples were collected once each month on the same day. Samples were collected using 1 L sterile polyethylene plastic bottles, which were washed with water to be sampled. A total of 48 samples were collected from these communities from the source and the point of use. Samples were transported to the laboratory after collection in an ice chest for further analysis. Data about the water quality, health concerns, and purification methods were collected from the households by conducting interviews using a questionnaire.

3.3 Sample Preparation

3.3.1 Heavy metals and anions

The 65% concentrated nitric acid (5 mL) was added to 45 mL of the water sample in a microwave digestion vessel. The samples were placed in a microwave digester (Mars One) for the digestion process. The solution was digested at 180°C for 15 minutes and cooled. The samples were filtered with a 0.22 µm syringe filter for the analysis of the anions (Edokpayi et al., 2021).

3.4 Sample Analysis

3.4.1 Physicochemical Parameters Analysis

The field measurements of physicochemical parameters such as pH, EC, temperature, and TDS were measured in triplicate using the 7-in-1 water quality testing meter (Hanna Instruments, Italy), and after each measurement, the water quality meter was rinsed with deionised water to avoid cross-contamination. Turbidity was measured using the turbidimeter (Thermo Scientific Eutech TN-100). The water samples were transferred into a turbidity cell that was pre-cleaned with de-ionised water for calibration purposes. The turbidimeter was calibrated as stipulated in the manufacturer's protocol.

3.4.2 Heavy Metal Analysis

The samples were analysed at an independent laboratory where analysis of heavy metals such as As, Ni, Hg, Zn, Cd, Cu, Cr, Se, Sb, Mn, Al, Fe, and Pb was performed with an Inductively Coupled Plasma Optical Emission Spectrometer (Agilent 5800 VDV ICP-OES, 2024, Agilent Technologies).

3.4.3 Anion Analysis

A Discrete analyser (AMS SmartChem® 600 Discrete Analyser, 2024) was used to analyse the concentrations of anions such as F⁻, Cl⁻, NO₂⁻, NO₃⁻, PO₄³⁻, and SO₄²⁻ at an independent laboratory.

3.4.4 Microbial Analysis

Samples were immediately analysed after collection to test for the total coliforms and faecal contaminants (*Escherichia coli*) present in the water for both the source and households using the vacuum membrane filtration method. Multiple sample cups were sterilised in a hot water bath at 100°C for 15 minutes. Further, the Millipore membrane filters (47 mm diameter and 0.45 µm pore size) from EMD Millipore, Billerica, MA, USA, were placed on the surface of the multiple sample cups (Edokpayi et al., 2021) with the use of forceps. Two dilutions were tested: 1 mL of the sample with 99 mL of deionised water, and 10 mL of the sample with 90 mL of deionised water were passed through the membrane filters. The filter paper was put in a sterile petri dish with an absorbent pad (47 mm diameter) with 2 mL (2×10⁻⁶ m³) of m-ColiBlue24 (EMD Millipore, Billerica, MA, USA). The samples were later incubated aerobically at 35°C for 24-48 hours each. Colony Forming Units (CFU/100 mL) were counted, and the dilution count was used. Blue-forming colonies were taken to be *E. coli*, whereas the red colour was taken to be other coliforms. The total coliforms counted were the summation of the blue and red colonies (Hach, 2018). The colony-forming unit was calculated using the equation:

$$CFU \text{ per } 100 \text{ mL} = \frac{\text{number of colonies} \times \text{dilution factor}}{\text{Volume}} \quad (3.1)$$

3.5 Water Quality Index

A water quality assessment was done to evaluate the risks associated with drinking groundwater in the study areas and check if the water is of high quality and suitable for consumption according to the WHO and SANS standards. The WQI was done in the following steps: firstly, each parameter was given weight based on its importance in the quality of water for consumption purposes. A maximum weight of 5 was given to a parameter of major importance in the water quality assessment, and a minimum weight of 1 was given to the parameters that are seen as unimportant to the overall water quality. Further, other parameters were given weights between 1 to 5 based on their importance in the water quality evaluation (SANS 241, 2015). The following formulae were used to calculate the Water Quality Index:

$$W_i = \frac{w_i}{\sum_{i=1}^n w_i} \quad (3.2)$$

Where, W_i is the relative weight, w_i is the weight for each selected parameter, and n is the number of parameters

$$q_i = \frac{C_i}{S_i} \times 100 \quad (3.3)$$

Where, q_i is the quality rating, C_i is the concentration of each parameter in each water sample in mg/L, and S_i is the recommended standard for each parameter as specified by SANS 241 and WHO in mg/L.

$$WQI = \sum_{i=1}^n W_i \times q_i \quad (3.4)$$

Table 3.2: WQI classification and rating (Madilonga et al., 2021)

WQI class	WQI rating
Excellent	<50
Good	50-100
Poor	100-200
Very poor	200-300
Unsuitable for drinking	>300

3.6 Human Health Risk Assessment

The communities of Matsa, Mamvuka, and Manyii depend on groundwater for consumption, and groundwater usage poses health risks to human health, primarily via skin contact and drinking. A health risk assessment analyses the harmful impact of environmental chemicals on humans. Therefore, this study calculated the groundwater contamination risks and analysed the children's and adults' health risks. The heavy metals were considered, and the assessment models and standards of the U.S Environmental Protection Agency (USEPA) were followed.

(i) Human exposure dose of heavy metals

The exposure risk pathways of humans to heavy metal contamination can be via three procedures such as inhaling contaminants through the mouth and nose, dermal absorption through skin exposure, and direct ingestion. Therefore, the most known exposures to water are direct ingestion and dermal absorption (Edokpayi et al., 2018a). The Exposure dose was calculated as follows (equations adopted from Edokpayi et al., 2018a):

$$Exp(ing) = \frac{C_{water} \times IR \times EF \times ED}{BW \times AT} \quad (3.5)$$

$$Exp(derm) = \frac{(C_{water} \times SA \times KP \times ET \times EF \times ED \times CF)}{(BW \times AT)} \quad (3.6)$$

Where, $Exp(ing)$ is the exposure dose via direct ingestion (mg/kg/day), C_{water} is the average concentration of heavy metal in water (mg/L), IR is the ingestion rate (2.2 L/day for adults, 1.8 L/day for children), EF is the exposure frequency (365 days/year), ED is the exposure duration (70 years for adult, and 6 years for children), BW is the average body weight (70 kg for adults, and 15 kg for children), AT is the average exposure time (365 days/year \times 70 years for adults, and 365 days/year \times 6 years for children). $Exp(derm)$ is the exposure dose via dermal absorption (mg/kg/day), SA is the skin area exposure (18 000 cm² for adults and 6 600 cm² for children), ET is the exposure time (0.58 hr/day for adult, and 1hr/day for children), CF is the conversion factor as 0.001, K_p shows dermal absorption(cm/h) considered as 0.001 for Cu, Fe, Mn, Cd, Al, Se, Sb, Hg, and As while 0.0006 for Zn, 0.002 for Cr, 0.0001 for Pb, and 0.0002 for Ni (Edokpayi et al., 2018a).

(ii) Non-carcinogenic risk assessment for human exposure to heavy metals

The non-carcinogenic risks for human exposure to heavy metals were established by comparing the computed contaminant exposures for dermal and ingestion routes with the RfD (USEPA, 2004) (see Table 3.1). The non-carcinogenic health risk assessment was calculated as follows:

$$HQ\left(\frac{ing}{derm}\right) = \frac{Exp_{ing/derm}}{RfD_{ing/derm}} \quad (3.7)$$

$$HI = \sum_{i=1}^n = (HQ_{ingestion} + HQ_{dermal}) \quad (3.8)$$

Where, $HQ_{ing/derm}$ is the hazard quotient, and $RfD_{ing/derm}$ is the ingestion/dermal reference dose (mg/kg/day). The RfD_{ing} and RfD_{derm} values were adopted from (USEPA,2004; & Bamuwanye et al., 2017) (Table 3.3). HI is the total hazard index presented by direct ingestion and dermal contact, and $HI < 1$ indicates safe for the population group; > 1 shows that the population group is at health risk of being exposed to contaminated groundwater.

Table 3.3: $RfDs$, SF, and average C_{water} for heavy metals during the dry and wet season

Heavy metal	RfD_{ing} (mg/kg/day)	RfD_{derm} (mg/kg/day)	SF (mg/kg/day)	C_{water} (dry season)	C_{water} (wet season)
Pb	1.40e-01	4.20e-04	8.50e-03	2.00e-03	BDL
Fe	7.00e-01	1.40e-01	-	4.63e-01	1.14e+00
Cd	5.00e-04	3.00e-05	6.10e-03	BDL	BDL
Cr	3.00e-03	8.00e-03	5.00e-01	BDL	BDL
Al	1.40e-01	2.00e-01	-	1.4e-01	3.71e-01
As	3.00e-04	1.20e-04	1.50e+00	1.0e-02	BDL
Ni	2.00e-02	8.00e-04	1.70e+00	1.2e-01	BDL
Mn	2.40e-02	9.60e-04	-	1.0e-01	1.6e-01
Zn	3.00e-01	6.00e-03	-	1.9e-01	1.5e-01
Cu	4.00e-02	8.00e-03	-	5.0e-02	1.13e-01
Se	5.00e-03	2.20e-03	-	1.0e-02	BDL
Sb	4.00e-04	8.00e-06	-	1.00e-03	BDL
Hg	3.00e-04	3.00e-04	-	1.00e-03	BDL

*BDL-Below Detection Limit

Chronic daily intake (CDI) of heavy metals via ingestion was calculated as follows:

$$CDI = C_{water} \times \frac{DI}{BW} \quad (3.9)$$

where C_{water} is the heavy metal concentration in water (mg/L), DI is the daily water intake (2.2 L/day per adult, and 1.8 L/day per child), and BW is the average body weight (70 kg per adult, and 15 kg per child).

(iii) Carcinogenic health risk of human exposure to heavy metals

Carcinogenic risk through ingestion was calculated using Equation 3.10:

$$CR_{ing} = Exp \times SF \quad (3.10)$$

Where CR_{ing} is the carcinogenic risk through ingestion, SF is the cancer slope factor. The SF of Pb, Cd, and Cr is $8.5e+00$, $6.1e+03$, and $5.0e+02$ (mg/kg/day), respectively. The USEPA cancer risk limit

is 1.0×10^{-4} – 1.0×10^{-6} , which determines a 1% chance per one million for people who consumed contaminated water with heavy metals. Hence, a carcinogenic risk higher than 1.0×10^{-4} cannot be tolerated (Rashid et al., 2023).

3.7 Quantitative Microbial Risk Assessment

The infection risk for the communities of Matsa, Mavuka, and Manyii due to the consumption of spring water was assessed using the Quantitative Microbial Risk Assessment method. This method involves four stages, which are “*hazard identification, dose-response valuation, exposure assessment, and risk characterisation*”. Hazard identification is the identification of bacteria and the nature of harmful health issues, as reported by Odiyo and colleagues (2020). For the dose-response evaluation, the *E. coli* dose was multiplied by 0.08, since Madilonga et al. (2021) have indicated that only 8% of *E. coli* detected are pathogenic. For this study, the dose of bacteria and illness probability were based on the beta-Poisson model (Equation 3.11):

$$P_{inf} = 1 - \left(1 + \frac{D}{\beta}\right)^{-\alpha} \quad (3.11)$$

P_{inf} is the infection probability, D is the average *E. coli* dose for each season and sampling point, and alpha and beta are the dose-response parameters.

For exposure assessment, it was considered that the community residents who rely on spring water for consumption were exposed for 365 days. The annual risk of infection and illness was calculated as follows:

$$P_{inf(annual)} = 1 - (1 - P_{inf})^n \quad (3.12)$$

$$P_{ill} = P_{inf(annual)} \times \left(\frac{P_d}{n}\right) \quad (3.13)$$

Where $P_{inf(annual)}$ is the annual infection probability, n is the number of days of exposure per year (365), P_{ill} is the illness probability, and P_d/n is the illness per infection probability, which is a constant value of 0.25.

3.8 Water treatment

A few methods for water purification, such as chlorine tablets, bleach, ceramic water filters, boiling, and plasma technology, were applied to test their effectiveness. For the use of chlorine tablets, 0.01 grams of chlorine tablets were poured into 500 mL of the water sample, and 30 minutes of contact time was allowed before microbial tests. For the second water treatment, a drop of bleach was poured into 500 mL of the sampled water and was also allowed 30 minutes of contact time before conducting microbial tests. Thirdly, for the boiling method, the sampled water was boiled and then allowed to

cool before running the tests, and fourthly; for the ceramic water filtration process, the water filter was first washed, and the sampled water was poured into a filter until the process was done, and it was therefore tested for the presence of microbial contaminants.

Lastly, for the plasma treatment, Manyii spring water (initial pH and temperature of 6.34 and 21.4 °C) and Mamvuka S2 spring water (initial pH and temperature of 6.92 and 23.6 °C) were used. A large amount of energy was applied to the gas, and plasma was generated. The gas was then ionised, consisting of various active species. The species from the ionised gas entered the water and formed more reactive $\cdot\text{OH}$ radicals that acted as an oxidiser for the contaminants in the water. Then the treated water was allowed to cool in the refrigerator at 4 °C and later taken to an independent laboratory for further microbial analysis.

3.9 Statistical Analysis

Independent t-tests were conducted using Microsoft Excel 2016 to assess the statistical influence of seasons affecting physicochemical, heavy metal, and anion parameters. Further, t-tests were also performed to compare the statistical effectiveness of various water treatment methods. A p-value < 0.05 and t-statistics > critical t-value were considered statistically significant. A box and Whisker graph was used to describe the distribution of anions at different sampling sites. Further, a Principal Component Analysis was used to describe the distribution of heavy metals across the sampling sites. Lastly, ECOSAR was used to test the ecological toxicity that the treatment methods have on the environment.

3.10 Ethical consideration

The University of Pretoria Research Ethics Committee granted ethical clearance (EBIT/260/2024) for this study. Permission to conduct the study was acquired from the University of Pretoria and the selected households. Participants were informed about the study, and informed consent was acquired from all. The ethical principles, such as voluntary participation, informed consent, anonymity, and confidentiality of participants, were considered during data collection, analysis, and reporting.

The following key ethical aspects were followed when conducting the study:

- The respondents were informed about the study, and consent was given by the participants before conducting the study
- The respondents were made aware that participation is voluntary, and they are allowed to withdraw at any time
- The participants were told that they are not forced to respond to any question they are not comfortable with

3.11 Quantitative data collection

A closed-ended structured interview questionnaire was used to collect data in the selected households. This method was chosen to ensure consistency of the interview and comparable responses from all the participants. The questionnaire was distributed to 15 households in the Matsa, Mamvuka, and Manyii villages, with 5 people from each village being interviewed. Adults over 18 years were randomly selected for an interview questionnaire, which included questions concerning the respondents' water use practices, hygiene practices, and their views of water quality and health. Interviews with the participants from these communities were conducted in November 2024, and participants were selected regardless of their gender. Further, people who have been residing within the communities (over 10 to 20 years) were asked to participate in the interview as they are bound to have more information regarding the water they use.

Limitations for the structured interviews:

- Time-consuming to conduct
- Responses could lack deeper knowledge
- Participants could give socially desirable responses
- The presence of the interviewer might influence the participant's responses

3.12 Quality assurance and data reliability

To ensure the accuracy and reliability of the data collected in this study, appropriate quality control measures were followed throughout the study period. The in-situ instruments were regularly calibrated, and distilled water was used to rinse the instruments, and the laboratory followed strict internal quality assurance for analysis to ensure precise and accurate results. Two replicates of each sample were taken during the microbial analysis. The questionnaires were administered to selected households, and the same version of the questionnaire was used for all the respondents. Data were reviewed and double-checked to minimise errors.

CHAPTER 4: RESULTS AND DISCUSSION

Introduction

This chapter presents the results of heavy metals, anions, physicochemical parameters, microbiological (*E. coli* and Total Coliform), water treatment, WQI, HHRA, QMRA, and questionnaire analysis.

4.1 Physicochemical parameters

Matsa Village (S1-S3)

The physicochemical results are presented in Tables 4.1 and 4.2 for both dry and wet seasons. Temperature for the spring water samples (S1) ranged from 27.6°C to 29.43°C, pH ranged from 5.8 to 5.86, EC ranged between 202-218 $\mu\text{S/m}$, TDS ranged from 103 to 107 ppm, and turbidity ranged from 0.26 to 0.35 NTU. Meanwhile, the household water samples' (S2 and S3) temperature ranged from 24.4°C to 26.7°C, pH ranged from 6.13 to 6.75, EC ranged between 208 and 916 $\mu\text{S/m}$, TDS ranged from 105 to 456 ppm, and turbidity ranged from 0.21 to 2.53 NTU. In the wet season, the spring water (S1) recorded temperature in the range of 26.23°C to 30.5°C, pH ranged from 6.02 to 6.03, EC ranged between 214 to 222 $\mu\text{S/m}$, TDS ranged from 107 to 110 ppm, and turbidity ranged from 0.2 to 0.64 NTU. For household water samples (S2 and S3), temperature ranged from 19.8°C to 26°C, pH ranged from 5.67 to 7.01, EC ranged between 92 to 222 $\mu\text{S/m}$, TDS ranged from 45 to 111 ppm, and turbidity ranged from 0.03 to 1.68 NTU (Table 4.2).

Mamvuka Village- Spring 1 (S4-S6)

For the dry season, temperature for the spring (S4) and household samples (S5 and S6) ranged from 24.27°C to 30.13°C, pH ranged from 5.34 to 6.77, EC from 92 to 103 $\mu\text{S/m}$, TDS from 47 to 52 ppm, and turbidity from 0.05 to 2.17 NTU. In the wet season, temperature ranged between 25.03°C and 29.83°C, pH from 5.53 to 6.67, EC from 95 to 121 $\mu\text{S/m}$, TDS from 47 to 62 ppm, and turbidity from 0.02 to 0.60 NTU for both the water source and households.

Mamvuka Village – Spring 2 (S7-S9)

Spring (S7) and its households (S8 and S9) during the dry season had temperatures between 23.97°C and 29.27°C, pH from 5.58 to 6.39, EC from 93 to 120 $\mu\text{S/m}$, TDS from 47 to 60 ppm, and turbidity from 0.15 to 51.09 NTU. In the wet season, temperature ranged between 22.2°C and 29.4°C, pH from 5.67 to 6.91, EC from 23 to 123 $\mu\text{S/m}$, TDS from 11 to 61 ppm, and turbidity from 0.10 to 6.53 NTU for both the water source and households.

Manyii Village (S10 – S12)

In the dry season, the spring (S10) and household samples (S11 and S12) recorded temperatures between 24.7°C and 27.3°C, pH ranged from 5.69 to 7.33, EC between 111 and 190 µS/m, TDS from 56 to 65 ppm, and turbidity from 0.15 to 5.61 NTU. In the wet season, temperature ranged between 23°C and 29.8°C, pH from 6.19 to 7.54, EC from 36 to 216 µS/m, TDS from 18 to 110 ppm, and turbidity from 0.06 to 51.5 NTU for both the water source and households.

The pH for all samples was acidic and within the recommended values for SANS 241 and WHO. Low pH values could be due to the carbon dioxide reacting with water. Further, the EC and TDS concentrations of the sampled spring and household water show that the water contains ions and salts; however, they both complied with the WHO and SANS 241 guidelines. Overall, the physicochemical parameter concentrations for the dry and wet seasons (Tables 4.1 and 4.2) were within the regulated limit standards for SANS 241 and WHO, except for S10, which contained elevated turbidity values in both dry and wet seasons; hence, the water may not be suitable for domestic uses. The result of this study relates to those obtained by Luvhimbi et al. (2022), as this study reported the pH values that ranged from 7.28 to 9.33, EC ranging between 0 to 867 µS/m, and TDS ranging between 0 to 562 ppm for the street tap samples (source), and pH ranging from 7.67 to 9.77, EC ranging from 0 to 903 µS/m.

Mutleni et al. (2023) also reported similar results, where the conditions of groundwater samples collected varied between acidic and alkaline, with pH ranges of 6.8 to 8.1, 6.8 to 10.9, and 6.8 to 7.9 for the schools, households, and communal boreholes within the study area, respectively. This study reported high pH values during the wet season as compared to the dry season, and this was due to infiltration from the precipitation. Mutleni and colleagues further recorded high EC values as of this study, which ranged from 351.4 to 1202 µS/m, and turbidity ranging between 0 to 0.40, 0 to 0.4, and 0 to 0.9 NTU for the schools, households, and boreholes. Seasonal variations of physicochemical parameters could be due to various factors, including increased rainfall during the wet seasons, which can increase the turbidity due to surface runoff into the water sources. Contrarily, dry seasons are often linked with high EC and TDS due to limited rainfall and higher evaporation rates, concentrating dissolved substances.

The t-test conducted showed that the mean temperature for the dry season was 26.69 °C with a standard deviation of 1.39, and 25.17 °C with a standard deviation of 3.45 for the wet season. The t-statistics were 1.61, and the p-value was 0.14; therefore, the difference in temperature between the two seasons is insignificant. The mean pH was 5.61 (SD = 1.82) and 6.08 (SD = 1.23) for the dry and

wet seasons. The t-statistics = -0.82 and p-value = 0.43; therefore, there is an insignificant difference. Further, the mean EC was 177.26 $\mu\text{S}/\text{m}$ (SD= 412.59) and 133.05 $\mu\text{S}/\text{m}$ (SD= 53.72) for both seasons, respectively. The t-test showed the t-statistics of 1.30 and a p-value of 0.22; therefore, this suggests that EC is not statistically influenced by the two seasons. The mean TDS for dry and wet seasons was 88.43 mg/L (SD= 65.06) and 66.43 mg/L (SD= 26.97), respectively. The t-test was 1.30 and the p-value was 0.22, showing an insignificant difference. Moreover, the mean turbidity for the dry season was 1.01 NTU (SD= 1.5) while for the wet season it was 4.33 NTU (SD=10.41), with the t-statistics of -1.28 and a p-value of 0.23, showing insignificant difference. Overall, the physicochemical parameters showed an insignificant difference between the two seasons, and this suggests that seasons do not influence the measured water quality parameters.

Table 4.1: Physicochemical parameters for the sampled spring and household water obtained in the dry season

Sampling Point	Statistics	Temperature (°C)	pH	EC (µS/m)	TDS (ppm)	Turbidity (NTU)
S1	Range	27.6-29.43	5.8-5.83	202-218	103-107	0.26-0.35
	Mean±SD	28.52±1.30	0.02±0.02	210.17±11.08	105.83±4.48	0.30±0.07
S2	Range	24.4-25.3	6.13-7.19	208-213	105-111	0.21-2.53
	Mean±SD	24.85±0.64	6.66±0.75	211.17±3.54	106±1.89	1.37±1.64
S3	Range	25.83-26.67	6.53-6.75	213-916	107-456	0.27-0.60
	Mean±SD	26.25±0.59	6.64±0.16	564.5±497.10	281.33±247.02	0.43±0.23
S4	Range	28.77-30.13	5.34-5.4	94-95	47-48	0.05-0.22
	Mean±SD	29.45±0.97	5.37±0.04	95.17±0.24	47.5±0.24	0.13±0.12
S5	Range	24.83-28.83	5.79-6.77	92-103	47-52	0.12-2.17
	Mean±SD	26.83±2.83	6.28±0.69	98±7.54	49±3.77	1.15±1.03
S6	Range	24.27-29.07	5.48-5.84	96-99	48-49	0.18-0.28
	Mean±SD	26.67±3.39	5.66±0.25	97.83±2.12	48.17±0.71	0.23±0.07
S7	Range	25.8-29.27	5.58-5.70	115-120	59-60	0.32-1.09
	Mean±SD	27.53±2.45	5.64±0.08	117.83±4.01	58.33±2.36	0.70±0.54
S8	Range	24.53-27.30	5.67-6.39	93-111	47-52	0.15-0.66
	Mean±SD	25.92±1.96	6.02±0.52	102.5±12.49	51.17±5.42	0.41±0.36
S9	Range	23.97-26.03	5.83-5.86	95-114	49-56	0.37-1.07
	Mean±SD	25±1.46	5.84±0.02	104.5±12.96	51.5±6.84	0.72±0.50
S10	Range	26.93-27.67	5.69-6.08	185-190	92-95	0.48-10.75
	Mean±SD	27.30±0.52	5.86±0.27	187.5±4.01	93.67±1.89	5.61±7.26
S11	Range	24.07-26.4	6.56-6.59	111-192	56-95	0.15-0.58
	Mean±SD	25.23±1.65	6.58±0.02	151.33±57.04	75.83±27.58	0.37±0.30
S12	Range	26.3-27.1	6.21-7.33	187-189	92-93	0.33-0.98
	Mean±SD	26.70±0.57	6.77±0.80	186.67±0	92.83±0.24	0.66±0.46
WHO (2017)		25	≥6.5 to ≤8.5	1700	≤1200	≤5
SANS 241 (2015)		25	≥5 to ≤9.7	1700	-	≤5

S1- Matsa spring, S2&S3- Matsa households, S4- Mamvuka spring 1, S5&S6- Mamvuka spring 1 households, S7- Mamvuka spring 2, S8&S9- Mamvuka spring 2 households, S10- Manyii spring, S11&S12- Manyii households

Table 4.2: Physicochemical parameters for the sampled spring and household water obtained in the wet season

Sampling Point	Statistics	Temperature (°C)	pH	EC (µS/m)	TDS (ppm)	Turbidity (NTU)
S1	Range	26.23-30.5	6.02-6.03	214-222	107-110	0.20-0.64
	Mean±SD	28.37±3.02	6.02±0	218± 5.66	108.5±2.12	0.42±0.31
S2	Range	19.8-28.23	6.91-7.01	220-222	110-111	0.10-0.89
	Mean±SD	24.02±5.96	6.96±0.07	221±1.41	110.83±0.24	0.50±0.56
S3	Range	22.13-26	5.95-6.68	92-216	45-108	0.03-1.68
	Mean±SD	24.07±2.73	6.32±0.52	154±87.68	76.67±44.31	0.86±1.16
S4	Range	28.17-29.83	5.53-5.66	95-99	48-49	0.02-0.13
	Mean±SD	29±1.18	5.60±0.09	97±2.36	48.33±0.94	0.08±0.08
S5	Range	26.9-29.1	6.37-6.47	100-119	50-60	0.37-0.51
	Mean±SD	15.33±1.56	6.42±0.07	109.67±13.67	54.67±7.07	0.44±0.10
S6	Range	25.03-27.33	5.67-6.33	95-121	47-62	0.23-0.60
	Mean±SD	26.18±1.63	3.07±0.47	108.33±18.38	53.83±9.19	0.41±0.26
S7	Range	24.23-27.5	5.67-5.82	119-123	59-61	0.10-0.89
	Mean±SD	25.87±2.31	4.49±3.31	121±2.38	60.33±1.41	0.49±0.56
S8	Range	22.2-29.4	6.52-7.29	23-104	11-52	0.15-6.41
	Mean±SD	25.8±5.09	6.91±0.55	63.33±57.04	31.33±28.76	3.28±4.43
S9	Range	22.33-27.07	6.14-6.60	23-98	11-49	0.24-6.53
	Mean±SD	24.7±3.35	6.37±0.32	60.83±53.03	30±26.40	3.38±4.45
S10	Range	25.83-28.07	6.19-6.22	188-199	95-99	22.83-51.5
	Mean±SD	26.95±1.58	6.21±0.02	193.33±7.54	96.83±3.06	37.17±20.27
S11	Range	23-29.8	7.22-7.34	37-211	18-105	0.3-4.26
	Mean±SD	26.4±4.81	7.28±0.09	123.83±123.27	61.83±61.52	2.28±2.80
S12	Range	22.03-28.77	7.13-7.54	36-216	18-110	0.06-5.31
	Mean±SD	25.4±4.76	7.34±0.29	126.33±127.28	64±65.05	2.69±3.72
WHO (2017)		25	≥6.5 to ≤8.5	1700	≤1200	≤5
SANS 241 (2015)		25	≥5 to ≤9.7	1700	-	≤5

S1- Matsa spring, S2&S3- Matsa households, S4- Mamvuka spring 1, S5&S6- Mamvuka spring 1 households, S7- Mamvuka spring 2, S8&S9- Mamvuka spring 2 households, S10- Manyii spring, S11&S12- Manyii households

4.2 Determination of Heavy metals in water

Tables 4.3 and 4.4 below present the average heavy metal concentrations for the dry and wet seasons. Table 4.3 shows that Cd and Cr were below the instrument's detection limit (<0.05) in all the sampling points, whereas Sb, As, Pb, Mn, Hg, Ni, and Se were only detected in a few. However, in the wet season (Table 4.4), Cd, Cr, Sb, As, Pb, Hg, Ni, and Se were below the instrument's detection limits.

Table 4.3 shows that the heavy metal concentrations in the dry season (Cu, Zn, Fe, and Al) from the spring water samples ranged from 0.016-0.061 mg/L, 0.04-0.338 mg/L, 0.145-2.03 mg/L, and 0.145-0.34 mg/L, respectively. It was also noted in the wet season (Table 4.4) that the concentrations of the same heavy metals ranged from 0.08-0.22 mg/L, 0.08-1.31 mg/L, 0.115-4.3 mg/L, and 0.165-0.855 mg/L. Zn, Fe, and Al concentration levels were higher in the wet season. In addition, the concentrations of Fe in point S3 (dry season) and S3 and S10 (wet season) were above the regulated standards of WHO and SANS 241, whereas; Al was detected higher than the regulated standards in S3 (Table 4.3), S6-S8, and S10-S12 in the wet season (Table 4.4). High Fe concentrations could have been due to the washing away of soil and the breaking down of rocks containing Iron, and high levels of Fe give the water a metallic taste (Sukmilin & Sangsirimongkolying, 2021). High concentrations of Al could pose serious health risks to the residents of the study area, as high levels of Al in drinking water may affect the nervous system, which has the possibility of causing Parkinson's, Alzheimer's, and Lou Gehrig's disease (Luvhimbi et al., 2022).

Some heavy metals were perceived to be above the WHO and SANS 241 recommended standard limit in dry and wet seasons (Tables 4.3 and 4.4). From Table 4.3, As was detected high in S2 (0.046 mg/L) and S12 (0.027 mg/L), both of which are household water samples. Mn and Ni were also detected as high in S7 (0.15 mg/L) and S6 (0.107 mg/L), respectively. High levels of Mn in sampling point S7 may affect the water taste and cause stains on clothes. From Table 4.4, Mn is again detected as high in S10 (0.115 mg/L). It was further observed from the dry and wet seasons that the household water was more contaminated than the water from the source. Although the concentrations differ according to various heavy metals, it was observed that the point of use is more contaminated than the sources, as most of the household's concentrations are higher than the sources (Tables 4.3 and 4.4).

Heavy metals such as As, Cu, Mn, Ni, Fe, and Al showed an increase from the sources to the households in both seasons. This increase could be due to several factors, such as storage facilities, duration of water stored, and whether the storage vessels are covered or not to prevent bacteria from interfering with the water collected (Luvhimbi et al., 2022). Urme et al. (2025) reported similar results to those of this study. Their study reported that groundwater is being contaminated by heavy

metals such as Fe and As. According to Maluleke et al. (2025) Ni is released into the environment by natural and anthropogenic activities such as weathering of mafic and ultramafic rocks and soils, and wastewater generated from the alloy industries. See Figure 4.1 for all the heavy metals that exceeded the recommended limits of SANS 241 and WHO.

Statistical results showed that the mean concentrations of heavy metals between dry and wet seasons were 0.09 with a standard deviation of 0.13, and 0.16 with a standard deviation of 0.32, respectively. The t-statistics were -1.33, critical t-value = 2.18, and p-value = 0.21. The t-statistic is less than the critical t-value, and the p-value is greater than the 0.05 significance threshold; therefore, we fail to reject the null hypothesis, indicating an insignificant difference between the two seasons. The Pearson correlation coefficient between the dry and wet seasons demonstrated a strong positive relationship ($r=1.0$), however, this does not imply that the observed difference is not statistically insignificant. It therefore means that it does not matter which season the samples were collected, the water is contaminated.

Table 4.3: Average Mean value concentrations of toxic metals measured in groundwater during the dry season in mg/L

Metal	LOQ	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	WHO	SANS 241
Sb	<0.05	BDL	BDL	0.001	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.02	≤0.02
As	<0.05	0.005	0.046	0.002	BDL	BDL	BDL	0.002	0.001	BDL	BDL	0.003	0.027	≤0.01	≤0.01
Cd	<0.05	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.003	≤0.003
Cr	<0.05	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.05	≤0.05
Cu	<0.05	0.044	0.016	0.2	0.036	0.055	0.061	0.037	0.04	0.062	0.05	0.034	0.055	≤2	≤2
Pb	<0.05	0.001	BDL	BDL	BDL	0.001	BDL	BDL	BDL	BDL	BDL	BDL	0.002	≤0.01	≤0.01
Mn	<0.05	BDL	BDL	BDL	BDL	BDL	BDL	0.15	BDL	BDL	BDL	BDL	BDL	-	≤0.1
Hg	<0.001	0.002	BDL	BDL	BDL	0.001	0.001	BDL	BDL	BDL	BDL	BDL	BDL	≤0.006	≤0.006
Ni	<0.05	BDL	BDL	BDL	BDL	BDL	0.102	BDL	BDL	BDL	BDL	BDL	BDL	≤0.07	≤0.07
Se	<0.1	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.04	≤0.04
Zn	<0.05	0.308	0.233	0.17	0.04	0.09	BDL	0.05	0.05	0.048	0.05	0.338	0.261	-	≤5
Fe	<0.05	0.34	0.295	2.03	0.2	0.515	0.34	0.21	0.145	0.51	0.315	0.16	0.5	-	≤2
Al	<0.05	0.245	0.145	0.34	0.165	0.195	0.185	0.175	0.145	0.195	0.215	0.17	0.15	-	≤0.3

* S1- Matsa spring, S2&S3- Matsa households, S4- Mamvuka spring 1, S5&S6- Mamvuka spring 1 households, S7- Mamvuka spring 2, S8&S9- Mamvuka spring 2 households, S10- Manyi spring, S11&S12- Manyi households

*BDL- Below Detection Limit *LOQ- Limit of Quantification

Table 4.4: Average Mean value concentrations of toxic metals measured in groundwater during the wet season in mg/L

Sampling point	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	WHO	SANS 241
Sb	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.02	≤0.02
As	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.01	≤0.01
Cd	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.003	≤0.003
Cr	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.05	≤0.05
Cu	0.065	0.17	0.22	0.065	0.09	0.115	0.135	0.08	0.105	0.055	0.12	0.13	≤2	≤2
Pb	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.01	≤0.01
Mn	BDL	0.06	BDL	BDL	BDL	BDL	0.31	BDL	BDL	0.115	BDL	0.06	-	≤0.1
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.006	≤0.006
Ni	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.07	≤0.07
Se	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.04	≤0.04
Zn	0.185	0.115	0.15	0.065	0.075	0.095	0.105	1.31	1.325	0.08	0.165	0.195	-	≤5
Fe	0.115	1.815	4.3	0.35	0.185	0.42	1.345	0.85	0.875	2.095	0.485	0.78	-	≤2
Al	0.165	0.23	0.3	0.18	0.17	0.315	0.785	0.415	0.24	0.855	0.345	0.45	-	≤0.3

* S1- Matsa spring, S2&S3- Matsa households, S4- Mamvuka spring 1, S5&S6- Mamvuka spring 1 households, S7- Mamvuka spring 2, S8&S9- Mamvuka spring 2 households, S10- Manyi spring, S11&S12- Manyi households

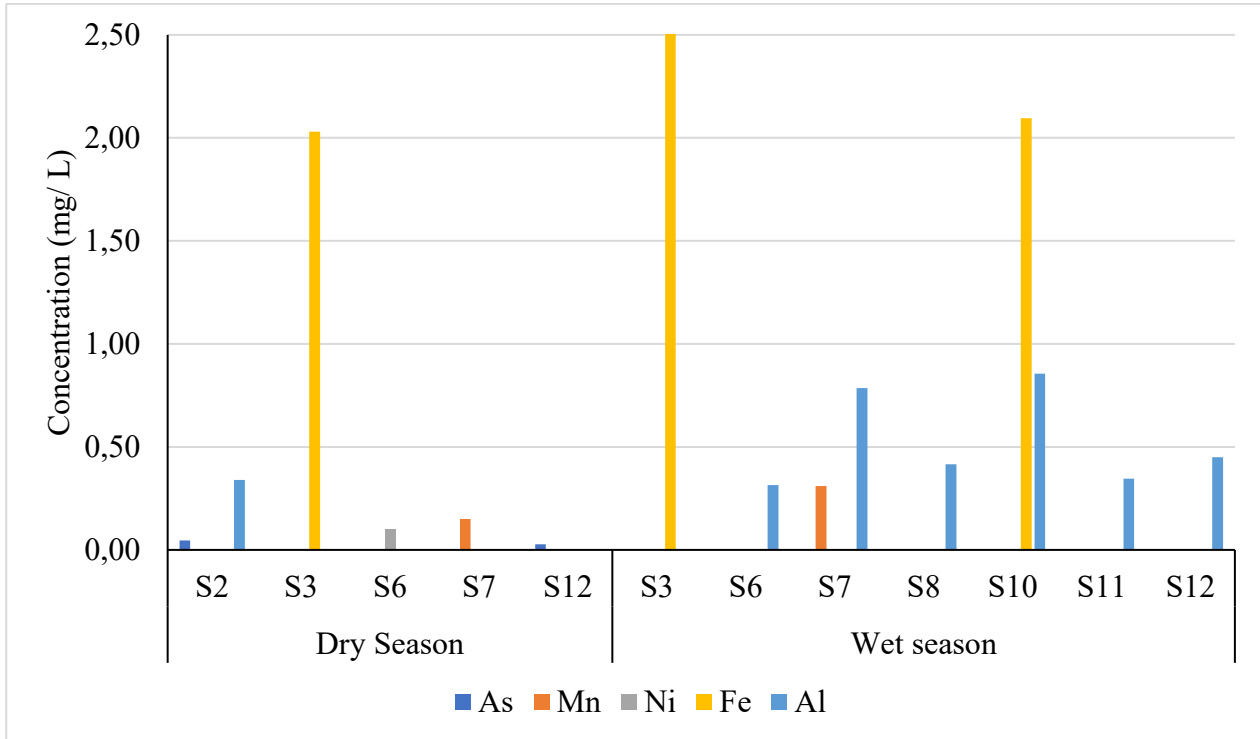


Figure 4.1: Concentration plot of heavy metals that exceeded the regulated SANS 241 and WHO limits during dry and wet seasons

Figures 4.2 and 4.3 illustrate the Principal Component Analysis (PCA) graphs displaying the distribution of heavy metals during the dry and wet seasons in the three communities. During the dry season, Fe strongly lies along the PC1 and away from the cluster, suggesting a distinct pattern. Al exhibits a strong positive relationship with PC2; meanwhile, As, Pb, Hg, Cu, and Zn are closely grouped along PC1 and somehow negative along the PC2 quadrant, indicating the possibility of shared contamination sources. The wet season PCA shows a dispersed distribution of these metals. Al shows a positive relationship along PC 2, whereas Zn is negatively linked with PC2. Fe is observed to have shifted to the centre; however, it remains positive along with PC1. Cu and As lie along the negative side of PC1. Overall, these graphs show that the relationships between the selected metals differ significantly between the two seasons. The metal variations between the seasons could be due to leaching, which affects the distribution of metals and interaction with the environment.

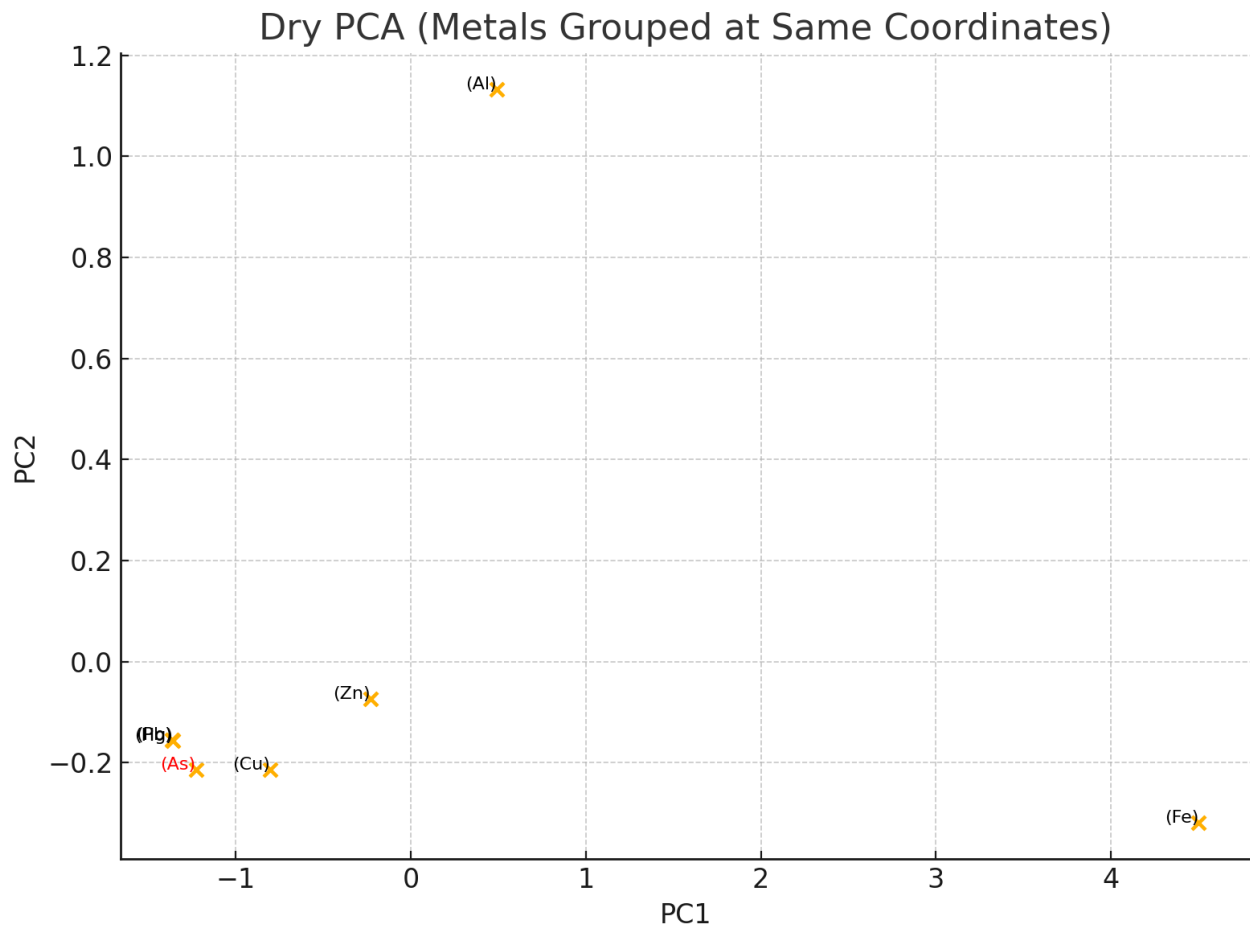


Figure 4.2: Distribution of heavy metals during the dry season

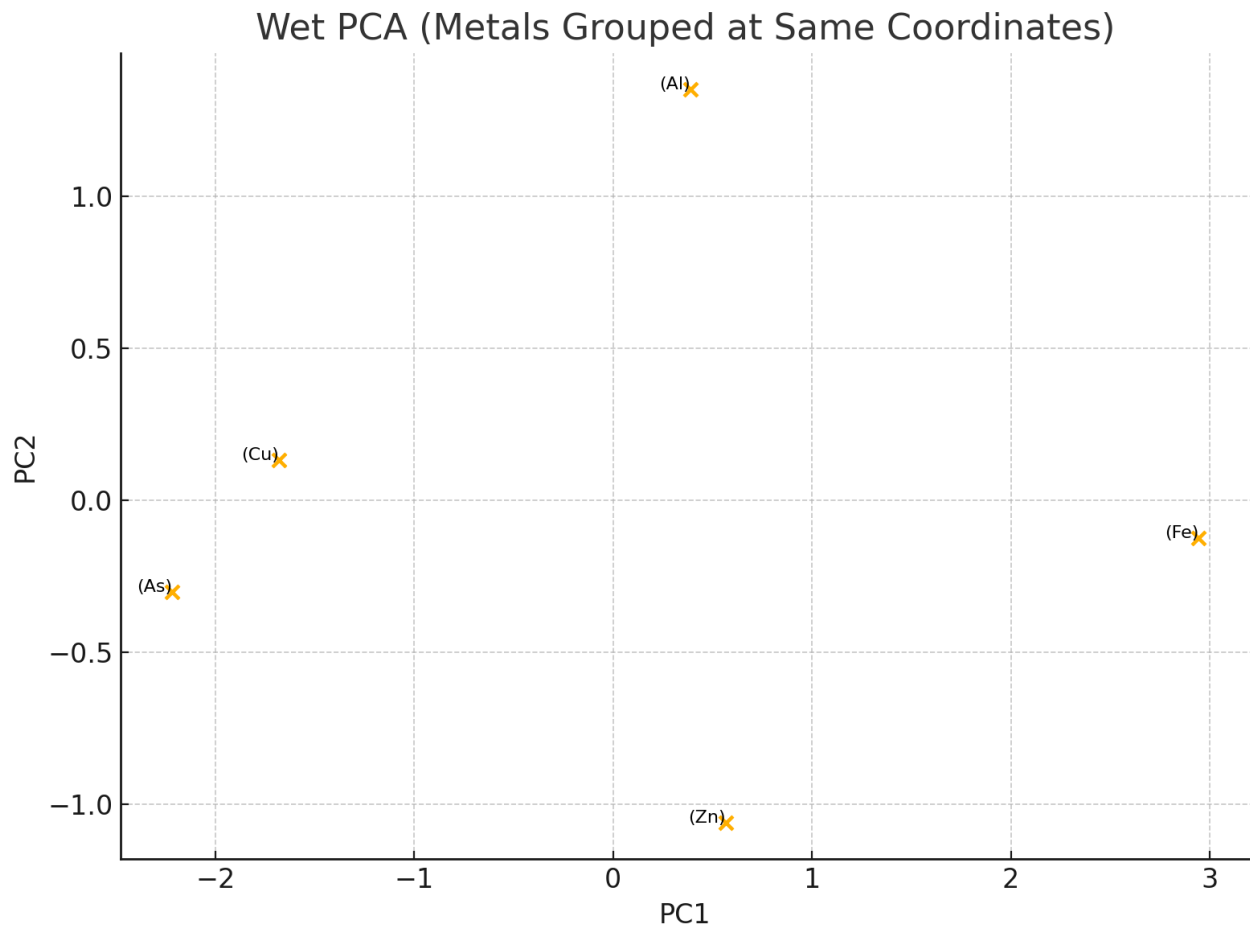


Figure 4.3: Distribution of heavy metals during the wet season

4.3 Determination of Anions in Water

Tables 4.5 and 4.6 describe the average concentrations of the selected most common anions in groundwater, obtained from various sampling points during the dry and wet seasons. The results show that the nitrite concentrations of all samples were below the instrument detection limit (<0.13 mg/L) in both dry and wet seasons. Similarly, phosphate was recorded below the detection limit (<0.2 mg/L), except for S3 and S11, which had concentrations of 1.1 mg/L and 0.21 mg/L, respectively. In the wet season (Table 4.6), phosphate was only detected in four different sampling points, including S1 (0.24 mg/L), S2 (0.22 mg/L), S11 (2.82 mg/L), and S12 (0.85 mg/L).

Chloride concentrations were shown to be higher in levels in comparison to the other anions studied. Regardless of this, chloride levels complied with the standard limit of SANS 241 (2015) and WHO (2017). The chloride concentrations ranged from 9.26- 133.16 mg/L in the dry season (Table 4.5) and 7.62-61.39 mg/L in the wet season (Table 4.6); however, in S9, it was below the instrument detection limit (<2). The dry season S3 sample was found to contain a high chloride concentration compared

to other sampling points. High chloride concentrations could be due to naturally occurring rocks, leaching, and agricultural runoffs.

It was perceived that the nitrate concentrations ranged from 1.40-2.24 mg/L in the dry season and 1.08-2.14 mg/L in the wet season. The presence of nitrate in springwater indicates that the agricultural application of fertilisers and naturally occurring rocks could be a major source of nitrate. Nitrate concentrations in the dry season could be a result of washing dead plants into the water bodies and naturally occurring rocks that contain salts. The springs from Matsa, Mamvuka, and Manyii villages are situated near the homesteads and farms where the community members practice subsistence farming. Furthermore, people from these communities use the spring water for domestic and irrigation purposes. Although agricultural activities are the main source of nitrate in water bodies, in this study, it is not the case since the nitrate levels recorded are low, and this could be due to several factors such as seasonal fluctuations, denitrification, dilution, and biological uptake. All the nitrate samples were within the regulated standard limit of drinking water set by SANS 241 and WHO (Tables 4.5 and 4.6).

Fluoride concentrations for the spring and household water samples ranged from 0.05 to 0.16 mg/L in the dry season and from 0.08 to 0.135 mg/L in the wet season (Tables 4.5 and 4.6). S2 was noted to have elevated fluoride levels in both seasons; however, it is within the recommended limits. It is also shown from the tables that the sulphate concentrations ranged from 2.2-4.86 mg/L in the dry season and 2.45-13.075 mg/L in the wet season. On the other hand, sulphate was below the instrument's detection limit (<2) at some sampling points (S1, S2, S7, and S9) in the dry season, whereas it was detected in all the sampling points during the wet season. Brima (2017) reported that high concentrations of sulphate have severe effects on humans and are corrosive to pipe fixtures. The presence of Sulphate in the water bodies during the wet season could be a result of run-off from agricultural factors such as farming, the use of fertilisers, and pesticides, and soil erosion. Overall, these results are similar to those of Ojekunle and colleagues (2020), who reported that the concentrations of Phosphate and Sulphate were below the recommended standard limits. It was further reported that it could have been since groundwater only contains base phosphate levels, and the soil's capacity to hold phosphate is low.

The box and whisker plot shows the concentration of anions in water samples collected during the dry seasons across sampling points S1 to S12 in the three communities (Figure 4.4). Chloride shows the highest concentrations with a wide interquartile range and several outliers of about 130 mg/L, and this shows a possible source of contamination. Sulphate shows moderate concentrations with one outlier, suggesting some variability within the sampling points. Nevertheless, nitrate, fluoride, nitrite, and phosphate exhibit low concentrations amongst all the samples, with low variation and a few to

no outliers. This implies uniform distribution and low contamination by these anions. The box and whisker plot shows that chloride and sulphate are the major ions in terms of variability, and this could be influenced by several anthropogenic activities, whereas other anions remain low in concentration. The box and whisker plot during the wet seasons (Figure 4.5) shows the distribution and variability of anion concentration in the water samples. Chloride shows to be the most dominant ion with concentrations ranging between 18 to 20 mg/L. Extreme outliers above 60 mg/L suggest high contamination that is likely to be due to soil erosion and anthropogenic activities. Sulphate shows moderate concentrations with a few high outliers, suggesting input from agricultural activities. The concentrations of phosphate are low; however, its outliers suggest nutrient enrichment, which is likely to be because of the use of fertilisers. Nitrate is also low (1.5 mg/L), suggesting minimised agricultural pollution, whereas nitrite and fluoride are present in low concentrations, suggesting low pollution. Overall, the presence of these ions is primarily influenced by natural processes.

Statistical results assumed that the mean concentration of anions was 6.37 with a standard deviation of 12.38 and 5.49 with a standard deviation of 9.55 in the dry and wet seasons, respectively. The t-test results showed that the t-statistic was 0.73, t-critical value = 2.57, and p-value = 0.5; therefore, we fail to reject the null hypothesis since the p-value exceeds the significance threshold ($p > 0.05$) and t-statistic < t-critical value. This shows that there is an insignificant difference between the two seasons. Further, the Pearson correlation coefficient between the two seasons was high ($r = 1.0$), and this indicates a very strong relationship between the two seasons.

Table 4.5: Average Mean concentrations of anions in groundwater during the dry season in mg/L

Sampling site	Cl ⁻	F ⁻	NO ₂ ⁻	NO ₃ ⁻	SO ₄ ²⁻	PO ₄ ³⁻
LOQ	<2	<0.05	<0.13	<0.5	<2	<0.2
S1	14.6	0.095	BDL	2.24	BDL	BDL
S2	12.28	0.16	BDL	2.165	BDL	BDL
S3	133.16	0.095	BDL	2.21	4.68	1.1
S4	11.23	0.05	BDL	1.465	4.4	BDL
S5	9.26	0.08	BDL	1.48	4.52	BDL
S6	10.67	0.06	BDL	1.65	2.2	BDL
S7	69.43	0.065	BDL	1.4	BDL	BDL
S8	15.545	0.065	BDL	1.455	2.95	BDL
S9	11.21	0.08	BDL	1.68	BDL	BDL
S10	11.33	0.07	BDL	1.985	7.255	BDL
S11	12.71	0.085	BDL	2.025	3.29	0.21
S12	65.375	0.1	BDL	2.16	4.86	BDL
WHO	≤250	≤1.5	≤3	≤50	-	-
SANS	≤300	≤1.5	≤0.9	≤11	≤250	-

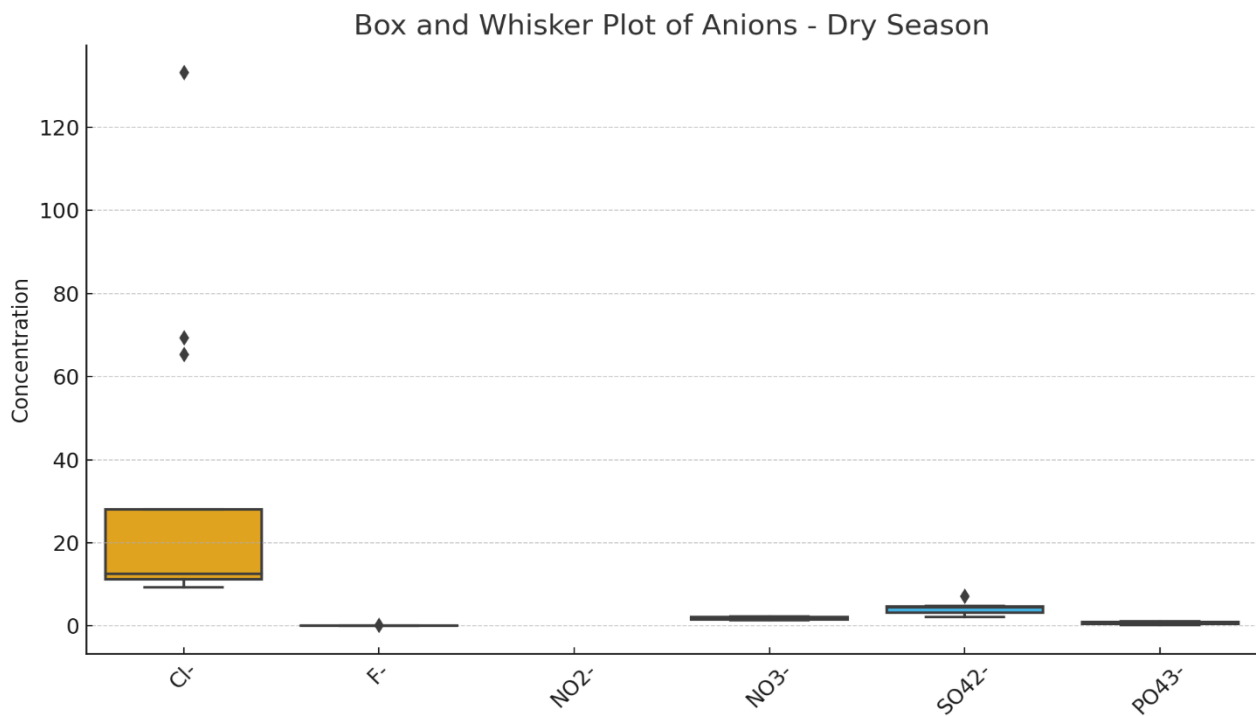


Figure 4.4: Box and Whisker of Anions in the dry season

Table 4.6: Average Mean concentrations of anions in groundwater during the wet season in mg/L

Sampling Site	Cl ⁻	F ⁻	NO ₂ ⁻	NO ₃ ⁻	SO ₄ ²⁻	PO ₄ ³⁻
LOQ	<2	<0.05	<0.13	<0.5	<2	<0.2
S1	20.415	0.105	BDL	2.02	5.1	0.24
S2	18.065	0.135	BDL	2.12	9.4	0.22
S3	15.55	0.095	BDL	1.26	6.76	BDL
S4	11.45	0.095	BDL	1.8	4.215	BDL
S5	59.26	0.085	BDL	1.38	4.58	BDL
S6	61.39	0.085	BDL	1.31	3.83	BDL
S7	16.29	0.065	BDL	1.08	5.73	BDL
S8	7.62	0.135	BDL	1.16	2.45	BDL
S9	BDL	0.13	BDL	1.39	3.29	BDL
S10	18.34	0.105	BDL	1.76	3.87	BDL
S11	18.52	0.08	BDL	2.03	13.075	2.82
S12	23.06	0.08	BDL	2.14	5.09	0.85
WHO	≤250	≤1.5	≤3	≤50	-	-
SANS 241	≤300	≤1.5	≤0.9	≤11	≤250	-

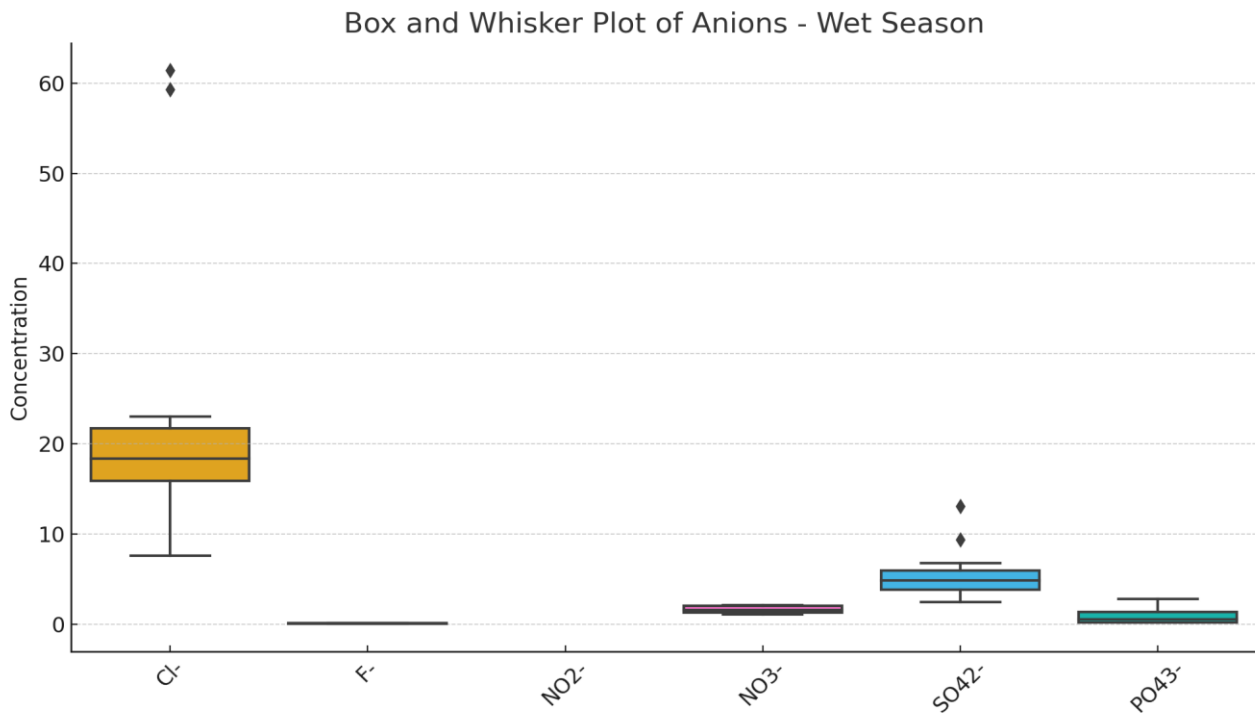


Figure 4.5: Box and Whisker in the wet season

4.4 Microbial Analysis

4.4.1 Escherichia coli (*E. coli*)

E. coli is regarded as a common measure of fecal contamination, and it is present in elevated amounts in both human and animal wastes (WHO, 2023). In this study, *E. coli* was analysed for groundwater samples in the dry and wet seasons (Figure 4.6(a)). Average *E. coli* counts for the dry season ranged from 82.5-892.5 CFU/100 mL and 95-2340 CFU/100 mL in the wet season. Looking at the *E. coli* count, the water quality of the samples exceeded the permissible limits in both dry and wet seasons, as according to WHO and SANS 241, no *E. coli* should be detected (0 CFU/100 mL) in 100 mL of drinking water samples. High counts of *E. coli* were observed from S1 (892.5 CFU/100 mL) in the dry season and S10 (2340 CFU/100 mL) in the wet season. This could mean a high infection possibility relating to the contamination of *E. coli* from consuming contaminated spring water in both wet and dry seasons for the residents in the study area. Further, the lower counts for *E. coli* were observed in S11 (82.5 CFU/100 mL) and S3 (95 CFU/100 mL) for the dry and wet seasons, respectively. Although these values are low, unacceptable for the drinking water recommended standard according to the WHO and SANS 241.

A similar study by Edokpayi et al. (2018a) reported the outbreak of diarrhea because of drinking groundwater that was contaminated with *E. coli* in the Vhembe District. This indicates that the presence of *E. coli* in drinking water is a human health threat to the communities of Matsa, Mamvuka, and Manyii. The results revealed that the *E. coli* counts from the sampled water increased from dry to wet seasons from sampling points S4-S12, except for S6. From sampling points S1-S3, *E. coli* levels fluctuate. In S1 and S3, the dry season *E. coli* levels are higher than the wet season level; however, that's not the case with S2, as the wet season level is higher than the dry season level. Murei et al. (2022) reported the presence of *E. coli* in borehole water samples, which ranged between 6 and 228 CFU/ 100 mL. Moreover, Aydamo et al. (2024) conducted a study in Ethiopia during the dry and wet seasons. This study assessed water from 288 households and collected approximately 220 stored water samples and 12 water samples from the water sources. The study found that about 43.2% of the household stored water was contaminated during the dry season, and 34.5% in the wet season. The *E. coli* from this study ranged from 0 to 310 CFU/100 mL and 0 to 284 CFU/ 100 mL during both dry and wet seasons. This study concludes that the higher contamination during the dry season is due to storage and unsafe water handling. Further from this study, the source of *E. coli* contamination could be from the anthropogenic activities practiced at Matsa, Mamvuka, and Manyii villages, such as the use of pesticides, poorly managed pit latrine toilets, and waste from livestock.

E. coli counts were higher during the wet season at some sampling points, particularly due to overflowing latrines, infiltration of contaminants into the groundwater during heavy rainfalls, increased surface run off, which transports fecal contaminants from nearby areas, and poorly managed sanitation into the water sources. Contrary, some points recorded elevated levels during the dry season, and this could be due to stagnant water, human and animal activities, and unprotected sources. Variations in *E. coli* levels across the sampling points can be associated with several factors, such as poor handling and storage. Sampling points S1 and S4 showed lower contamination as compared to their households (point of use) (S2, S3, S5, and S6), suggesting poor handling or storage at the household level. Contrarily, S7 and S10 (sources) had elevated *E. coli* counts, and this could be due to exposure to surface runoff, close-by sanitation facilities, and agricultural wastes. This also affected their households (S8, S9, S11, and S12). These variations might be a result of unprotected sources, sanitation infrastructure, surrounding land uses, and hygiene practices at the household collection and storage points.

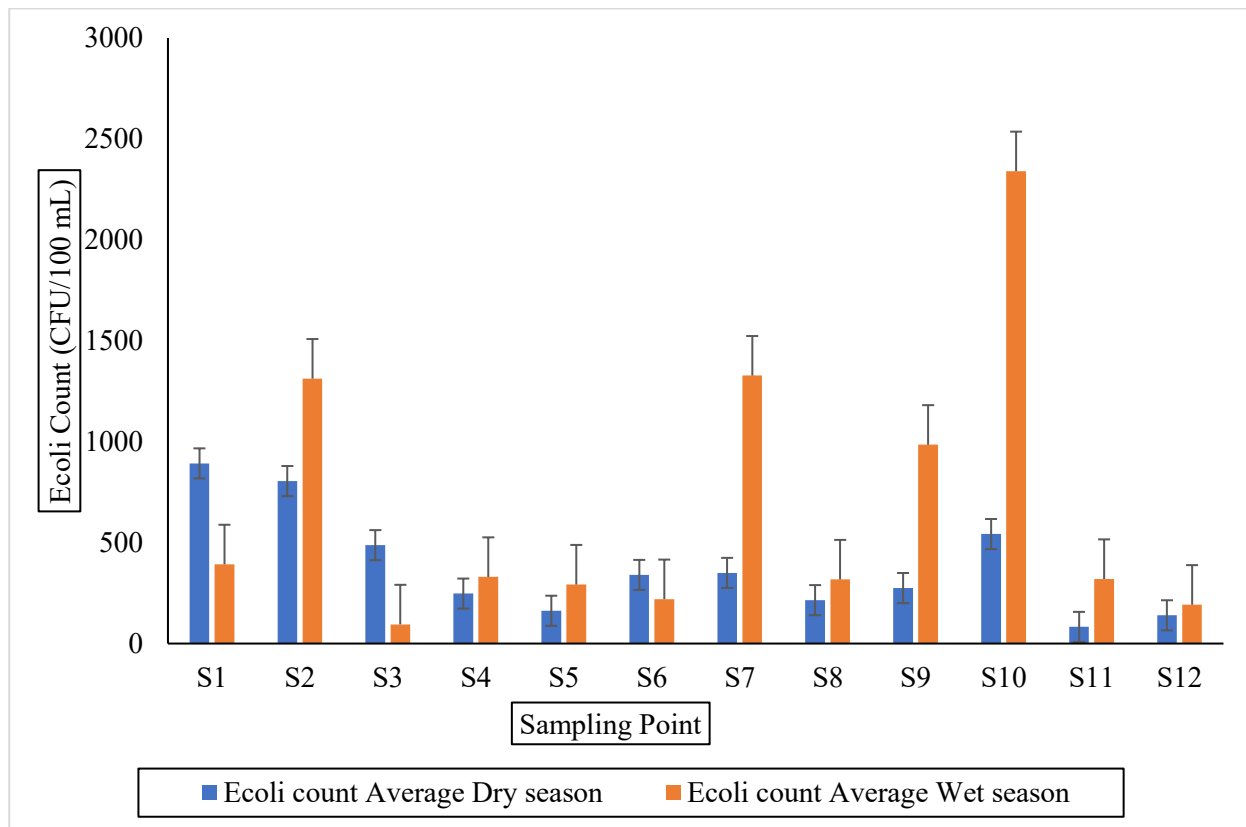


Figure 4.6 (a): Average *E. coli* contamination for the dry and wet seasons

4.4.2 Total Coliforms

In this study, the average Total coliform counts for the dry and wet seasons ranged from 1980-9547.5 CFU/100 mL and 1405-13565 CFU/100 mL, respectively (Figure 4.6 (b)). The Total coliform count for the sampled water showed that the water quality is poor, as the total coliform count exceeded the permissible limits in both dry and wet seasons. According to WHO and SANS 241, the total coliform count in drinking water should not exceed 10 CFU/100. In the dry season, higher levels of total coliform were observed from sampling points S5 (9547.5 CFU/100 mL) and S10 (13565 CFU/100 mL) in the wet season. The presence of total coliform > 10 CFU/100 mL in the drinking water means that the water is contaminated and unsuitable for human consumption; therefore, it poses health risks to the communities of Matsa, Mamvuka, and Manyii.

Lower total coliform counts were observed from sampling point S1, with 1980 CFU/100 mL and 1405 CFU/100 mL in both the dry and wet seasons. Regardless of the total coliform counts in S1 being low, they still exceed the recommended values of drinking water by WHO and SANS 241; therefore, they still pose a huge risk to the communities. Unlike the *E. coli* results in Figure 4.6 (a) with a specific trend, the total coliform results showed no trend as the counts fluctuated from sampling points S1-S12.

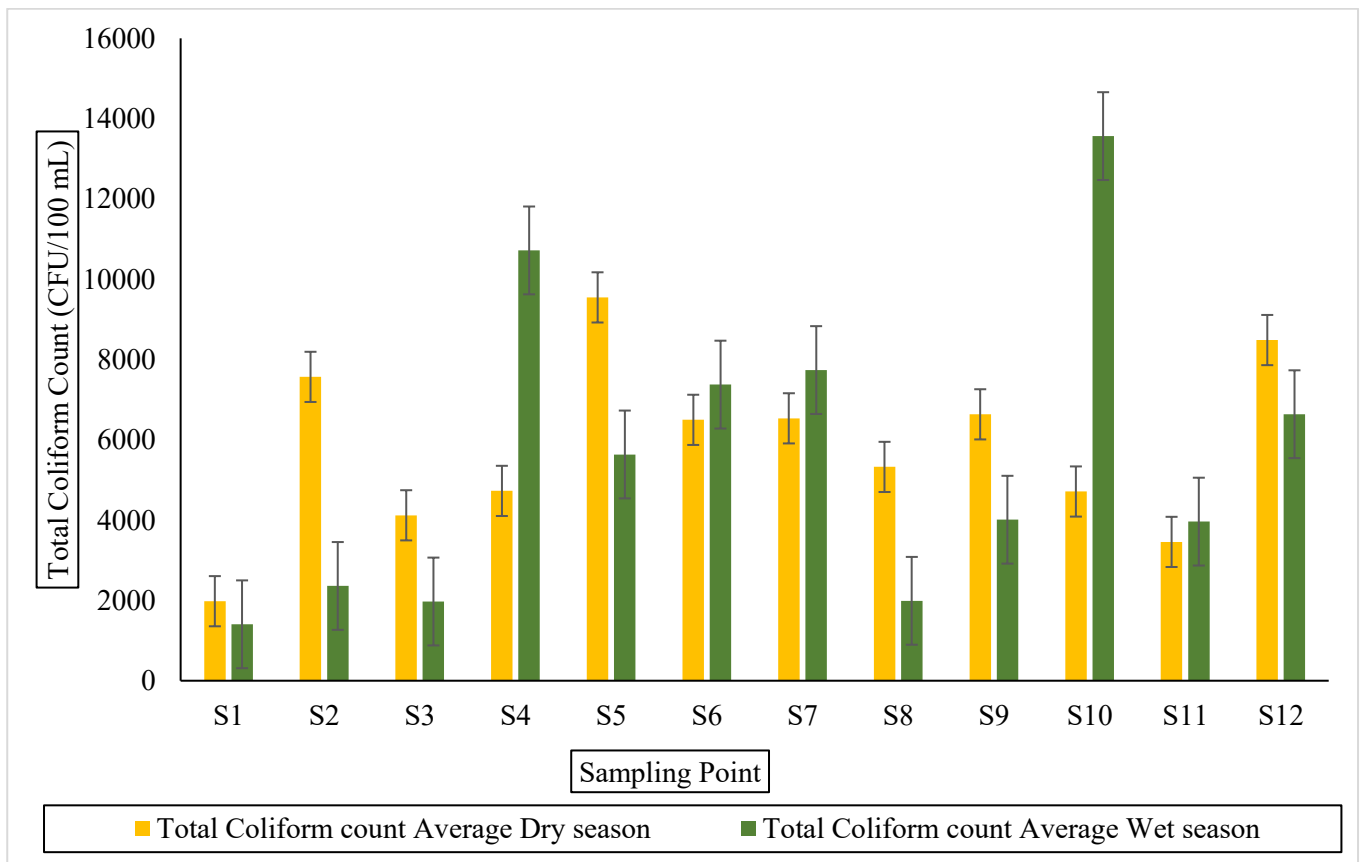


Figure 4.6 (b): Average total Coliforms contamination for the dry and wet seasons

4.5 Water Quality Index

The WQI determines the overall water quality status, which is suitable for determining possible treatment and uses. However, the WQI does not consider microbial water quality parameters (Madilonga et al., 2021). The SANS 241 guideline standards were used for the WQI calculation, and the rating for the sampled water was assessed using the selected physicochemical parameters. The table below (Table 4.7) presents how the WQI for the selected physicochemical parameters considered during the study period was determined. The WQI of the chosen parameters during the dry and wet seasons fell between excellent and poor water quality. These findings are similar to those of Olasoji et al. (2019), whose results ranged from excellent to poor, with 22.36-157.94 throughout the study. High WQI values were observed from Chloride, which makes the groundwater unsuitable for drinking purposes and other domestic uses in both the dry and wet seasons. These WQI values show that the water is unsuitable for consumption and agricultural purposes. Other parameters showed that the groundwater samples are suitable for drinking and other domestic purposes as they fell within the excellent water quality class (<50). However, this does not mean the water is not contaminated as the sum WQI shows that the water is within the poor water quality class (100-200), and Figures 4.6 (a) and (b) show that the water is contaminated microbiologically, and proper treatment methods should be applied before water usage.

Table 4.7: Physicochemical parameters used for WQI determination

Parameter	Si (SANS 241)	wi	Dry season			Wet season			WQI (Mean)
			Wi	qi	WQI	qi	WQI		
pH	5-9.7		4	0.04	274.88	11.95	259.46	11.28	11.62
EC	1700		4	0.04	0.33	0.01	0.36	0.02	0.01
TDS	1200		5	0.05	14.77	0.80	11.09	0.60	0.70
Temp	25		2	0.02	353.72	7.69	265.72	5.78	6.73
Nitrate	11		5	0.05	16.64	0.90	14.73	0.80	0.85
Sulphate	250		4	0.04	171	0.07	2.25	0.10	0.09
Phosphate	-		4	0.04	-	-	-	-	-
Chloride	1.5		5	0.05	2093.33	113.77	1636	88.91	101.34
Fluoride	300		5	0.05	0.03	0	0.03	-	-
Zinc	5		1	0.01	2.98	0.03	3.9	0.04	0.04
Arsenic	0.01		5	0.05	120	6.52	-	-	3.26
Cadmium	0.03		5	0.05	-	-	-	-	-
Chromium	0.05		5	0.05	-	-	-	-	-
Copper	2		5	0.05	2.85	0.15	5.65	0.31	0.23
Iron	2		2	0.02	23.15	0.50	56.75	1.23	0.87
Lead	0.01		5	0.05	20	1.09	-	-	0.54
Manganese	0.1		5	0.05	150	8.15	136	7.39	7.77
Mercury	0.006		5	0.05	16.67	0.91	-	-	0.45
Nickel	0.07		2	0.02	145.71	3.17	-	-	1.58
Aluminium	0.3		4	0.04	64.67	2.81	123.67	5.38	4.09
Antimony	0.02		5	0.05	5	0.27	-	-	0.14
Selenium	0.04		5	0.05	25	1.36	-	-	0.68
Sum			92	1.00		160.17		121.84	141.01

4.6 (i) Human Health Risks of Heavy Metal Concentrations

The health risk assessment model was based on evaluating the potential health risks that heavy metals could pose to children and adults within the study areas through direct ingestion and dermal absorption. The exposure level (Exps) through direct ingestion and dermal absorption was evaluated for the dry (July and August 2024) and wet season (September and November 2024). The human health-related risks linked with ingestion and dermal exposure were presented using the average concentrations of heavy metals (As, Cd, Cr, Zn, Cu, Mn, Fe, Al, Se, Sb, Hg, Ni, and Pb) in water for the dry and wet seasons.

Fe ($5.56e-02$), Al ($2.33e-02$), Mn ($1.8e-02$), Zn ($1.79e-02$) and Ni ($1.22e-02$), are the primary contributors to health exposure via direct ingestion path for children, while only Fe ($1.46e-02$) for adult in the dry season is the major contributor due to their high average values (Table 4.8). During the wet season (Table 4.9), children had a high Fe value of $1.36e-01$, meanwhile adults had Fe ($3.57e-02$) and Al ($1.17e-02$) being the contributors of health exposure via direct ingestion. Cd and Cr were not detected in the analysed samples, indicating little or no exposure from these metals.

The exposure levels via the dermal contact paths were also assessed for children and adults in the sampled springwater during the dry and wet seasons. Fe ($2.04e-05$ and $1.19e-05$) is the major contributor to adverse health risks associated with consuming contaminated water in study areas for children and adults in the dry season. During the wet season, Fe ($4.99e-05$) and Al ($1.63e-05$) for children and Fe ($1.69e-05$) for adults are the main contributors to causing health-related infections through dermal contact.

Fe, Al, Mn, and Zn are the primary influences of non-carcinogenic health effects, and their mean values for the dry season exceed those in the wet season; therefore, this means that there is a higher possibility of health risk in the usage of household and spring water during the dry season. The level of exposure for children was higher than that of adults, which suggests that children are more prone to health risks associated with consuming contaminated water with heavy metals. This could be because children have lower body weight with a high ingestion rate. These findings are similar to those of Edokpayi et al. (2018a), who reported that children were more exposed to the potential health risks of consuming contaminated water.

The Hazard Quotients for direct ingestion (HQ_{ing}) for the dry season ranged from $1.71e-03$ - $4.80e+00$ for children in the dry season, and $7.80e-02$ - $6.80E-01$ for the wet season; meanwhile, for adults ranged between $4.49e-04$ - $1.26e+00$ and $5.10e-02$ - $1.78e-01$ for dry and wet seasons, respectively. As contributed to potential health risks and adverse effects of consuming contaminated groundwater, as its HQ_{ing} level >1 during the dry season for both children and adults. However, the

rest of the metals show no potential health risk as their HQing <1 in both seasons. The hazard quotient for dermal contact (HQ_{derm}) was also evaluated, and the values ranged from 4.27e-05 -6.88e-03, and 2.49e-05 - 4.02e-03 for both children and adults in the dry season, whereas in the wet season, it ranged from 8.16e-05 - 6.23e-03 for children, and 2.77e-05 - 2.11e-03 for adults. All the heavy metals' HQ_{derm} <1 in both seasons; therefore, there is no potential health risk posed by these metals via dermal contact in both children and adults.

(ii) Chronic Daily Intake and Carcinogenic Risk Assessment

The CDI and CR_{ing} mean values for the heavy metals present in groundwater sampled from the spring and households through direct ingestion and dermal contact for both children and adults are shown in Tables 4.8 and 4.9 for dry and wet seasons. The CDI via ingestion (CDI_{ing}) values for the selected metals ranged from 1.20e-04 - 5.56e-02 and 3.14e-05 - 1.46e-02 for children and adults in the dry season (Table 4.8); meanwhile, the index for the wet season ranged from 1.36e-02 - 1.36e-01, and 3.55e-03 - 3.57e-02 (Table 4.9), respectively. The CDI_{ing} levels of heavy metals throughout the study ascended in order of Cd, Cr, Hg, Sb, Pb, Se, As, Cu, Ni, Zn, Mn, Al, and Fe in the dry season, and Pb, Cd, Cr, As, Ni, Se, Sb, Hg, Cu, Mn, Zn, Al, and Fe in the wet season. High CDI_{ing} values of Fe were observed for both age groups in both dry and wet seasons. This study suggests natural factors such as soil erosion, run-off, weathering of rocks, and dissolving of minerals as the major causes of Fe in groundwater.

The selected heavy metals (As and Ni) were estimated to have a carcinogenic risk (CR_{ing}) for the groundwater in the study areas in the dry season. The elevated concentrations of As and Ni during the dry season are due to anthropogenic activities and geogenic sources such as wastewater recharge, rock and water interaction, agricultural activities, and weathering (Ullah et al., 2022). The CR_{ing} values for children and adults ranged from 2.04e-06 - 2.08e-02, and 5.34e-07 - 5.45e-03 for the dry season; meanwhile, in the wet season, no carcinogenic risk was posed by all the heavy metals as none of them were detected. This study shows that As and Ni could be hazardous to both children and adults, as their carcinogenic index values are above the recommended limit of USEPA (<1e-04) in the dry season. CR_{ing} of As and Ni presented values of 2.16e-03 and 2.08e-02 for children and 5.66e-04 and 5.45e-03 for adults, assuming high cancer risk, more especially for children. These results request for attention to As and Ni, as it is revealed that children are more exposed to the risks than adults.

Edokpayi and colleagues (2018b) reported that the interaction of groundwater and surface water resulting from excessive infiltration of rainwater carrying Copper from automobiles can increase the amount of this metal in groundwater. The presence of these metals in the sampled groundwater can

enhance cancer effects on humans. The findings of this study reveal that all the studied age groups are prone to be affected by cancer, with the chances of children being more exposed to cancer risks than adults. This study's findings are like those of Edokpayi et al. (2018b), which reported elevated CRing levels of Pb and Cr in the groundwater samples from household and communal boreholes in the Muledane area within the Vhembe district. It is therefore similar concerning the CRing levels of Pb in the groundwater. Although the Pb CRing values of this study are within the recommended range, due to its level of toxicity, its level of exposure is concerning. Sharma et al. (2021) also conducted a study in India that reported children being more prone to carcinogenic risks than adults due to ingestion of Fe and Mn in groundwater. Krishna et al. (2019) also reported that the high CDI is mostly due to human activities such as the usage of agricultural chemicals, which are left as runoff from the fields. Overall, mitigation measures need to be considered to avoid the possible carcinogenic risks for residents within the study areas.

Table 4.8: Dry season HHRA indices for cancer risks from direct ingestion and dermal contact for children and adults

Heavy metal	Exping (Children)	Exping (Adults)	Expderm (Children)	Expderm (Adults)	HQing (Children)	HQing (Adults)	HQderm (Children)	HQderm (Adults)	CDIing (Children)	CDIing (Adults)	CRing (Children)	CRing (Adults)
Pb	2.4e-04	6.29e-05	8.80e-08	5.14e-08	1.71e-03	4.49e-04	2.10e-04	1.22e-04	2.40e-04	6.29e-05	2.04e-06	5.34e-07
Fe	5.56e-02	1.46e-02	2.04e-05	1.19e-05	7.94e-02	2.08e-02	1.46e-04	8.50e-05	5.56e-02	1.46e-02	ND	ND
Cd	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cr	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Al	2.33e-02	6.1e-03	8.54e-06	4.99e-06	1.66e-01	4.36e-02	4.27e-05	2.49e-05	2.33e-02	6.10e-03	ND	ND
As	1.44e-03	3.77e-04	5.28e-07	3.09e-07	4.80e+00	1.26e+00	4.40e-03	2.57e-03	1.44e-03	3.77e-04	2.16e-03	5.66e-04
Ni	1.22e-02	3.21e-03	4.49e-06	2.62e-06	6.12e-01	1.60e-01	5.61e-03	3.28e-03	1.22e-02	3.21e-03	2.08e-02	5.45e-03
Mn	1.8e-02	4.71e-03	6.60e-06	3.86e-06	7.50e-01	1.96e-01	6.88e-03	4.02e-03	1.80e-02	4.71e-03	ND	ND
Zn	1.79e-02	4.68e-03	6.56e-06	3.83e-06	5.96e-02	1.56e-02	1.09e-03	6.39e-04	1.79e-02	4.68e-03	ND	ND
Cu	6.84e-03	1.79e-03	2.51e-06	1.47e-06	1.71e-01	4.48e-02	3.14e-04	1.83e-04	6.84e-03	1.79e-03	ND	ND
Se	1.2e-03	3.14e-04	4.40e-07	2.57e-07	2.40e-01	6.29e-02	2.00e-04	1.17e-04	1.20e-03	3.14e-04	ND	ND
Sb	1.2e-04	3.14e-05	4.40e-08	2.57e-08	3.00e-01	7.86e-02	5.50e-03	3.21e-03	1.20e-04	3.14e-05	ND	ND
Hg	1.2e-04	3.14e-05	4.40e-08	2.57e-08	4.00e-01	1.05e-01	1.47e-04	8.57e-05	1.20e-04	3.14e-05	ND	ND

Table 4.9: Wet season HHA indices for cancer risks from direct ingestion and dermal contact for children and adults

Heavy metal	Exping (Children)	Exping (Adults)	Expderm (Children)	Expderm (Adults)	HQing (Children)	HQing (Adults)	HQderm (Children)	HQderm (Adults)	CDling (Children)	CDling (Adults)	CRing (Children)	CRing (Adults)
Pb	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fe	1.36e-01	3.57e-02	4.99e-05	1.69e-05	1.95e-01	5.10e-02	3.57e-04	1.21e-04	1.36e-01	3.57e-02	ND	ND
Cd	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cr	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Al	4.45e-02	1.17e-02	1.63e-05	5.53e-06	3.18e-01	8.33e-02	8.16e-05	2.77e-05	4.45e-02	1.17e-02	ND	ND
As	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mn	1.63e-02	4.27e-03	5.98e-06	2.03e-06	6.80e-01	1.78e-01	6.23e-03	2.11e-03	1.63e-02	4.27e-03	ND	ND
Zn	2.34e-02	6.013e-03	8.58e-06	2.91e-06	7.80e-02	2.04e-02	1.43e-03	4.85e-04	2.34e-02	6.13e-03	ND	ND
Cu	1.36e-02	3.55e-03	4.97e-06	1.69e-06	3.39e-01	8.88e-02	6.22e-04	2.11e-04	1.36e-02	3.55e-03	ND	ND
Se	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sb	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

*ND_Not Detected

The computed values for HI (sum of HQs) (Table 4.10) for children were 7.60e+00 and 1.62e+00 in dry and wet seasons, respectively. The adults' indices were 2.00e+00 and 4.25e-01 for the two seasons. These HI values are >1, and this could have been driven by high HQs for As and Ni, showing that these metals should be considered more in mitigation efforts. A study by Odiyo et al. (2020b) reported HI values >1 for both children and adults, which correspond to the outcomes of this study. Generally, HI and HQ for As and Ni in both seasons via direct ingestion and dermal contact were >1. This means that the use of spring water within the study areas poses adverse hazardous health impacts to both children and adults (Naveedulla et al., 2014).

Table 4.10: Summary averages of HI for the dry and wet seasons

Heavy metal	Dry season		Wet season	
	HQing+HQderm (Children)	HQing+HQderm (Adults)	HQing+HQderm (Children)	HQing+HQderm (Adults)
Pb	1.92e-03	5.71e-04	ND	ND
Fe	7.95e-02	2.09e-02	1.95e-01	5.11e-02
Cd	ND	ND	ND	ND
Cr	ND	ND	ND	ND
Al	1.66e-01	4.36e-02	3.18e-01	8.33e-02
As	4.80e+00	1.26e+00	ND	ND
Ni	6.18e-01	1.64e-01	ND	ND
Mn	7.57e-01	2.00e-01	6.86e-01	1.80e-01
Zn	6.07e-02	1.62e-02	7.94e-02	2.09e-02
Cu	1.71e-01	4.50e-02	3.40e-01	8.90e-02
Se	2.40e-01	6.30e-02	ND	ND
Sb	3.06e-01	8.18e-02	ND	ND
Hg	4.00e-01	1.05e-01	ND	ND
ΣHI	7.60e+00	2.00e+00	1.62e+00	4.25e-01

4.7 Quantitative Microbial Risk Assessment (QMRA)

Previous literature has reported that *E. coli* is often used in the computation of Quantitative Microbial Risk Assessment, and it is commonly known to cause diseases (Ahmed et al., 2020). Pathogens contaminating groundwater leave the water toxic for domestic use. Tables 4.11 and 4.12 present the QMRA results for the samples collected from the springs and households of Matsa, Mamvuka, and Manyii villages in the dry and wet seasons. The microbial water quality analyses reported that the sampled water is contaminated with *E. coli* and total coliform (Figures 4.6 (a) and (b)). The average ingested doses of *E. coli* ranged from 12-140 CFU/100 mL and 12-252 CFU/100 mL for the dry and wet seasons, respectively.

The average doses acquired by Ahmed and colleagues (2020) and Odiyo and colleagues (2020a) in India and the Vhuronga 1 region in Limpopo Province reported the ranges of ingested doses of *E. coli* to be 3.31-92.5 and 0-2.50 CFU/day, respectively. On the other hand, this study reports similar values to those of Odiyo and colleagues (2020a) in both dry and wet seasons. Illnesses such as vomiting, headaches, abdominal cramps, and nausea could result from the consumption of *E. coli* contaminated water (WHO, 2023). The wet season ranges for risk of infection per day are higher than the dry season, and this could be due to more waste from livestock and agricultural run-off to the water bodies since there is more precipitation in the wet season than the dry season.

The QMRA technique was further used in this study to anticipate the probability of infection per year and illness within the study areas during the dry and wet seasons because of exposure to microbiologically unsafe water. All the sampling points had an extremely high annual *E. coli* risk infection of 100%, while the risk of illness was 25% (Tables 4.11 and 4.12). The acquired values for risk of infection per year for this study are similar to those of Ahmed and colleagues (2020), with recorded values of 97.9-100 %. Furthermore, they reported the risk of illness to range from 34.9-35%. Odiyo et al., (2020a) and Enitan-Folami et al. (2020) declared the extensive breakout of diarrhea infection as a result of consuming groundwater contaminated with *E. coli*-contaminated within the Vhembe District. This shows that these contaminants are diarrheagenic and are critical to the health of rural communities within the Vhembe District.

Another similar QMRA study was conducted by Kouname et al. (2017) where they evaluated the health risks associated with the consumption of salad irrigated with wastewater in Cote d'Ivoire. In this study, two pathogens, including *E. coli* were evaluated as the diarrhea causing organisms, and the results were evaluated using the exponential and the beta-Poisson model. Results from their study anticipated that the risks of diarrhea from consuming the contaminated water ranged between 0.002%

and 0.046% for *E. coli* O157:H7. Further, they reported the risks of diarrhea from the consumption of green salad, with the annual risk of *E. coli* O157:H7 ranging from 0-1 per person.

Table 4.11: Risk probability of infection for Matsa, Mamvuka, and Manyii villages households in the dry season

Sampling Point	Dose Jul	Dose Aug	Average Dose (CFU/100 mL)	Pinf/day (CFU/day)	Pinf/year	Pillness
Matsa S1	48	232	140	0.21	1	0.25
Matsa S1H1	144	72	108	0.20	1	0.25
Matsa S1H2	56	88	72	0.18	1	0.25
Mamvuka S1	16	40	28	0.14	1	0.25
Mamvuka S1H1	24	8	16	0.11	1	0.25
Mamvuka S1H2	40	16	28	0.14	1	0.25
Mamvuka S2	24	40	32	0.14	1	0.25
Mamvuka S2H1	16	48	32	0.14	1	0.25
Mamvuka S2H2	48	28,8	38,4	0.15	1	0.25
Manyii S1	24	104	64	0.18	1	0.25
Manyii S1H1	0	24	12	0.10	1	0.25
Manyii S1H2	24	16	20	0.12	1	0.25

Table 4.12: Risk probability of infection for Matsa, Mamvuka, and Manyii villages' households in the wet season

Sampling Point	Dose Sep	Dose Nov	Average Dose (CFU/100 mL)	Pinf/day (CFU/day)	Pinf/year	Pillness
Matsa S1	72	0	36	0.15	1	0.25
Matsa S1H1	368	16	192	0.23	1	0.25
Matsa S1H2	16	8	12	0.10	1	0.25
Mamvuka S1	32	32	32	0.14	1	0.25
MamvukaS1H1	72	8	40	0.15	1	0.25
MamvukaS1H2	32	16	24	0.13	1	0.25
Mamvuka S2	96	208	152	0.22	1	0.25
MamvukaS2H1	40	24	32	0.14	1	0.25
MamvukaS2H2	72	232	152	0.22	1	0.25
Manyii S1	176	328	252	0.24	1	0.25
Manyii S1H1	80	16	48	0.16	1	0.25
Manyii S1H2	32	24	28	0.14	1	0.25

4.8 Water Treatment Techniques

Various water purification methods were used to find the most effective water purification method that can be recommended to the communities of Matsa, Mamvuka, and Manyii. From Figure 4.7 (a) below, chlorine tablets and plasma treatment were the best techniques for removing 100 % of *E. coli* (3145 CFU/100 mL) from the Manyii spring water. Moreover, at Mamvuka S2, chlorine tablets, boiling, and plasma treatment were the best employed techniques to kill 100 % of *E. coli* (1975 CFU/100 mL). From the results presented, the three methods (boiling, plasma treatment, and chlorine tablets) could be the recommended water purification methods as they removed 100% of the pathogens from the contaminated water; although boiling could not kill everything at the Manyii spring, however, it removed 99.46 % of the *E. coli*. Ceramic filters and bleach removed 99.4% and 99.24%, 98.79% and 99.54% at the Manyii and Mamvuka S2 springs, respectively.

The presence of total coliform from Manyii and Mamvuka S2 was extremely high; therefore, the use of the plasma treatment technique removed 100% of the total coliforms (10575 CFU/100 mL) from the Mamvuka S2 spring and 99.82% at the Manyii spring. The use of chlorine tablets removed 99.96% and 99.91% of the total coliforms present in the spring water at Manyii and Mamvuka S2 springs, respectively (Figure 4.7 (b)). The log reduction graph (Figure 4.8) illustrates how effective each treatment method is at eliminating *E. coli* and Total Coliforms at the Manyii and Mamvuka S2 springs. Plasma technology and Chlorine tablets had the highest log reduction, ranging between 4.3 to 4.5, meaning they removed almost all the microorganisms present in water. Boiling treatment was also effective, especially at Mamvuka S2. Ceramic filters illustrated low log reduction ranging between 1.8 to 2.3, meaning they were less effective compared to other methods. The graph (Figure 4.8) illustrates that chlorine tablets and plasma technology were the most effective at eliminating bacteria in water.

Moreover, the final *E. coli* and Total Coliforms graph (Figure 4.9) illustrates the remaining pathogen levels after using various water treatment methods at the selected springs. Plasma technology had the lowest final counts, with both *E. coli* and Total Coliforms reduced to zero, indicating high effectiveness. Boiling also showed low pathogenic levels, especially at Mamvuka. Contrarily, ceramic filters and bleach left higher final levels, especially at Manyii, meaning they are less effective. Overall, this graph illustrates that plasma, chlorine, and boiling are the most effective and reliable in reducing microorganisms in water. A similar study was conducted by Ihsan and Derosya (2024), who reported and recommended the use of chlorine tablets as it is easy to employ, cheap, and less toxic to the environment. Furthermore, Naicker et al. (2023) compared various water treatment methods as of this study and reported that plasma technology and chlorination are effective in removing contaminants from contaminated water.

A two sample means t-test conducted showed that across all methods, there was no statistical significance difference in the treatment effectiveness. The t-test conducted showed that the t-statistic for the ceramic filter method was 1 with a critical t-value of 12.7 and p-value = 0.49. The t-statistic for chlorine tablets 1 with a critical t-value of 12.7 and p-value = 0.5, while the boiling t-test showed the t-statistics of 1.02, critical t-value of 12.7, and a p-value of 0.49. Further, the bleach and plasma t-test were 1, critical t-value of 12.7, and p-value was 0.48 and 0.5, respectively. These results show an insignificant effect, and it can therefore be concluded that the water purification methods tested are all effective and can all treat water, as there is no statistical evidence that one method outperforms the other; however, the cost of the methods determines which one can be recommended for the communities.

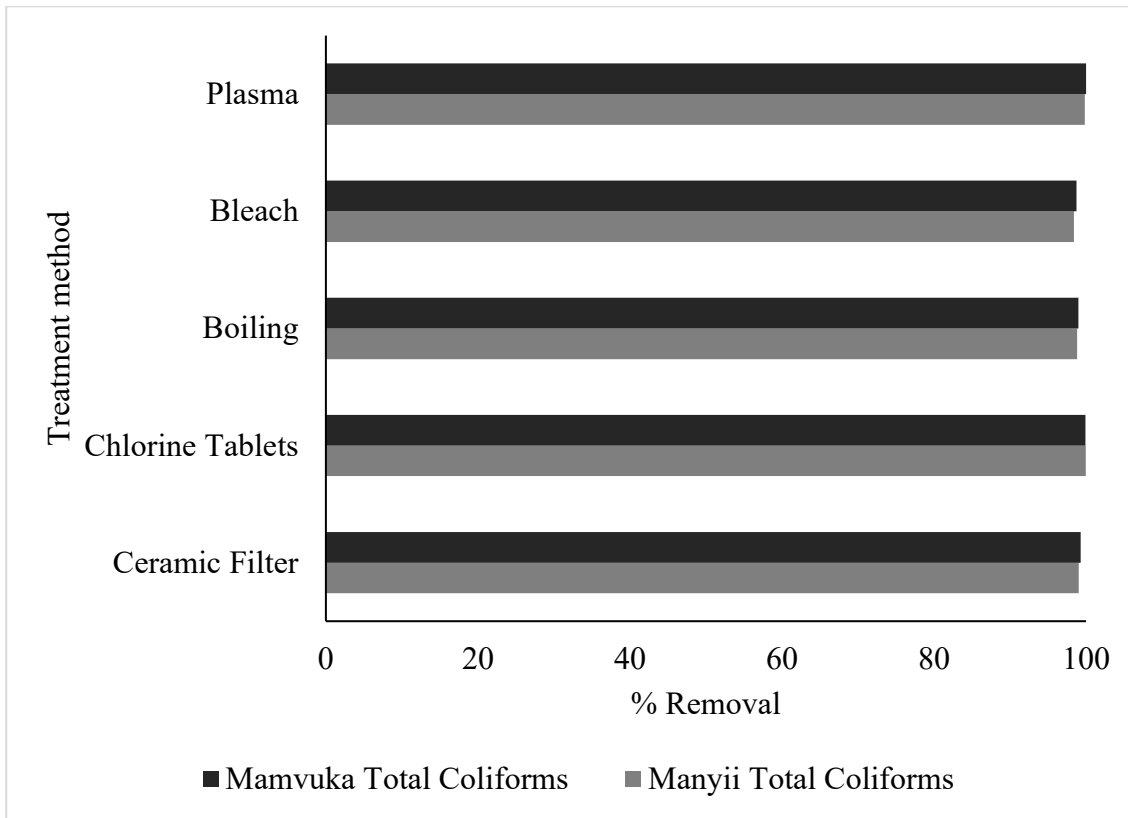


Figure 4.7 (a): Percentage removal for the employed water treatment methods- *E. coli*

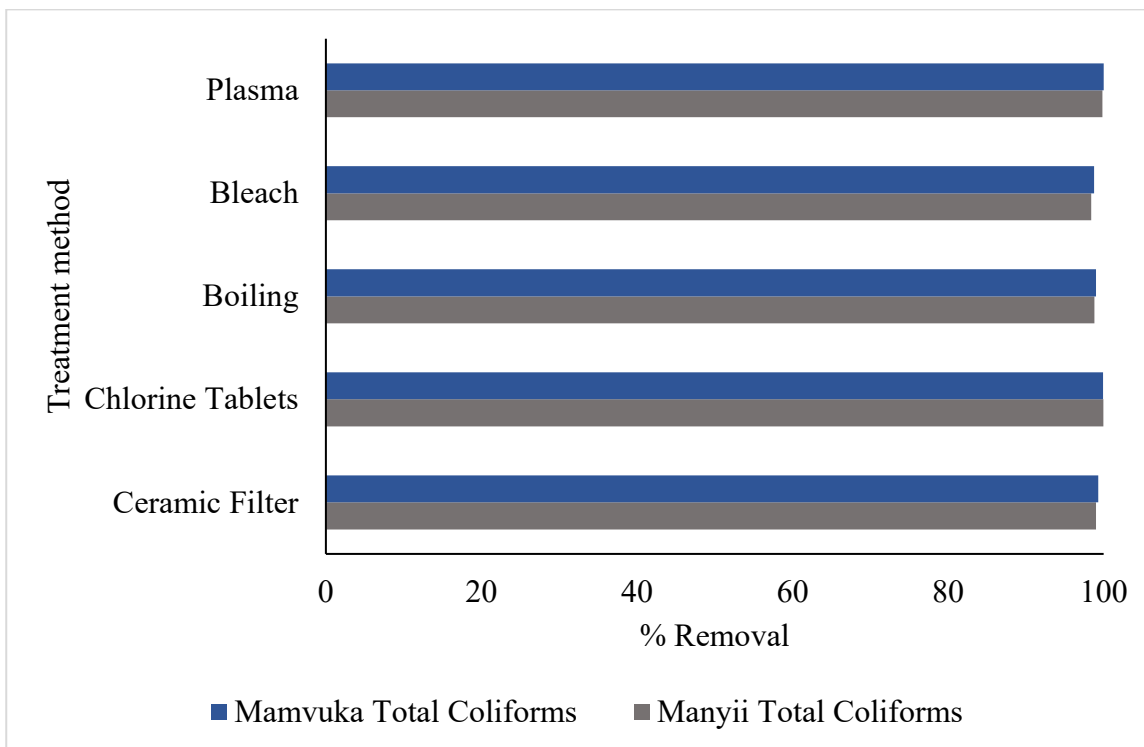


Figure 4.7 (b): Percentage removal for the employed water treatment methods- Total Coliforms

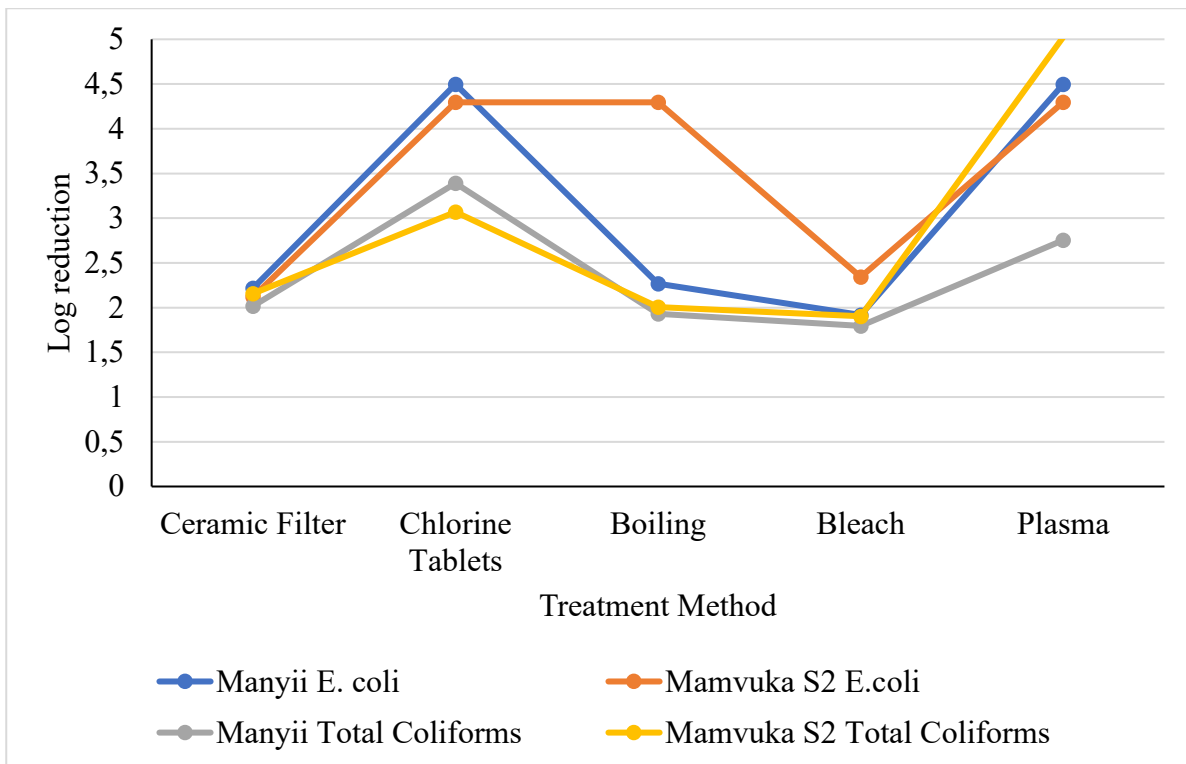


Figure 4.8: Log reduction for the treated water

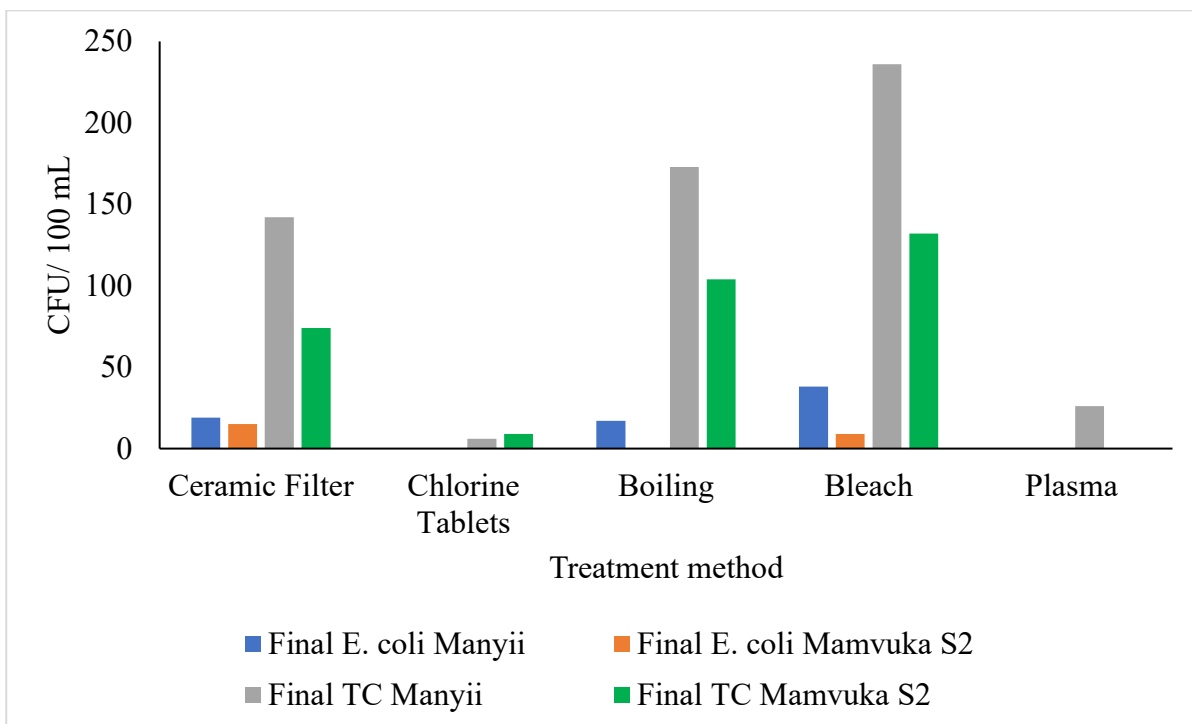


Figure 4.9: *E. coli* and Total Coliforms count after treatment

Moreover, a toxicology test was done to test the treatment methods' influence on the environment (Table 4.13). The ECOSAR results for the assessed water treatment methods showed varying degrees of environmental toxicity based on the LC50 and EC50 values. Chlorine tablets showed high LC50 values for fish (16300 mg/L), Daphnia (7090 mg/L), and green algae (1770 mg/L), meaning it has low aquatic toxicity. Plasma technology produced two oxidants, namely hydrogen peroxide and Ozone. Hydrogen peroxide showed moderate toxicity, with low LC50 and EC50 values for fish (3.30 mg/L), daphnia (26.7 mg/l), and algae (1.62 mg/L). Ozone demonstrated high LC50 values for fish (14900 mg/L), daphnia (6510 mg/L), and algae (1620 mg/L), suggesting low toxicity. Bleach showed moderate toxicity to fish (1.63 mg/L) and algae (1.77 mg/L); meanwhile, daphnia's LC50 is 16300 mg/L, indicating low toxicity. These tests indicate that even though all methods are effective for treating water, bleach and Plasma may pose higher ecological risks compared to others.

Table 4.13: Toxicological results for the treatment methods employed

Method	Chemical	Fish LC50 (mg/L)	Daphnid LC50 (mg/L)	Algae EC50 (mg/L)	Toxicity Level
Chlorine Tablets	HOCl	1.63e04	7.09e03	1.77e03	Low
Plasma	H ₂ O ₂	3.30e00	2.67e01	1.62e00	Moderate
	O ₃	1.49e04	6.51e03	1.62e03	Low
Bleach	NaOCl	1.6304	1.63e04	1.77e03	Moderate

4.9 Questionnaire analysis

In this study, 15 interview participants were administered questionnaires, and all were completed. From Figure 4.10 below, 46.67 % of households from the study areas had their primary drinking water source as spring water, 26.67% depended on their private boreholes, while the other 26.67% bought water for their household uses. From the households that use spring water as a primary source (n=7), 14.29% reported that they have been using spring water for a period of one to five years, whereas 85.71% were reported to have been using that water for over 10 years. The residents reported that they have been using the spring water since they were born; therefore, they never had access to municipal-treated water. It was further reported that of those whose primary source of drinking water is spring, 14.29% depend on private boreholes as a secondary source, 42.86% have no other sources, while the other 42.86% depend on other sources such as rainfall and buying (Table 4.14).

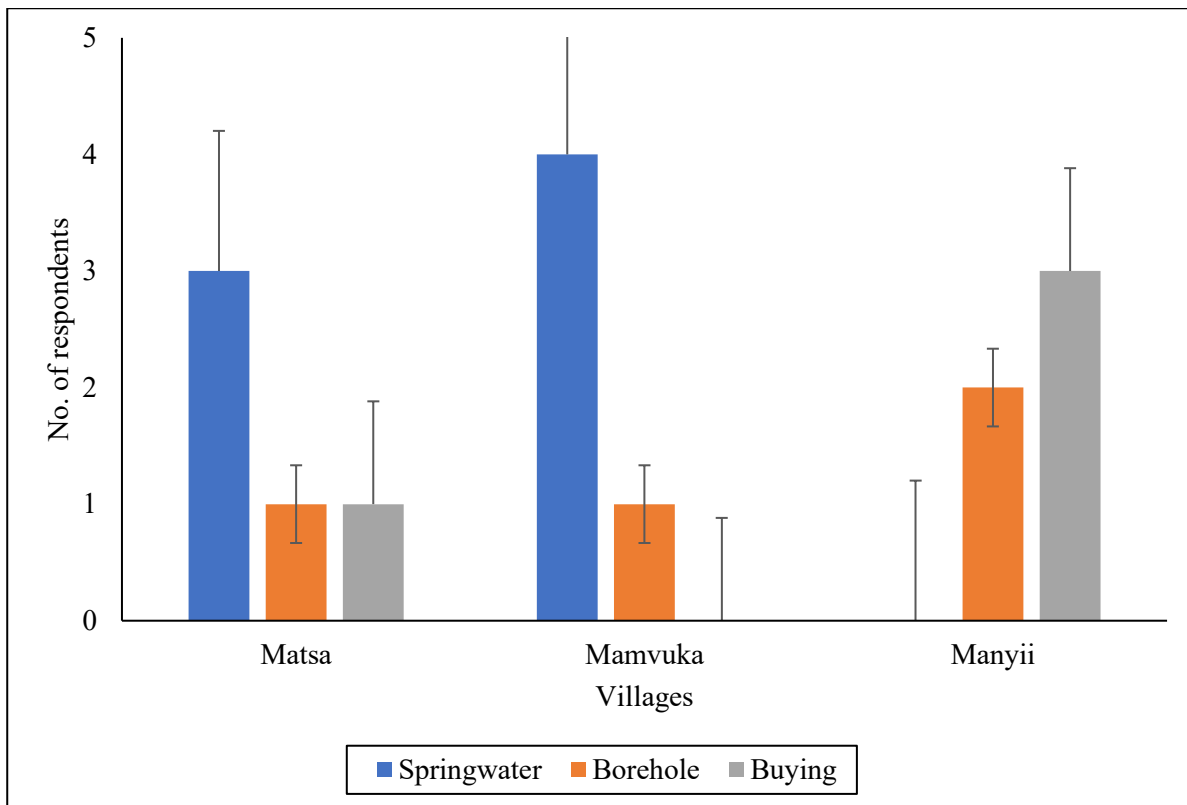


Figure 4.10: Primary water sources in the three study areas. Sample size (n=15)

Regardless of the water sources used by different households within the study areas, 26.67% of households responded that they treat their water before consumption, while 73.33% responded that they consume the water without any treatment (Figure 4.11). The residents from households where they do not treat their water before consumption reported that due to high prices of electricity, and insufficient funds; they are unable to treat this water, whereas some reported that they have been drinking this water for years without any treatment, and they never felt sick; therefore, there is no need for them to treat the water. Of those that treat the water before consumption (n=4, 26.67%), 20% of them use the method of boiling, while 6.67% reported using bleach.

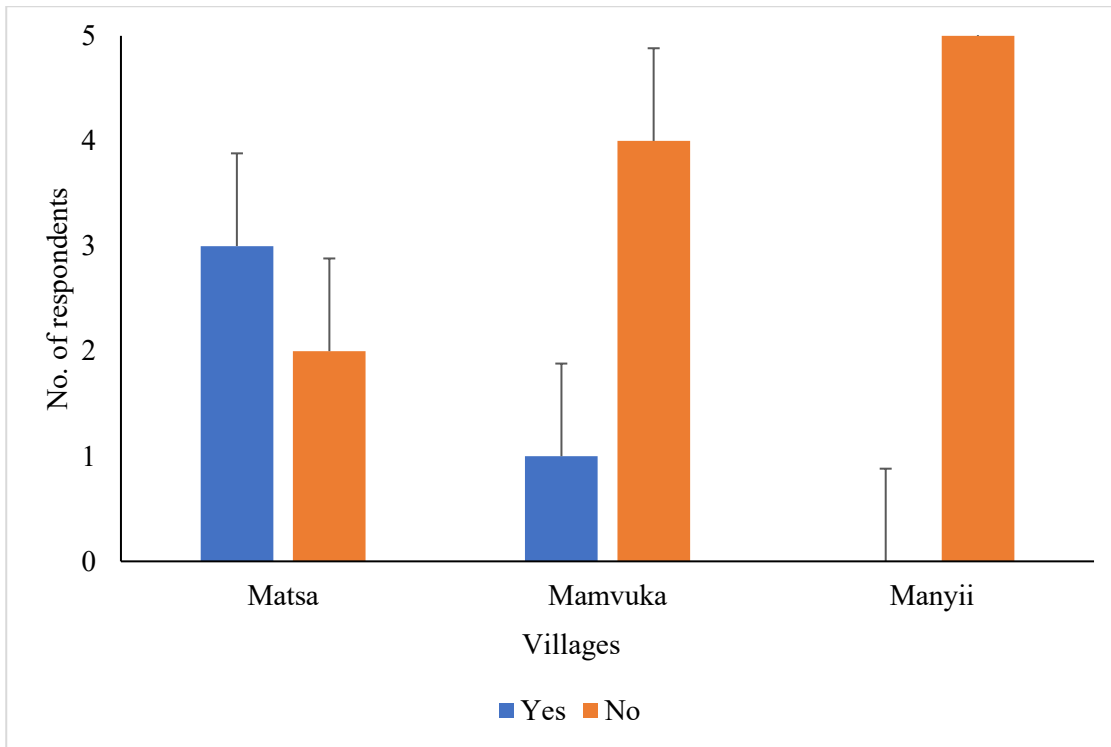


Figure 4.11: Number of people who treat and do not treat their water before consumption

The respondents (n=14, 93.33%) reported that they use the water they collect from their primary and secondary sources for all the domestic uses in their households, whereas 6.67% (n=1) reported that they only use the water for drinking (Figure 4.4). 53.33% of the households reported that they stored water in drums, 33.33% used water tanks, and 13.33% used plastic buckets (Figure 4.12, see Figure 4.14 for storage examples). The respondents (n=9, 60%) reported that they store water in the storage containers for less than a week before they collect again, 26.67% between one to two weeks, and 13.33% for about a month. All the households (n=15, 100%) reported that their storage containers were covered. Approximately 86.67% of the respondents reported that they could not get sick from consuming water, while 20% knew the risks linked with the usage of untreated water, as they perceived that it causes Cholera and Diarrhea.

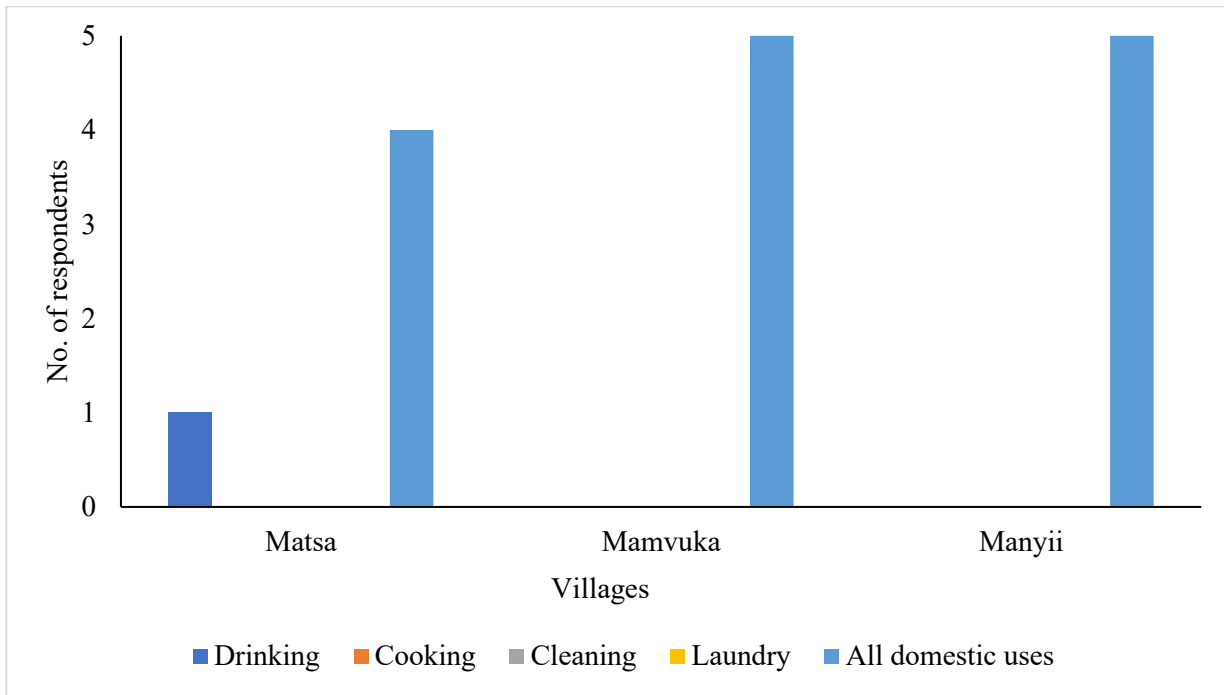


Figure 4.12: Domestic water uses in the study areas

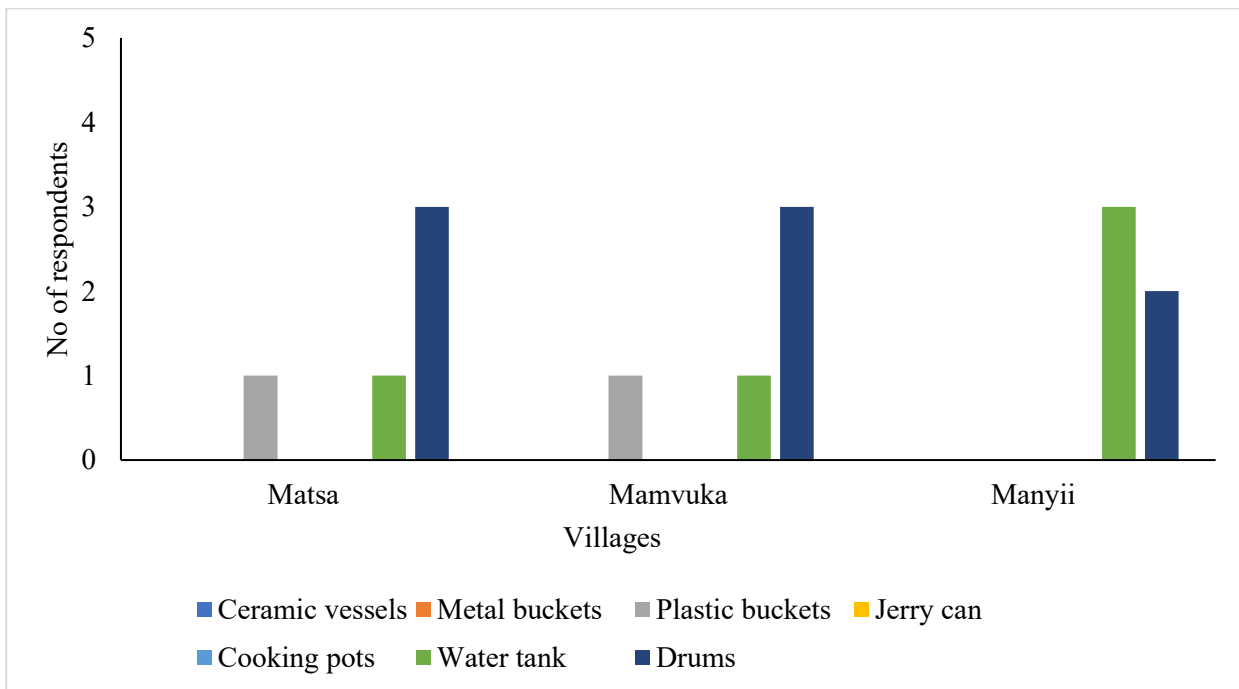


Figure 4.13: Water storage used in the three study areas

Most of this study's finding corresponds to those of Luvhimbi and colleagues (2022), as they reported that about 96.5% of the households had their storage containers covered. Further, on the treatment of water, only 7.8% of the households were reported to treat their water using the boiling method. Murei et al. (2022) conducted a similar study using structured questionnaires to understand the community's water sources, storage facilities, and treatment methods used to purify water. This study reported that only 7% of the households (70 households, 360 individuals) treated their water, even though about 31% knew about boiling water and 26% knew about the use of chlorine tablets. It further reported that people from the study area used tanks to store their water, similar to those from this study. Moreover, Luvhimbi et al. (2022) reported that 82.6% of the respondents showed that they could not get sick from consuming untreated water, whereas 17.4% reported that they could get diseases such as Cholera, diarrhoea, fever, ear infections, malnutrition, rash, and flu. These findings are similar to those of this study, as 86.67% of the respondents in this study reported that they could not get sick, and 20% perceived that they knew the consequences of consuming untreated water.

Table 4.14: Water supply and practices at Matsa, Mamvuka, and Manyii households

Variables		Frequency	%
Are you satisfied with your water?	Spring water	7	46.67
	Borehole	4	26.67
	Buying	4	26.67
For how long have you been using spring water?	1-5 years	1	14.29
	>10 years	6	85.71
Besides spring water, what is your secondary drinking water source?	None	3	42.89
	Private borehole	1	14.29
	Other	3	42.89
Do you usually treat water before use?	Yes	4	26.67
	No	11	73.33
Water purification methods?	Boil	3	20
	Bleach/Chlorine	1	6.67
Do you use the collected water for drinking only or all your domestic uses in the household?	Drinking	1	6.67
	All	14	93.33
What is your water stored in?	Plastic buckets	2	13.33
	Water tank	5	33.33
	Drums	8	53.33
For how long is the water stored before another collection?	Less than a week	9	60
	Between one to two weeks	4	26.67

	< a month	2	13.33
Are storage vessels covered all the time?	Yes	15	100
What kind of sicknesses do you think the water causes?	None	13	86.67
	Cholera	2	13.33
	Diarrhea	1	6.67

Water handling storage used in the study areas



Figure 4.14: Water handling storages used in the study areas

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The findings of this study showed that the measured physicochemical parameters, such as temperature, pH, TDS, EC, and turbidity, met the standards of WHO and SANS 241, except for the turbidity of S10 in the dry season, which ranged from 0.48-10.75 NTU. Looking at the average heavy metal concentrations recorded from all the sampling points, it can be concluded that they are within the recommended standard limits; however, certain metals, such as As, Mn, Ni, Al, Fe, and Al, exceeded the limits in both dry and wet seasons. The concentrations of heavy metals gradually increase in the wet season; hence, the consumption of the groundwater without treatment during the wet season can have adverse health effects.

The microbial results presented that the groundwater from the study areas is highly contaminated with *E. coli* and Total coliforms, with high contamination levels during the wet season, and fails to comply with the WHO and SANS 241 recommended standards. All the sampling points can be categorised as poor water quality that needs proper treatment. From the various treatment techniques applied to treat the sampled water, all the treatment methods were found to be effective and can work best to remove *E. coli* and Total coliforms. However, to avoid more ecological risks and contaminating the environment and aquatic animals, boiling, ceramic filters, and chlorine tablets are recommended as they pose low risks to the environment compared to plasma and bleach. This suggests the use of these methods by the communities of Matsa, Mamvuka, and Manyii before consumption.

The human consumption of contaminated groundwater poses non-carcinogenic health risks due to metals such as Fe, Al, Mn, and Zn levels for both adults and children. Overall, ingestion and dermal contact with the contaminated groundwater could cause adverse health effects. Heavy metals (As and Ni) in the groundwater pose carcinogenic risk for both children and adults, and they exceed the recommended limits of USEPA ($<1e-04$).

The wet season samples showed a higher risk of infection from *E. coli*, with the probability of illness of 25% for all the sampling points, suggesting a high risk of public health concerns. Therefore, it can be concluded that the communities of Matsa, Mamvuka, and Manyii are prone to being infected with waterborne diseases and health concerns due to the chemical and microbial contamination, and this supports the need for water treatment within the areas.

Key findings from the structured interviews revealed that most households in these communities depend on spring water as their primary drinking source, with most of them using it for over 10 years and having no access to municipal water. Only a few households treat their water, with boiling being the main treatment method employed, while most consume it untreated because of costs and believing it is safe for use. Water in these communities is used for all domestic needs, and stored in covered drums or tanks, mostly for less than a week before another collection. Meanwhile, storage practices are good, but most of the residents are not aware of the associated health risks of consuming contaminated water, with only a few associating untreated water with illnesses such as cholera and diarrhea.

Limitations of the study

The limitations of this study are as follows:

- Lack of historical data on water quality and health issues related to the consumption of groundwater in these villages
- Lack of awareness amongst villagers about water quality issues resulting in resistance to participate in surveys

5.2 Recommendations

Regular groundwater monitoring should be conducted to determine the water quality within the study areas. More of the microbial parameters for water quality need to be assessed in future studies. Moreover, an understanding needs to be raised in the communities about the importance of water management, together with the health effects of consuming untreated and contaminated water. The communities of Matsa, Mamvuka, and Manyii should be notified of possible treatment options that they can use to treat their water before consumption. Affordable water treatment systems should be implemented to remove hazardous microbiological contaminants.

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APPENDICES

Appendix A

Table A1: July heavy metal concentrations in groundwater in mg/L

Sampling Point	Sb	As	Cd	Cr	Cu	Pb	Mn	Hg	Ni	Se	Zn	Fe	Al
Matsa S1	<0.001	0.005	<0.001	<0.025	0.028	0.001	<0.025	0.002	<0.025	<0.001	0.556	0.47	0.31
Matsa S1 H1	<0.001	0.002	<0.001	<0.025	0.016	<0.001	<0.025	<0.001	<0.025	<0.001	0.395	0.25	0.14
Matsa S1 H2	0.001	0.002	<0.001	<0.025	<0.010	<0.001	<0.025	<0.001	<0.025	0.001	<0.025	0.55	0.38
Mamvuka S1	<0.001	<0.001	<0.001	<0.025	0.012	<0.001	<0.025	<0.001	<0.025	<0.001	0.042	0.18	0.15
Mamvuka S1 H1	<0.001	<0.001	<0.001	<0.025	0.010	0.001	<0.025	0.001	<0.025	<0.001	<0.025	0.64	0.18
Mamvuka S1 H2	<0.001	<0.001	<0.001	<0.025	0.072	<0.001	<0.025	0.001	0.102	<0.001	<0.025	0.51	0.21
Mamvuka S2	<0.001	0.002	<0.001	<0.025	0.013	<0.001	0.150	<0.001	<0.025	<0.001	<0.025	0.21	0.18
Mamvuka S2 H1	<0.001	0.001	<0.001	<0.025	<0.010	<0.001	<0.025	<0.001	<0.025	<0.001	<0.025	0.15	0.19
Mamvuka S2 H2	<0.001	<0.001	<0.001	<0.025	0.014	<0.001	<0.025	<0.001	<0.025	<0.001	0.026	0.59	0.19
Manyii S1	<0.001	<0.001	<0.001	<0.025	<0.010	<0.001	<0.025	<0.001	<0.025	<0.001	<0.025	0.08	0.12
Manyii S1 H1	<0.001	0.003	<0.001	<0.025	0.017	<0.001	<0.025	<0.001	<0.025	<0.001	0.615	0.15	0.12
Manyii S1 H2	<0.001	0.003	<0.001	<0.025	0.019	0.002	<0.025	<0.001	<0.025	<0.001	0.451	0.71	0.16

Table A2: August heavy metal concentrations in groundwater in mg/L

Sampling Point	Sb	As	Cd	Cr	Cu	Pb	Mn	Hg	Ni	Se	Zn	Fe	Al
Matsa S1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.05	0.06	0.21	0.18
Matsa S1 H1	<0.05	0.09	<0.05	<0.05	<0.05	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.34	0.15
Matsa S1 H2	<0.05	<0.05	<0.05	<0.05	0.20	<0.05	<0.05	<0.005	<0.05	<0.1	0.17	3.51	0.30
Mamvuka S1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	<0.05	0.22	0.18
Mamvuka S1 H1	<0.05	<0.05	<0.05	<0.05	0.10	<0.05	<0.05	<0.005	<0.05	<0.1	0.09	0.39	0.21
Mamvuka S1 H2	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.005	<0.05	<0.1	<0.05	0.17	0.16
Mamvuka S2	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	0.05	0.21	0.17
Mamvuka S2 H1	<0.05	<0.05	<0.05	<0.05	0.04	<0.05	<0.05	<0.005	<0.05	<0.1	0.05	0.14	0.10
Mamvuka S2 H2	<0.05	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.43	0.20
Manyii S1	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.005	<0.05	<0.1	0.05	0.55	0.31
Manyii S1 H1	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.005	<0.05	<0.1	0.06	0.17	0.22
Manyii S1 H2	<0.05	0.05	<0.05	<0.05	0.09	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.29	0.14

Table A3: September heavy metal concentrations in groundwater in mg/L

Sampling Point	Sb	As	Cd	Cr	Cu	Pb	Mn	Hg	Ni	Se	Zn	Fe	Al
Matsa S1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.11	0.16
Matsa S1 H1	<0.05	<0.05	<0.05	<0.05	0.14	<0.05	<0.05	<0.005	<0.05	<0.1	0.11	0.42	0.25
Matsa S1 H2	<0.05	<0.05	<0.05	<0.05	0.13	<0.05	<0.05	<0.005	<0.05	<0.1	0.13	0.24	0.35
Mamvuka S1	<0.05	<0.05	<0.05	<0.05	0.07	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.13	0.13
Mamvuka S1 H1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.09	0.15
Mamvuka S1 H2	<0.05	<0.05	<0.05	<0.05	0.08	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.13	0.36
Mamvuka S2	<0.05	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.12	0.14
Mamvuka S2 H1	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.15	0.14
Mamvuka S2 H2	<0.05	<0.05	<0.05	<0.05	0.08	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.16	0.22
Manyii S1	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	0.15	<0.005	<0.05	<0.1	0.07	2.23	0.55
Manyii S1 H1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.005	<0.05	<0.1	0.07	0.10	0.16
Manyii S1 H2	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.29	0.16

Table A4: November heavy metal concentrations in groundwater in mg/L

Sampling Point	Sb	As	Cd	Cr	Cu	Pb	Mn	Hg	Ni	Se	Zn	Fe	Al
Matsa S1	<0.05	<0.05	<0.05	<0.05	0.07	<0.05	<0.05	<0.005	<0.05	<0.1	0.29	0.12	0.17
Matsa S1 H1	<0.05	<0.05	<0.05	<0.05	0.20	<0.05	0.06	<0.005	<0.05	<0.1	0.12	3.21	0.21
Matsa S1 H2	<0.05	<0.05	<0.05	<0.05	0.31	<0.05	<0.05	<0.005	<0.05	<0.1	0.17	8.36	0.25
Mamvuka S1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.005	<0.05	<0.1	0.06	0.57	0.23
Mamvuka S1 H1	<0.05	<0.05	<0.05	<0.05	0.12	<0.05	<0.05	<0.005	<0.05	<0.1	0.08	0.28	0.19
Mamvuka S1 H2	<0.05	<0.05	<0.05	<0.05	0.15	<0.05	<0.05	<0.005	<0.05	<0.1	0.11	0.71	0.27
Mamvuka S2	<0.05	<0.05	<0.05	<0.05	0.16	<0.05	0.31	<0.005	<0.05	<0.1	0.13	2.57	1.43
Mamvuka S2 H1	<0.05	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	<0.005	<0.05	<0.1	2.55	1.55	0.69
Mamvuka S2 H2	<0.05	<0.05	<0.05	<0.05	0.13	<0.05	<0.05	<0.005	<0.05	<0.1	2.57	1.59	0.26
Manyii S1	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	0.08	<0.005	<0.05	<0.1	0.09	1.96	1.16
Manyii S1 H1	<0.05	<0.05	<0.05	<0.05	0.12	<0.05	<0.05	<0.005	<0.05	<0.1	0.26	0.87	0.53
Manyii S1 H2	<0.05	<0.05	<0.05	<0.05	0.20	<0.05	0.06	<0.005	<0.05	<0.1	0.31	1.27	0.74

Appendix B

Table B1: July anion concentrations in groundwater in mg/L

Sampling site	Cl	F	NO ₂	NO ₃	SO ₄	PO ₄
Matsa S1	14.90	0.09	<0.13	2.13	<2	<0.2
Matsa S1H1	13.38	0.16	<0.13	2.14	<2	<0.2
Matsa S1H2	250.80	0.09	<0.13	2.18	7.24	<0.2
Mamvuka S1	10.54	0.05	<0.13	1.35	3.74	<0.2
Mamvuka S1H1	9.21	<0.05	<0.13	1.33	4.52	<0.2
Mamvuka S1H2	9.90	0.06	<0.13	1.71	<2	<0.2
Mamvuka S2	127.60	0.07	<0.13	1.36	<2	<0.2
Mamvuka S2H1	18.25	0.06	<0.13	1.31	<2	<0.2
Mamvuka S2H2	7.46	0.07	<0.13	1.39	<2	<0.2
Manyii S1	13.21	0.07	<0.13	2.57	2.30	<0.2
Manyii S1H1	13.13	0.10	<0.13	2.56	2.01	0.21
Manyii S1H2	116.90	0.09	<0.13	1.78	4.86	<0.2

Table B2: August anion concentrations in groundwater in mg/L

Sampling point	Cl	F	NO₂	NO₃	SO₄	PO₄
Matsa S1	14.30	0.10	<0.13	2.35	<2	<0.2
Matsa S1H1	11.18	<0.05	<0.13	2.19	<20	<0.2
Matsa S1H2	15.52	0.10	<0.13	2.24	2.12	1.10
Mamvuka S1	11.92	0.05	<0.13	1.58	5.06	<0.2
Mamvuka S1H1	9.31	0.08	<0.13	1.63	<2	<0.2
Mamvuka S1H2	11.44	0.06	<0.13	1.59	2.20	<0.2
Mamvuka S2	11.26	0.06	<0.13	1.44	<2	<0.2
Mamvuka S2H1	12.84	0.07	<0.13	1.60	2.95	<0.2
Mamvuka S2H2	14.96	0.09	<0.13	1.97	<2	<0.2
Manyii S1	9.45	0.07	<0.13	1.40	12.21	<0.2
Manyii S1H1	12.29	0.07	<0.13	1.49	4.57	<0.2
Manyii S1H2	13.85	0.11	<0.13	2.54	<2	<0.2

Table B3: September anion concentrations in groundwater in mg/L

Sampling point	Cl	F	NO₂	NO₃	SO₄	PO₄
Matsa S1	16.67	0.08	<0.13	2.02	5.29	<0.2
Matsa S1H1	14.45	0.09	<0.13	2.12	13.45	0.22
Matsa S1H2	8.39	0.08	<0.13	1.26	<2	<0.2
Mamvuka S1	7.02	0.09	<0.13	1.8	3.36	<0.2
Mamvuka S1H1	101.1	0.06	<0.13	1.38	<2	<0.2
Mamvuka S1H2	107.6	0.07	<0.13	1.31	<2	<0.2
Mamvuka S2	9.71	0.05	<0.13	1.08	<2	<0.2
Mamvuka S2H1	13.04	0.11	<0.13	1.16	<2	<0.2
Mamvuka S2H2	<2	0.1	<0.13	1.39	<2	<0.2
Manyii S1	16.22	0.09	<0.13	1.76	<2	<0.2
Manyii S1H1	18.52	0.1	<0.13	2.03	17.95	2.82
Manyii S1H2	23.06	0.1	<0.13	2.14	6.62	0.85

Table B4: November anion concentrations in groundwater in mg/L

Sampling point	Cl	F	NO₂	NO₃	SO₄	PO₄
Matsa S1	24.16	0.13	<0.13	<0.5	4.91	0.24
Matsa S1H1	21.68	0.18	<0.13	<0.5	5.35	<0.2
Matsa S1H2	22.71	0.11	<0.13	<0.5	6.76	<0.2
Mamvuka S1	15.88	0.1	<0.13	<0.5	5.07	<0.2
Mamvuka S1H1	17.42	0.11	<0.13	<0.5	4.58	<0.2
Mamvuka S1H2	15.18	0.1	<0.13	<0.5	3.83	<0.2
Mamvuka S2	22.87	0.08	<0.13	<0.5	5.73	<0.2
Mamvuka S2H1	2.2	0.16	<0.13	<0.5	2.45	<0.2
Mamvuka S2H2	<2	0.16	<0.13	<0.5	3.29	<0.2
Manyii S1	20.46	0.12	<0.13	<0.5	3.87	<0.2
Manyii S1H1	<2	0.06	<0.13	<0.5	8.2	<0.2
Manyii S1H2	<2	0.06	<0.13	<0.5	3.56	<0.2

Appendix C

Table C1: July and August Risk Probability of infection

Sampling Point	QMRA- July					QMRA- August				
	<i>E. coli</i>					<i>E. coli</i>				
	1 mL	Dose	Pinf/day	Pinf/year	Pillness	1 mL	Dose	Pinf/day	Pinf/year	Pillness
Matsa S1	600	48	0.16	1	0.25	2900	232	0.23	1	0.25
Matsa S1H1	1800	144	0.21	1	0.25	900	72	0.18	1	0.25
Matsa S1H2	700	56	0.17	1	0.25	1100	88	0.19	1	0.25
Mamvuka S1	200	16	0.11	1	0.25	500	40	0.15	1	0.25
Mamvuka S1H1	300	24	0.13	1	0.25	100	8	0.08	1	0.25
Mamvuka S1H2	500	40	0.15	1	0.25	200	16	0.11	1	0.25
Mamvuka S2	300	24	0.13	1	0.25	500	40	0.15	1	0.25
Mamvuka S2H1	200	16	0.11	1	0.25	600	48	0.16	1	0.25
Mamvuka S2H2	600	48	0.16	1	0.25	360	28	0.14	1	0.25
Manyii S1	300	24	0.13	1	0.25	1300	104	0.2	1	0.25
Manyii S1H1	0	0	0	0	0	300	24	0.13	1	0.25
Manyii S1H2	300	24	0.13	1	0.25	200	16	0.11	1	0.25

Table C2: September and November Risk Probability of infection

Sampling Point	QMRA-September					QMRA-November				
	<i>E. Coli</i>					<i>E. Coli</i>				
	1 mL	Dose	Pinf/day	Pinf/year	Pillness	1 mL	Dose	Pinf/day	Pinf/year	Pillness
Matsa S1	900	72	0.18	1	0.25	0	0	0	0	0
Matsa S1H1	4600	368	0.25	1	0.25	200	16	0.15	1	0.25
Matsa S1H2	200	16	0.11	1	0.25	100	8	0.12	1	0.25
Mamvuka S1	400	32	0.14	1	0.25	400	32	0.18	1	0.25
Mamvuka S1H1	900	72	0.18	1	0.25	100	8	0.12	1	0.25
Mamvuka S1H2	400	32	0.14	1	0.25	200	16	0.15	1	0.25
Mamvuka S2	1200	96	0.19	1	0.25	2600	208	0.26	1	0.25
Mamvuka S2H1	500	40	0.15	1	0.25	300	24	0.17	1	0.25
Mamvuka S2H2	900	72	0.18	1	0.25	2900	232	0.27	1	0.25
Manyii S1	2200	176	0.22	1	0.25	4100	328	0.28	1	0.25
Manyii S1H1	1000	80	0.18	1	0.25	200	16	0.15	1	0.25
Manyii S1H2	400	32	0.14	1	0.25	300	24	0.17	1	0.25

Appendix D

Table D1: *E. coli* and Total Coliform count for dry and wet season

<i>E. coli</i> count	Total Coliform							
	July	August	September	November	July	August	September	November
Sampling Point S1	315	1470	735	50	420	3540	2350	460
S2	1010	600	2375	250	4105	11030	3025	1695
S3	390	585	125	65	905	7335	2740	1205
S4	150	345	230	430	3255	6200	11755	9680
S5	245	80	515	70	7865	11230	2015	9255
S6	515	165	335	105	9380	3615	6810	7940
S7	395	305	680	1975	8925	4145	4900	10575
S8	125	305	275	360	9925	725	1755	2225
S9	370	180	480	1490	2620	10650	4345	3675
S10	15	1070	1535	3145	410	9015	12385	14745
S11	0	165	515	125	5270	1645	1595	6330
S12	160	120	205	180	15595	1375	7605	5670

Appendix E: Ethical Clearance Approval



Faculty of Engineering,
Built Environment and
Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en
Inligtingtegnologie / Lefapha la Boetšenere,
Tikologo ya Kago le Theknolotši ya Tshedimošo

15 November 2024

Reference number: EBIT/260/2024

Ms OV Tshikombeni
Department: Chemical
Engineering
University of Pretoria
Pretoria 0083

Dear Ms OV Tshikombeni,

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Research Ethics Committee refers. Conditional approval is granted.

This means that the research project entitled "Water quality, health risk assessment, and treatment options for groundwater in Matsa, Mamvuka, and Manyii villages in Limpopo Province" is approved under the strict conditions indicated below. If these conditions are not met, approval is withdrawn automatically.

Conditions for approval:

Where applicable, approval from the community/village leader(s) is required.

This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Code of Ethics for Scholarly Activities of the University of Pretoria, or the Policy

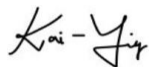
and Procedures for Responsible Research of the University of Pretoria. These documents are available on the website of the EBIT Ethics Committee.

If action is taken beyond the approved application, approval is withdrawn automatically.

According to the regulations, any relevant problem arising from the study or research methodology as well as any amendments or changes, must be brought to the attention of the EBIT Research Ethics Office.

The Committee must be notified on completion of the project.

The Committee wishes you every success with the research project.



Prof K.-Y. Chan

Chair: Faculty Committee for Research Ethics and Integrity

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION
TECHNOLOGY

Appendix F: Informed Consent

1. INFORMED CONSENT.

- 1.1. I, _____ hereby voluntarily grant my permission for participation in the project as explained to me by _____
- 1.2. The nature, objective, possible safety and health implications (if any) have been explained to me and I understand them.
- 1.3. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.
- 1.4. I understand that my participation is voluntary, and I can withdraw at any time.
- 1.5. I give my consent to be voice recorded without mentioning my name and contact details during the recording. Before I provide any information which is directly linked to my company, the researcher should show me a letter of permission from my company.
- 1.6. I understand that all data collected for this study will be stored on a safe and secure platform managed by the University of Pretoria. To be signed at location where necessary and if possible.

Participant *	Signature of participant
Place signed:	Date:

** Participant name and place of signage may be omitted if the participant so chooses.*

Designated researcher** (May NOT be omitted)	Signature of designated researcher
Place signed:	Date:

*** I affirm that I am signing this form in good faith, complying with all the necessary permissions, stipulations and requirements.*

APPENDIX G: INTERVIEW QUESTIONNAIRE

Research Project Topic: Water quality, health risk assessment, and treatment options for groundwater in Matsa, Mamvuka, and Manyii villages in Limpopo Province

Introduction: Greetings, my names are Ondwela Ventetia Tshikombeni. A master's student at the University of Pretoria under the Department of Chemical Engineering. I would like to ask you questions about your primary drinking water source and your perspective on a suitable water treatment option within your village for research purposes.

Motivation: The motivation of this study is based on the access to quality and available water for human consumption in South Africa. For the past few years, the communities of Matsa, Mamvuka, and Manyii villages have been without directed piped water from the municipality and are dependent on groundwater for drinking and other domestic uses. The situation at the Matsa, Mamvuka, and Manyii villages causes a serious threat to public health as it could lead to waterborne diseases. This study contributes to the United Nations Sustainable Development Goals (UN SDGs) goal 6 of ensuring equal access to potable water for everyone. World Health Organisation (2023) reported that approximately 703 million people globally still lack access to potable drinking water. Therefore, the purpose of this study is to understand the water quality in the Matsa, Mamvuka, and Manyii villages and its associated health risks based on their currently available water sources and to explore suitable treatment options to make the water safe depending on the detected level of contamination. It is essential to assess and implement innovative strategies for safe and sustainable drinking water sources for these communities. The success of this study would contribute to the minimisation of water-related health risks and provide an alternative treatment method.

Date: _____ Questionnaire code: _____

Town: _____ Informed consent provided: _____

Section A: Water accessibility			
#	Question	Code	Response
1	What is your primary source of drinking water? If Spring continue with question 2-3.	Municipal treated source = 01 Spring water = 02 Borehole = 03 Buying= 04 Other=05, If _____ other, specify.....	<input type="checkbox"/> <input type="checkbox"/>

2	For how long have you been using the spring water?	< 1 year=01 1-5 years=02 6-10 years=03 >10 years=04 If >10 years, please be specific.....	<input type="checkbox"/> <input type="checkbox"/>
3	Besides spring water, what is your secondary drinking water source?	None = 01 River or Stream = 02 Private borehole = 03 Other = 04 If other, specify.....	<input type="checkbox"/> <input type="checkbox"/>
4	Do you treat your collected water prior drinking?	Yes = 01 No = 02	<input type="checkbox"/> <input type="checkbox"/>
5	Which water purification or treatment method do you usually use at household level for the drinking water?	Storage and Settlement= 01 Boil=02 Use Bleach/Chlorine=03 Strain using a cloth=04 Other = 05, Specify.....	<input type="checkbox"/> <input type="checkbox"/>
6	Do you use this collected water for drinking only or all your domestic uses in your household?	Drinking=01 Cooking=02 Cleaning=03 Laundry=04 All of the above=05	<input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>
7	What is your collected water stored in?	Ceramic vessels = 01; metal buckets = 02; plastic buckets = 03; jerrycan = 04; cooking pots = 05; water tank =06; Drums= 07; Other= 08, Specify.....	<input type="checkbox"/> <input type="checkbox"/>
8	For how long is the water usually stored before collecting another fresh water?	< a week= 01 1 to 2 weeks = 02 < a month = 03	<input type="checkbox"/> <input type="checkbox"/>
9	Are storage vessels covered all the time?	Yes = 01 No = 02	<input type="checkbox"/> <input type="checkbox"/>
10	What kind of sicknesses do you think the consumption of this water causes?		
	Diarrhea		<input type="checkbox"/> <input type="checkbox"/>
	Cholera		<input type="checkbox"/> <input type="checkbox"/>
	If other, Specify _____		

END

APPENDIX H: WATER STORAGES IN THE STUDY AREAS

