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Water Quality Assessment of Rooftop-Harvested Rainwater and its Potential Uses in Vhembe District Municipality

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A dissertation submitted to the Faculty of Science, Engineering, and Agriculture in fulfillment of the award of Master of Earth Sciences' degree in Hydrology and Water Resources

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DECLARATION

By submitting this dissertation, I, Vele Livhuwani hereby declare that the work presented in this dissertation entitled “Water Quality Assessment of Rooftop-Harvested Rainwater and its Potential Uses in Vhembe District Municipality”, being submitted for the award of Master’s degree in the University of Venda, under the Faculty of Science, Engineering, and Agriculture, is my original work and has not been submitted before for any examination, diploma, degree, or other similar qualification in this or any other university. Other persons’ information used in this study has been acknowledged and all references cited are compiled in a list of references.

Signed…………………………..   Date……07/08/2023…………………

Vele Livhuwani

ABSTRACT

Rainwater is a major water source which can be harvested and used for various domestic purposes. It is believed that rainwater is free from impurities and soft in nature, making it an alternative source of water for various potential uses, if harvested. This study explores the potential uses of harvested rainwater in the Vhembe District of South Africa. To achieve this, the perception of people towards rainwater's uses, was assessed as well as the quality of rainwater harvested from various roof types. The physicochemical (pH, turbidity, electrical conductivity, salinity, temperature, and total dissolved solids), microbiological (faecal coliform and total coliform) characteristics, and heavy metals levels in the water were monitored using standard protocols, such as multimeter, membrane filtration technique, and ICP-OES. The relationship between water quality and roof types was also evaluated.

Using 110 questionnaires, a survey was conducted with community members who harvest rainwater. The results showed that washing of clothes accounted for the most use of harvested rainwater at 82.73%, in Vhembe District Municipality (VDM). The people of VDM perceived the roof-harvested rainwater as their alternative source of water after municipal-supplied water; 3.6% of the respondents indicated that they have not experienced any adverse effects from the use of harvested rainwater. The reason why residents consider rainwater harvesting has been reported to be mainly due to poor service delivery with respect to water supply by the municipalities.

Most of the harvested rainwater's physical parameters analysed were within the permissible limit of the South African National Standards and World Health Organisation Standards. In comparing all the roof types (slate, steel, aluminium, concrete and thatched) used as catchments for harvesting rainwater, thatched roofs showed very poor standards in terms of physicochemical and microbiological quality of the collected rainwater.

The Water Quality Index was evaluated based on the physicochemical parameters focusing on heavy metals and *E. coli*. All the roof-harvested samples collected in the VDM from the three research areas have an excellent water quality, except water collected from thatched roofs. The results showed that the inclusion of *E. coli* as a parameter to compute WQI will result in high water quality index value, thereby, proving that pathogenic microorganism play a major role in reducing the quality of water. No carcinogenic risk was computed, based on the levels of trace metals recorded in this study, as the computed Hazard Index and Quotient were all less than 1. Quantitative microbial risk assessment (QMRA), a modelling technique used to estimate the probability of infection and subsequent illness when exposed to pathogenic microorganisms was also calculated. The QMRA calculations all showed the possibility of risk associated with the consumption of rooftop harvested rainwater. This means that continuous consumption of rooftop harvested rainwater without any treatment could pose a great risk to human health, therefore, simple point-of-use water treatment method is recommended prior to the consumption of rooftop-harvested rainwater such as boiling and addition of bleach in order to disinfect harvested rainwater before consumption and food preparation.

KEYWORDS: Perception, QMRA, Rainwater harvesting, Rooftop materials, Water quality, Water quality index

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DEDICATION

This dissertation is dedicated to my Lord and Saviour, Jesus Christ, for the life He has graced me with. “A little one shall become a thousand, and a small one a strong nation. At the right time, I, the Lord, will make it happen.” (Isaiah 60:22)

I also dedicate my dissertation to my supervisor and my co-supervisor who have been giving me continuous support. To my grandmother, mother, the rest of my family, church family (CWMC) and to my many friends, I appreciate having all of you in my life.

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SCHOLARLY OUTPUTS FROM THIS STUDY

TOPIC	RESEARCH OUTPUT	STATUS
Physicochemical and microbiological quality of roof harvested rainwater in Vhembe District Municipality	Article	In draft, to be published with International Journal of Engineering and Technology (IJET).
Perception and acceptability of the public towards the use of harvested rainwater in the northern region of South Africa	Article	In draft, to be published with International Journal of Water Resources and Environmental Engineering.
Quantitative Microbial Risk Assessment (QMRA) of *E. coli* for roof harvested rainwater.	Article	In draft, to be published with Journal of Water and Health.

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LIST OF ABBREVIATIONS

AAS- Atomic Absorption Spectrometry

Ag- Silver

Al- Aluminium

ALS- Average of Likert Scores

AS- Arsenic

AT- Average Time

AWB- African Water Bank

B- Boron

BC- Before Christ

BOD- Biochemical Oxygen Demand

BW- Average Body Weight

CBD- Central Business District

Ca- Calcium

Cd- Cadmium

CF- Unit Conversion Factor

Co- Cobalt

Cr- Chromium

CR_{ing}- Carcinogenic risk via ingestion route

Cu- Copper

C_{water}- Average concentration of metals in water

DO- Dissolved Oxygen

DWS- Department of Water and Sanitation

EC- Electrical Conductivity

E. coli- *Escherichia coli*

ED- Exposure Duration

EF- Exposure Frequency

EPA- Environmental Protection Agency

ET- Exposure Time

EXP_{ing}- Exposure dose through ingestion

EXP_{derm}- Exposure dose through dermal adsorption

FC- Faecal Coliform

Fe- Iron

G- Gram

Ga- Gallium

HCl- Hydrochloric acid

HG- Mercury

HNO_3- Nitric acid

IC- Ion Chromatography

ICP-MS- Inductively Coupled Plasma Mass Spectrometry

ICP-OES- Inductively Coupled Plasma Optical Atomic Spectrophotometer

In- Indium

INWQS- Interim National Water Quality Standards

IR- Ingestion Rate

IWRM- Integrated Water Resource Management

K- Potassium

Km- Kilometer

K_p- Dermal Permeability Coefficient in Water

M- Meter

Max- Maximum

Mg- Magnesuim

Min- Minimum

ML- Milliliter

Mm- Millimeter

Mn- Manganese

Mg/L- Milligrams per liter

Mo- Molybdenum

Na- Sodium

NGO- Non-Governmental Organization

NH_3- Ammonia

Ni- Nickel

Nm- Nanometer

NTU- Nephelometric Turbidity Unit

NWRA- National Water Resources Authority

O_3- Ozone

Pb- Lead

PCR-Polymerase Chain Reaction

PPM- Parts Per Million

QMRA- Quantitative Microbial Risk Assessment

RF- Radiofrequency

RTRWH- Rooftop Rainwater Harvesting

RWH- Rainwater Harvesting

RWHS- Rainwater Harvesting System

SA- **South Africa**

SANS- South African National Standards

Sb- Antimony

Se- Selenium

SF_{ing}- Carcinogenic Slope Factor

Si- Silicon

SI- Sub Index

Sn- Tin

Sr- Strontium

TC- Total Coliform

TDS- Total Dissolved Solids

UK- United Kingdom

USA- United States of America

V- Vanadium

WQI- Water Quality Index

WHO- World Health Organization

WWC-World Water Council

Zn- Zinc

µs- Microsemen

ºC- Degree Celsius

CHAPTER ONE: GENERAL INTRODUCTION

1.1. INTRODUCTION

Water is a very important natural resource required for the survival of humans and all other creatures (Sharifah et al., 2022). There are more than a billion people around the world who do not have access to adequate clean and safe water supplies, as well as standard sanitation (Afangideh and Udokpoh, 2021). With continuous industrialisation in developing countries, it is expected that water resources will become insufficient to meet the demands of the society (Banda and Kumarasamy, 2020). The Sustainable Development Goal 6 (SDG 6) aim to achieve universal access to safe and clean drinking water by 2030 (UN-Water, 2018). Countries in the Sub-Saharan Africa (including South Africa) are among those facing serious challenges with the issue of water scarcity (Nzelibe et al., 2022), however, roof-rainwater harvesting has been observed as able to play a crucial role in supplying water for drinking and other domestic uses (Aroh, 2022).

Rainwater harvesting is defined as a technique of accumulating rainwater from any impermeable surface and storing it for a suitable use, and rooftop rainwater harvesting is a process in which rainwater is accumulated from the roof catchments (Aryal et al., 2022). Rooftop-rainwater harvesting is regarded as a simple and effective method to harvest water for domestic purposes (Noor -E- Zakir and Ekram, 2020). The United Nations (UN) SDG goal 6 also suggested harvesting and reusing rainwater as a measure for improving universal access of drinking water by 2030 (UN-Water, 2018). Harvested rainwater can be stored either in tanks for future uses or it can be used to recharge groundwater check dams through recharge trenches or permeable pavements (Zabidi et al., 2020).

There are, however, problems concerning the quality of rainwater since there are possibilities that roof-harvested rainwater might be contaminated with physical and chemical pollutants, such as heavy metals and microbiological pathogens (Anabtawi et al., 2022). The quality may vary according to the geographic location of the catchment, climatic conditions, condition and type of the roof, organic composition in the roof gutters, animal faeces on the rooftop, condition of the storage tanks, and the operation and maintenance of the tank (Hamilton et al., 2019; Rawan et al., 2022).

The public's perception is also very important since it provides clarity on acceptance of rooftop rainwater harvesting to meet water demands, rainwater safety and the uses of harvested rainwater in households (Noor -E- Zakir and Ekram, 2020). People's perception towards the use and quality of rooftop-harvested rainwater varies; this might be influenced by topographical location (whether collection is done in urban or rural settlements) and financial stability (whether household heads have low or high socio-economic status) (Ogbiye et al., 2021).

1.2. STATEMENT OF THE PROBLEM

The issue of climate change and population growth in developing countries have increased the stress on water resource's availability (Nipun et al., 2022). The problem of population growth is prominent in Sub-Saharan Africa and South Asia, where less than 75% of the population have access to safe and clean drinking water (Oskam et al., 2021). Currently in South Africa, there is a rapidly growing population who do not have access to safe drinking water, especially, in the rural and informal settlements (Mbanga et al., 2020). This is mainly due to the unavailability and inadequate maintenance of water infrastructures in some communities mostly in the rural areas of South Africa in most provinces of the country (Lebek and Krueger, 2023).

Developing countries, especially those with extensive rural areas, are faced with lots of water-related challenges involving inadequate quality, quantity, and challenges with water supply systems (Tenebe et al., 2020). South Africa is a low to middle-income country where access to clean water and sanitation remains inequitable and inadequate, especially in the remote rural areas and disadvantaged socio-economic groups. These face challenges in service delivery and are highly dependent on the central government's unequal water-supply services (Abrams et al., 2021; Oskam et al., 2021). The inequality obscures any reliability of the services.

It has been evident that the issues of water scarcity are strongly connected to the challenges of the quality of water since the deterioration in the water quality (mostly from anthropogenic activities) makes it unsafe for consumption (Mbanga et al., 2020). As the quality of water sources deteriorates, it becomes more expensive and difficult to supply potable water to the people (Afangideh and Udokpoh, 2021).

Rooftop rainwater harvesting (RWH) has been recognized as a potential alternative water supply source which can help communities to become self-resilient by eliminating their reliance on water supplied by the municipalities (Nipun et al., 2022). RWH is an appropriate system to consider as it includes several strengths, such as independency, reduction of pressure on water resources, proximity and easy to use storage tanks affordable by most (Judeh et al., 2022). Rooftop-rainwater harvesting, however, should be practised with the proper knowledge and maintenance of equipment to ensure the harvested water's quality, thus reducing the chances of contaminated water and health concerns (Afsari et al., 2022).

Rainwater-harvesting systems can provide water for purposes not requiring drinking-water quality levels. There is, therefore, a need to assess the quality of rainwater from different roofing materials within the areas of Vhembe District Municipality that already practise RWH. This current study will investigate the common roof types used as catchments for rainwater harvesting in the study area.

1.3. MOTIVATION OF THE STUDY

The issue of insufficient availability of clean water is a global challenge (Tenebe et al., 2020). It has been estimated that about 1.2 billion people in the world are struggling with accessing clean and safe water and it has been projected that in the next four decades the demand for water will increase drastically due to a prediction of 40-50% in population growth; billions of people will also have no access to safe and clean water due to the depletion and contamination of water resources (Owusu and Asante, 2020). Rainwater harvesting is one of the alternative sources of water and has been identified as a simple and adaptable method to mitigate the scarcity of water (Ogbiye et al., 2021).

Rooftop rainwater harvesting is considered suitable to meet the water demand and has increasingly been used as an alternative for different uses (Aryal et al., 2022). Even though rooftop rainwater harvesting is perceived as an alternative solution to water demand problems, from an ecological point of view, it is essential that rooftop-harvested rainwater should be tested for microbial pathogens and chemical contaminants before it can be used for domestic purposes (Rawan et al., 2022).

Rainwater is regarded as a valuable water source because of its purity as it, usually, is free from minerals, salts, and man-made contaminants, with a nearly neutral pH; this makes it an appropriate alternative water source (Majumdar et al., 2020; Zdeb et al., 2020). Other than conserving water, rainwater harvested from rooftops also helps with the reduction of flooding and soil erosion caused by runoff. It also helps to conserve the energy input required at the treatment plants to pump water since water usage from the taps will be reduced when communities use rainwater (Judeh et al., 2022). There could, however, be potential health risks associated with rooftop-harvested rainwater because there could be the presence of microbial and chemical contaminants, therefore, it is essential for the quality of the collected water to be assessed prior to usage (Mao et al., 2020). Tenebe et al. (2020) assert that good quality of harvested rainwater is essential to protect the health of the public, especially, when rainwater is consumed.

Currently, the major sources of water supplied for drinking and other domestic purposes are surface water (rivers, reservoirs, and lakes) and groundwater (wells and aquifers), however, these two sources are being terribly polluted due to various factors, such as erosion, litter, oil or grease, and runoff, that can be linked to numerous health and environmental issues (Tenebe et al., 2020). These major water supply systems, therefore, are considered vulnerable to contamination (Judeh et al., 2022). This study would also serve as a reference point for water managers and households seeking methods to provide clean, safe, and reliable rooftop-harvested rainwater.

Worldwide, most of the studies on rainwater harvesting cover the quantity of the harvested rooftop water and the design of the rainwater harvesting systems, but the quality of the harvested rooftop rainwater used for potable purposes has not received significant attention nor adequately documented (Noor -E- Zakir and Ekram, 2021; Afangideh and Udokpoh, 2021). Researchers from universities, industrial consultants, and non-governmental organisations usually focus on the installation, costs, and the quantity of rooftop rainwater, rather than on the quality of the water (Noor -E- Zakir and Ekram, 2021; Judeh et al., 2022). The quality aspects of harvested rainwater requires to be addressed, therefore, the aim of this study is to fill the data gaps identified, in published data, on the suitability of rainwater harvesting in terms of its quality and its potential uses in Vhembe District of the Limpopo Province.

1.4. OBJECTIVES

1.4.1. Main objective

The main objective of this study is to assess the perception of people towards the use of rooftop-harvested rainwater, to determine the quality of rooftop-harvested rainwater collected from five different types of rooftop materials and any associated health risks in three different areas, around Vhembe District, South Africa.

1.4.2. Specific objectives

The objectives of this study are:

- To assess the perception and attitude of people towards the use of roof-harvested water.
- To determine the physicochemical (metals, and physical parameters) and microbiological (*Escherichia coli* and total coliforms) characteristics of the harvested water from different roof types (slate, steel, concrete, aluminium and thatched).
- To compute the health risk associated with trace metals in roof-harvested rainwater.
- To evaluate the suitability of using roof-harvested rainwater, using the water quality index.
- To compute the health risks associated with any microbial levels detected in rooftop-harvested rainwater, using QMRA.

1.5. RESEARCH QUESTIONS

- What are people’s perceptions towards the use of harvested rainwater?
- What are the levels of physicochemical (metals and physical parameters) and microbiological water quality parameters rainwater harvested from slate, steel, concrete, aluminium and thatched roofs?
- What is the suitability of rooftop-harvested rainwater for various uses?
- What is the potential health risk associated with heavy metals in roof-harvested water?
- What are the health risks associated with microbial levels in roof-harvested rainwater, using QMRA?

1.6. STUDY AREA

1.6.1. Geographical location

The Vhembe District Municipality is one of the five districts of the Limpopo Province (Figure 1.1), one of the nine provinces of the Republic of South Africa. It comprises of **four** local municipalities, namely, Thulamela, Makhado, Musina, and Collins Chabane, which were all established in 2000. The capital of Vhembe District is Thohoyandou.

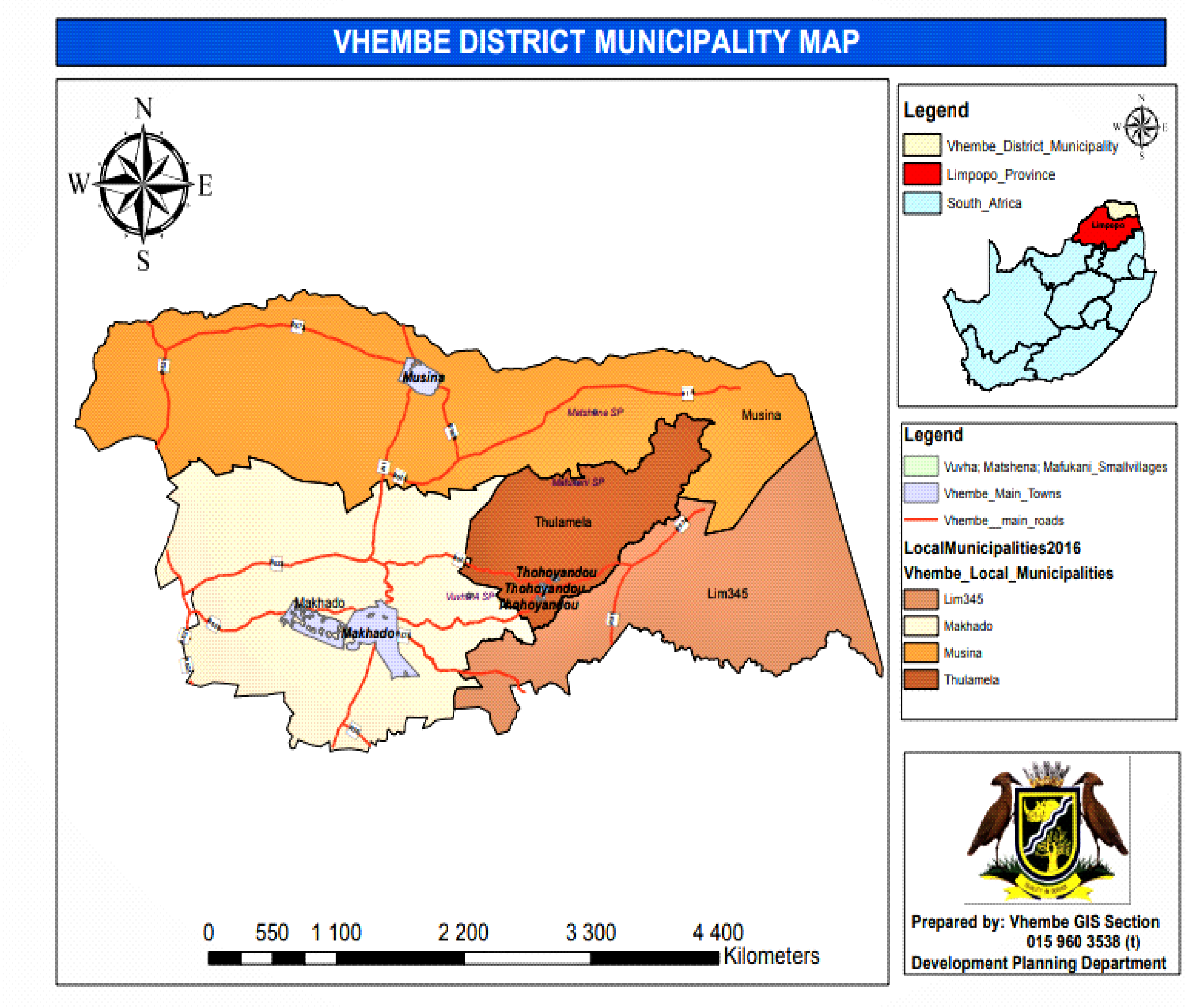


Figure 1.1: A map showing the region of Vhembe District Municipality (Source: Vhembe GIS Section, 2018)

1.6.2. Climatic conditions

The average annual precipitation of Vhembe District is 820 mm with the rainfall season starting from October extending to April each year, and a dry winter season that starts in May and ends in August, with September being the transition month (Netshifhefhe et al., 2018). Thohoyandou is part of the Southpansberg region, and it receives high rainfalls with hot summers and cool winters. The area, however, is moderately warm throughout the year with temperatures between 16 and 44 ºC.

1.6.3. Topography

The Vhembe District covers an area of about 25 597 km² with most people living in villages. It is located at 22º 56´ S and 30º 28´ E in the far north of the country, where it shares its northern border with Zimbabwe, eastern border with Mozambique and north-western border with Botswana. Vhembe District Municipality comprises of a steep slope with the altitude varying between 420 and 1 020 m above mean sea level.

1.6.4. Population

Vhembe District Municipality is home to approximately 537 454 people who stay within a 2,966.4 km area which covers 13.86% of the total area of the Vhembe District (Enitan-Folami et al., 2019). It is a multi-cultural area comprised of many different ethnic groups, such as Vendas, Tsongas, Pedis, and Indians. The District of Vhembe has experienced a rapid population growth in the last decade (Edokpayi et al., 2018).

1.7. OUTLINE OF THE STUDY

Chapter 1 introduces the general background of the study as well as the statement of the problem, motivation, objectives, description of the study area and research questions.

Chapter 2 provides a summary of some literature relevant to this study. The literature review focuses on previously conducted rainwater-harvesting studies, policy documents with special reference to the benefits of rainwater harvesting, the negative impacts of rooftop-rainwater harvesting, the components of rooftop harvesting, the effects of roofing materials on the quality of the harvested water, the suitability of harvested rainwater for various uses, the history of rainwater harvesting in other countries, as well as the current state of rainwater harvesting in South Africa.

Chapter 3 gives the overall research approach including materials and methods used, research sites, data collection and sampling, instruments, procedures, and data analysis.

Chapter 4 presents and discusses the results on the survey carried out on the public who practice, RWH in the VDM.

Chapter 5 provides discussion and interpretation of the research results. It further compares the obtained results with the findings of prior research.

Chapter 6 presents the conclusion or the general thoughts regarding the obtained findings in Chapter 5 and offer suggestions for further research.

CHAPTER TWO: LITERATURE REVIEW

2.2. BACKGROUND TO RAINWATER HARVESTING (RWH)

The practice of rainwater harvesting dates to the late Neolithic to early Bronze Age period, when after the establishment of the first permanent settlements, the ancient people in Mesopotamia (known today as Jordan and Iraq), realised that it was impossible to live without water and that rainwater harvesting is one of the method to supply water (Al-Houri and Al-Omari, 2021). The Middle East countries were also the first in the world, followed by Southern Mesopotamia over 9 000 years ago, to practise rainwater harvesting for domestic and agricultural uses (Jeloudar and Han, 2012). The authors also reported that the history of water harvesting in Mesopotamia dates to 4500 BC, followed by the Negev Desert region (now Israel) in the 10th century BC. After that time, rainwater harvesting received attention and interest from most countries of the world - Germany, Italy, Spain in Europe, India, China, Malaysia, Korea, Japan in Asia, Kenya, Australia, New Zealand, Canada, Brazil, several states of USA, and some other countries in Africa - as an alternative source of water supply (Yannopoulos et al., 2017).

Rainwater harvesting is usually taken to mean immediate collection of rainwater from surfaces upon which it has fallen directly during rainfall (Afangideh and Udokpoh, 2021). In line with SDG Goal 6 (Ensure availability and sustainable management of water and sanitation for all), South Africa has developed the Rainwater Harvesting Programme, aimed at providing access to water, and to enable poor households, all year round to produce fresh vegetables at home through methods of channelling harvested rainwater (Lebek and Krueger 2023; UN-Water, 2018). Ancient Romans were the master engineers who used to build their cities with infrastructure that diverted rainwater into large cisterns, thus, collecting water for drinking, bathing, washing, irrigation and for livestock (Mohammad, 2020).

The origin of rainwater harvesting in South Africa has been difficult to trace due to historical issues surrounding the colonial and apartheid era, however, there is evidence that rainwater harvesting has been practised in the country for a long time (Kahinda and Taigbenu, 2011; WRC, 2017) as can be seen in the map showing the number of RWH tanks per each of the provinces in South Africa (Figure 2.1).

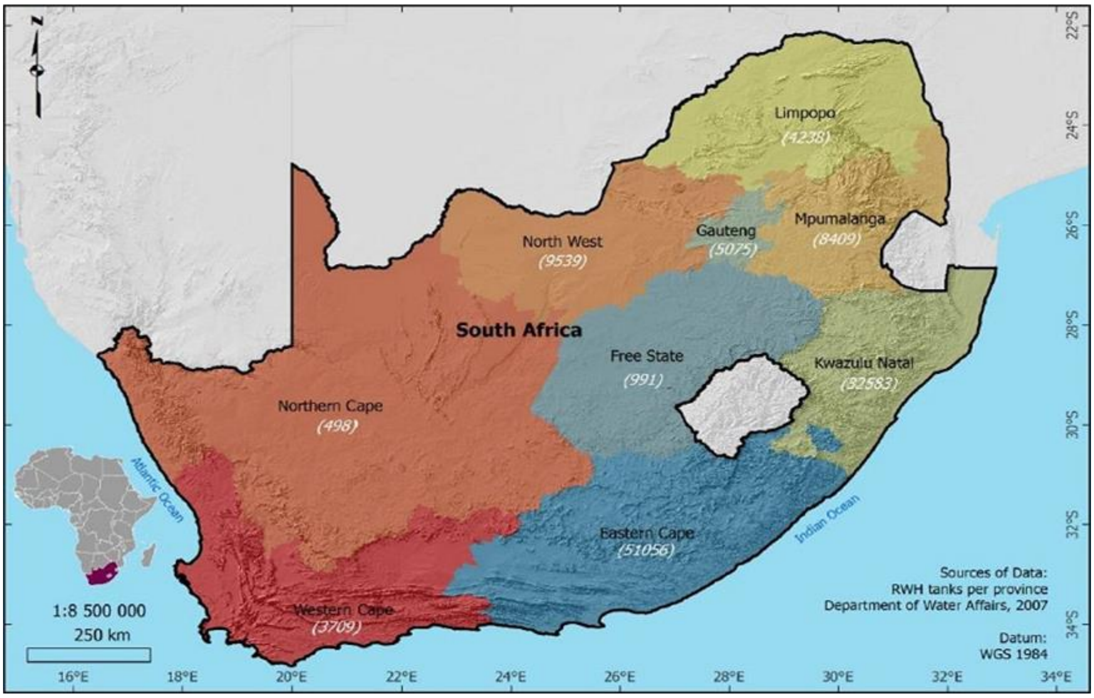


Figure 2.1: A map showing RWH tanks per province in South Africa (Source: DWS, 2014)

2.3. HISTORICAL TRENDS OF ROOFTOP RAINWATER HARVESTING (RTRWH)

Rooftop rainwater harvesting is an old practice that has been used by people as a technique for the provision of water for drinking and other domestic purposes for about 4000 years (Rawan et al., 2022). Al-Houri and Al-Omari (2021) state that rainwater harvesting has been practised in the regions of India, China, Minoa, Crete, and in the Indus valley, South Asia, during the third millennium century BC. Also, around the third century BC, rooftop rainwater harvesting was made compulsory in the region of Tamil Nadu, India (Patel and Shah, 2015).

A water harvesting technology in the form of dams started around 2000 years BC to provide water for domestic and agricultural purposes in Yemen (Taher, 2014). In 2001, the federal government of Brazil launched programmes that were aimed at regulating investments and taking actions related to water management; it was at this time when technologies and training in capturing and storing rainwater for agricultural purposes were given to families of farmers to complement the supply of water for human consumption purposes (Teston et al., 2018).

The middle east has a rich history of harvesting rainwater, where people survived by capturing water from the hillside and storing it in cisterns (Mohammad, 2020). Recently, an international non-governmental organisation (NGO) known as the African Water Bank (AWB) committed to harvesting and storing rainwater on a large scale by optimising and enhancing the rainwater harvesting system (Qi et al., 2019). Qi et al. (2019) also mentioned that Kenya is a very water-stressed country, and the practice of rainwater harvesting is currently regarded as an underutilised tool and harvested water is mainly used for agricultural and drinking purposes.

In Nigeria, new developments in rainwater harvesting are currently being put in place to avoid errors of the past, where people, especially, in rural areas had limited supply of freshwater and water resources were located far from their homes (Mohammed et al., 2018). To reduce the demand for water from the mains supply in the Adelaide region of South Australia, new houses were required to have rainwater tanks for some domestic uses following a millennium drought in Australia in 2006 (Malambo and Huang, 2016).

Morey et al., (2016) recorded the usage status of harvested rainwater in the current century for several countries. In China, it was earlier stated that harvested rainwater was initially used for irrigation purposes, but rooftop rainwater harvesting is presently practised for drinking water purposes. In Bermuda, rainwater is used only for the construction of buildings. Morey et al., (2016) further mentioned that in America, in Colorado, water rights' laws restrict rainwater harvesting unless the owner of the property possesses a permit to install rooftop water collection systems. Companies in Beijing also use rainwater as their main water source for industrial processes (Morey et al., 2016).

Rainwater harvesting is also not a new technique in South Africa with over 26 500 households distributed in all the provinces in South Africa using harvested rainwater as their main source of water supply (Kahinda and Taigbenu, 2011). The Department of Water and Sanitation (DWS) supports a national rainwater harvesting programme, which has a narrow but important focus on the construction of above and below-ground rainwater storage tanks by rural households for food gardens and other water uses (PMG, 2022). Several municipalities now use roof rainwater tanks for domestic purposes. The use of harvested rainwater as a major source of drinking water in South Africa is most common in KwaZulu-Natal and in the Eastern Cape Provinces where there are unequal provision and unreliability of municipal water services (Van de Voorde et al., 2009). Kahinda and Taigbenu. (2011) mentioned that as rainwater harvesting has helped South Africa to meet the SDG target of halving the number of people without access to clean water and basic sanitation by 2015, however, the quality should also be considered as a way of increasing the level of appropriate sanitation (DWS, 2015).

2.4. RAINWATER HARVESTING STUDIES ALL OVER THE WORLD

Rawan et al. (2022) assessed the quality of rooftop harvested rainwater in the District of Dir Lower of Khyber Pakhtunkhwa, Pakistan. Trace metals and physicochemical parameters were analysed according to the World Health Organization (WHO) and standard methods for the examination of water and wastewater. In general, all the parameters were found to be within the guideline limits in all the harvested rainwater samples except for some trace metals such as iron (Fe) and lead (Pb) which had the highest mean concentrations of 0.95 mg/L and 0.056 mg/L, respectively, which were above the permissible limit of the WHO's guidelines for drinking water. It was concluded that roof harvested rainwater is suitable for drinking and other domestic consumption if there is proper care and maintenance of the storage system.

Zdeb et al. (2020) assessed the quality of roof-harvested rainwater and the possibility of its economic use in Rzeszów, Europe. Increased turbidity and microbiological contamination were identified in roof-harvested water samples. Contact of rainwater with cement and ceramic tile roofs increased the pH of rainwater to 7.0. It was concluded that only rainwater collected from galvanized steel roof type would be usable as an alternative for drinking water.

Noor -E- Zakir and Ekram (2021) assessed peoples' perception of rainwater harvesting to meet water demand at Khulna University of Engineering and Technology, in the coastal regions of Bangladesh. A total of 198 questionnaires were distributed to people at the Khulna University campus to obtain their insights on rainwater harvesting. It was found that 94.82% of the respondents practised rainwater harvesting, and they thought harvested rainwater should be used for non-potable consumption without any treatment. Most of the respondents, however, were more likely to use rainwater for washing purposes.

Aryal et al. (2022) assessed the suitability of rooftop-harvested rainwater in terms of quantity and quality, as a source of drinking water in Tarakeshwor Municipality of Kathmandu, Nepal. The volume of harvested rainwater was observed as being sufficient to address the issue of water demand, with a mean rainfall of 1664 mm on a catchment area of 372 m^2, in the study area. The values of physicochemical parameters of the samples collected were all within the National Drinking Water Quality Standards and WHO guidelines except for the levels of faecal coliforms recorded (Aral et al., 2022; WHO, 1989).

A study was conducted by Ayog et al. (2016), with the main aim of assessing the impact of rooftop materials on the quality of harvested water. Samples of the first flush runoff from the rainwater were collected from two different types of roofs and analysed for physicochemical parameters (pH, total suspended solids, turbidity, and dissolved oxygen (DO)). The parameters measured were then checked against the water quality threshold limit of the Interim National Water Quality Standards (INWQS) for Malaysia. Results showed that the first flush of harvested rainwater from the two different types of rooftops was relatively good in terms of the quality. Table 2.1 lists the concentration limits of water classes and uses for pH, TSS, turbidity, and DO according to INWQS of Malaysia (Ayog et al., 2016).

Table 2.1: Concentration limits of water classes and uses according to INWQS of Malaysia (Source: Ayog et al., 2016).

Parameters`	**Class**					
	I	**IIA**	**IIB**	**III**	**IV**	**V**
DO (mg/L)	7	5-7	5-7	3-5	<3	<1
pH	6.5-8.5	6-9	6-9	5-9	5-9	-
TSS (mg/L)	25	50	50	150	300	300
Turbidity (NTU)	5	50	50	-	-	-

Class		**Uses**
I		Conservation of natural environment Water Supply I - Practically no treatment necessary Fishery I - Very sensitive aquatic species
II	**IIA** **IIB**	Water Supply II - Conventional treatment Fishery II - Sensitive aquatic species Recreational use, body contact
III		Water Supply III - Extensive treatment required Fishery III - Common, of economic value and tolerant species; livestock drinking
IV		Irrigation
V		None of the above

2.5. THE COMPONENTS OF A ROOFTOP RAINWATER HARVESTING SYSTEM

A rooftop rainwater harvesting system consists of five major components which are - rainfall (the main process that feeds other sources with rainwater), a catchment surface (the collection area, such as roofs and other surfaces on which the rain falls before collection), first flush diverter (an outlet chamber which diverts or collects the first flow of water away from the catchment system), conveyance system (a system where rainwater is transported from the roof and delivered into a storage reservoir), and a storage tank (a reservoir that stores the collected rainwater for further usage) (Rawan et al., 2022; Judeh et al., 2022). A schematic diagram presented in Figure 2.2 below shows the main constituents of a rainwater harvesting system.

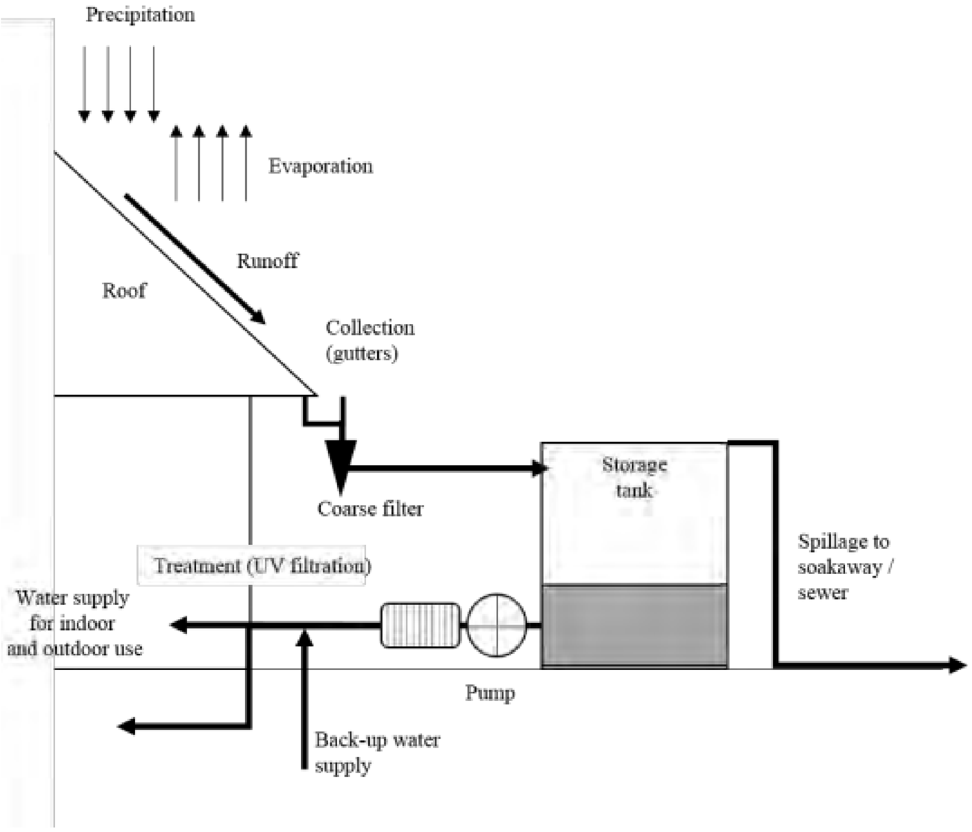


Figure 2.2: Schematic diagram showing a rainwater harvesting system (Source: Fisher-Jeffes, 2015)

2.6. THE BENEFITS OF RAINWATER HARVESTING

Rainwater harvesting has a great potential of filling the gap created by insufficient water supply, especially in rural areas where the method is mostly utilized (Tenebe et al., 2020). The implementation of rainwater harvesting systems has a huge potential as a sustainable alternative source of water to cope with water scarcity, particularly, at the household level and can become economically feasible (Khanal et al., 2020).

Rooftop-rainwater harvesting systems use simple technologies that are easy to install and to operate, and local people can easily be trained to operate them ensuring full control of their own harvesting systems. This means local people will have improved quality water at sufficient quantity at their doorstep (Mohammad, 2020). The usage of harvested rainwater as a supplementary source means that groundwater will be less likely to be over-exploited and will thus also bring about a reduction in energy and time spent by household members for cultivation of crops and water collection (Owusu and Asante, 2020). Rainwater harvesting has a variety of advantages, such as lowering the cost of water supply and providing an efficient and cost-effective back-up source of water in areas which face insufficient water resources (Zabidi et al., 2020). In rooftop rainwater harvesting, water collected from the roof of the building is diverted into a storage tank with no land wasted for storage purposes and without the displacement of the population (Dagwal et al., 2016).

The harvested rainwater has many different potential uses, such as bathing, washing the dishes, washing of clothes and cars, and much more. With the practice of rainwater harvesting, there would be a reduction in stress on other water sources used for supplying water to the community (Morey et al., 2016; Noor -E- Zakir and Ekram, 2021). Using rainwater harvesting as an alternative source, mainly in rural areas, has advantages in terms of health improvement (excess rainwater used for vegetable and crop production leads to a better diet), poverty reduction (income can be generated with sale of surplus produce), education and equity (more time can be spent on educational and personal development especially for young girls as time saved will now can be used for school attendance and homework rather than travelling long distances to fetch and transport water from sources far away from the homestead), and the reduction in water-related diseases as the quality of rainwater is usually better than water from other sources (fewer sick days and more time for economic activities) (Mohammed et al., 2018).

In addition to collecting rainwater for domestic purposes, RWH can also have the following benefits: passive cooling of buildings in cities during summer, enhancing local food security, reducing living costs and consumption of energy, controlling erosion, averting flooding, reviving dead waterways, minimising water pollution, as well as community building (Judeh et al., 2022; Gwoździej-Mazur et al., 2022).

In Malaysia, the RWH approach has benefited communities by enabling them to meet their demands for water supply, by using the collected water for non-potable uses such as toilet flushing and washing vehicles. This ensures that a lot of treated water is saved (Asmuni et al., 2016). In various regions of Australia, Bangladesh and Korea, the communities have been surviving by collecting rainwater and adjusting their crops and agricultural patterns according to the available rainfall (Ogbiye et al., 2021). The use of harvested rainwater in the agricultural sectors increases job opportunities for the villagers, thereby, increasing household income and providing children with a better chance of education (Zabidi et al., 2020).

2.7. FACTORS AFFECTING ROOFTOP-HARVESTED RAINWATER (RTHRW)

2.7.1. Types of roofing materials

The type of rooftop used as catchments can determine the amount and quality of harvested rainwater (Afangideh and Udokpoh, 2021). Factors of roofing materials that influence the quality of harvested rainwater include - roughness of the roofing, chemical characteristics, age of the roof, surface coating, and the orientation and slope of the roof (Friedler et al., 2017). Several studies have shown that the type of roofing materials does affect the quality of the harvested water.

Olaoye and Olaniyan (2012) compared the quality of four roof types: asbestos, aluminium, concrete, and corrugated plastic. Asbestos roofs had the highest mean values of pH (6.75), aluminium (3.9 mg/L), copper (0.03-0.04 mg/L), hardness (84-86 mg/L), nitrate (37.9-39 mg/L), and sulphate (11-14 mg/L). Microbial contamination was reported in rainwater samples from asbestos, concrete, and corrugated plastic roofs, except for rainwater samples from aluminium roofs which were free from all coliform bacteria. Samples from concrete and corrugated plastic roofing materials also had some level of contamination. Rainwater samples from aluminium roofs were reported to have the highest level of magnesium (36-38 mg/L) but it was shown to be the most suitable roofing material for RTRWH.

An investigation into the quality of roof-harvested rainwater from corrugated iron, aluminium, and asbestos roofs was done by Ojo (2019). From roofs of corrugated iron, aluminium, and asbestos, all the harvested rainwater samples were found to be slightly acidic with average pH values of 6.13, 6.25, and 6.15, respectively. Higher heavy-metal concentrations were reported in samples of harvested rainwater from asbestos and corrugated iron roofs, with the average values for iron at 0.52 mg/L and 0.605 mg/L as well as for lead at 0.3 mg/L and 0.715 mg/L, respectively. These compared to the harvested rainwater from aluminium roofs, had lower heavy-metal concentrations and no microbiological contaminants were detected in any of the samples.

Findings from a study by Al-Amoush et al. (2018), presented the average concentrations of the major cations and anions (sodium, potassium, magnesium, calcium, chlorine, nitrate, bicarbonate, and sulphate) in the rainwater harvested from all the rooftop types;

these arranged from highest to lowest order were – thermal insulation>asphalt>seal coat>concrete>mixed asphalt>mixed concrete>metal roofing.

2.7.2. Climatic factors, including ambient air quality of the area

Greenhouse gases suspended in the air and bio-aerosols containing microbes can become incorporated into the rainwater and affect its quality, and together with wind direction and roof orientation, they have a huge impact on the quality of rooftop-harvested rainwater (RTHRW) (Afangideh and Udokpoh, 2021). High solar radiation acts as a sanitiser on roof surfaces, especially in sub-Saharan Africa where temperatures are usually higher than the global mean temperature (Owusu and Asante, 2020).

Friedler et al., (2017) described air-related factors that influence the quality of RTHRW, and they included the local meteorological factors (weather, season, and length of antecedent dry period) wind characteristics, vapour pressure and water solubility. They further monitored quality of air containing air pollution parameters (O2, SO2, NO2, PM2.5 and PM2.5-10) in rooftop-harvested rainwater. It was concluded that those compounds undergo oxidation in the atmosphere to form strong acids (nitric and sulphuric acids) that may dissolve in rainwater and degrade its quality.

The water quality also varies according to the location. In the study by Owusu and Asante (2020), it was reported that the variations in the quality of harvested rainwater were due to the weather conditions, rainfall intensity, industrial, urban, and agricultural activities, and that lower levels of heavy metals, turbidity, hardness, and bacteria were found in rural areas that are characterised by very limited industrial activities and low population density.

Judeh et al. (2022) explain that rain droplets in the atmosphere can absorb air contaminants such as nitrite, carbon dioxide, and sulphate, thus reducing the quality of roof-harvested rainwater. Mao et al. (2020) conducted a study that was comparing the quality of harvested rainwater under different meteorological conditions in Shanghai, China. It was found that weather patterns and climatic features could have significant influence on the water quality parameters, and that harvested rainfall was a principal meteorological indicator.

2.7.3. Frequency of rainfall

Contamination of roof-harvested runoff is affected by rainfall characteristics such as - the season, the length of time between rain events and rainfall intensity (Mendez et al., 2010).

Total rainfall determines the feasibility of rainwater harvesting because in an area where rain falls throughout the year, the collected amount will likely never run low, however, the fewer the annual rain days or the longer the dry periods, the more the need for rainwater storage (Mohammed et al., 2018). The feasibility of RTRWH, therefore, depends on the amount and the patterns of rainfall in an area (Rahimi, 2018).

The quality of harvested rainfall can deteriorate due to less dilution (Mohanty et al., 2018). The highest concentrations of pollutants are mainly detected during low rainfall and long dry periods of atmospheric deposition preceding rainfall events, whereas the pollutants become less concentrated in a heavy rainstorm (Radaideh et al., 2009). Morales-Pinzon et al., (2015) concluded that the frequency of rainfall does influence the quality of rainwater since it was proved that the high rainfalls in the areas of the study, reduced the accumulation of turbidity, heavy metals, and microorganisms due to the water's constant recirculation.

2.8. THE QUALITY OF ROOFTOP-HARVESTED RAINWATER (RTHRW)

Rainfall is initially free of chemical and microbial compounds but as it drops or gravitates towards the surface of the earth, it starts to deteriorate in quality (Mao et al., 2020). In general, the surfaces from which rainwater is collected are high above the ground and are isolated from most sources of contamination, but the quality of RTHRW is often compromised by dust, inorganic materials, mosquito larvae, debris, fumes from automobiles, bacteria, and heavy metals contained in roofing material (Tenebe et al., 2020). As the quality of roof-harvested rainwater deteriorates, it becomes more expensive to supply potable water to the people (Afangideh and Udokpoh, 2021). Table 2.2 below lists water contaminants, their sources, their risks and mitigation measures. The acidic nature of ambient rainwater may cause roofing materials to leach chemical compounds such as lead, zinc, copper, chromium, and cadmium into the harvested rainwater (Judeh et al., 2022).

2.9. POTENTIAL USES OF RTHRW

In several studies conducted by various authors, it is evident that the development of rooftop rainwater harvesting is progressing (Mohammad, 2020; Nzelibe et al., 2022;

Igbinosa et al., 2017). Successful rainwater harvesting has led to an improvement in the economic development and health and well-being of people, while also being environmentally sensitive (Mao et al., 2020; Tenebe et al., 2020). Zabidi et al., (2020) caution that it is essential to know whether the collected rainwater is suitable for its intended or potential use; to evaluate the suitability of the water, the regulatory standards for the physical, chemical, and microbiological quality must all be taken into consideration.

Table 2.2: Contaminants of harvested rainwater, sources and their risks and mitigation measures (Taher, 2014)

Contaminant	Source	Risk/Mitigation
Dust, ash and debris	Surrounding dirt and vegetation; volcanic activity	Moderate: can be minimised by regular roof and down-pipe maintenance
Pathogenic bacteria	Bird and other animal droppings on rooftop, attached to dust	Moderate: can be minimised by the use of first-flush device and disinfection by chlorine
Heavy metals	Dust, particularly in urban and industrialised areas, roof materials	Low: unless downwind of industrial activity such as a metal smelter or rainfall is acidic
Other inorganic and organic contaminants, for example, mosquito larvae	Industrial discharge into the air, use of unsuitable tank or roofing materials Mosquitoes laying eggs in the guttering or tank.	Low: unless very close to the ocean or downwind of large-scale industrial activity

Some of the potential uses of harvested rainwater require a low-cost treatment and other uses may not require treatment at all, that is, where rooftop-harvested water can be used directly without any form of treatment (Qi et al., 2019). Regardless of whether the quality of harvested rainwater is known or not, rainwater has been used for gardening and for potted plants because it is not chlorinated (Julius et al., 2013); another potential use of rainwater is for laundry purposes since rainwater is soft, it reduces the need for detergents.

Rooftop rainwater harvesting is also suitable for domestic purposes, instead of water supplied from springs and wells which are often contaminated with salts (Mbanga et al., 2020). Mohammed et al. (2018) mentioned that rainwater that is collected from the roof catchments is usually found to be potable, hence, may be used for drinking, cooking, general home cleaning purposes, gardening, filling of swimming pools, laundry, car washing, and for animal to drink.

Table 2.3 indicates the suitability of harvested rainwater for domestic use purposes by showing the acceptable qualities given in terms of Jordanian Drinking Water Standards (JDWS) for chemical parameters, heavy metals, and microbiological characteristics, and the Jordanian Standard (JS) for reuse in irrigation (JS 893/2002).

Table 2.3: The suitability of collected water for drinking and irrigation purposes (WHO, 1989).

Parameter	**Units**	**Min.**	**Max.**	**Average**	**Max. Level mg/L JDWS**	**Reclaimed water standards (JS 893/2002)**
pH	…….	7.1	8.9	7.96	6.5-8.5	6.9
Alkalinity	mg/L $CaCo_3$	22	250	65.09	…….	…….
Hardness	mg/L $CaCo_3$	16	352	108.18	500*****	……
Turbidity	NTU	0.1	4	0.7	5*****	10
TDS	mg/L	26	393	138.47	1500*****	1500
COD	mg/L	6	142	34.78	*****	100
NO_3-N	mg/L	0.20	8.10	1.56	70*****	30
NH_4-N	mg/L	0	0.1	0.06	0.5	…….
PO_4	mg/L	0.23	4.41	1.27	…….	…….
Lead	mg/L	0.00	0.18	0.01	0.01	5
Iron	mg/L	0.00	0.338	0.01	1.0*****	5
Chromium	mg/L	0.00	0.0988	0.012	0.05	0.1
TC	MPN/100 mL	<2.2	40	19.6	…….	…….
Faecal coliforms	MPN/100 mL	<2.2	15	5	0	≤1 000******
E. coli	MPN/100 mL	<2.2	9	4.3	0	100

*****In the absence of a public water source of better quality, **Source: WHO, 1989, JS: Jordanian Standard, JDWS: Jordanian Drinking Water Standards

2.10. ANALYTICAL METHODS FOR TESTING WATER'S CHEMICAL QUALITY

2.10.1. Ion chromatography

Ion chromatography (also known as ion-exchange chromatography) is a process that separates charged biomolecules based on their affinity to the ion exchanger. For this process, the sample is allowed to pass through the chromatographic column and molecules bind to oppositely charged sites in the stationary phase (Rahman, 2020). A picture showing an ion chromatography instrument is given in Figure 2.3.

Figure 2.3: An ion chromatography instrument (Rahman, 2020)

An ion chromatography system (Metrohm 850 Professional IC) has an injection loop of 20 µL, a Dionex™ IonPac™ AG14 Guard Column (4 × 250 mm), and a conductivity detector and when using it, multiple working solutions of different concentrations (1, 5, 10 and 20 mg/L) have to be prepared to calibrate each anion to be analysed. An eluent from sodium bicarbonate and sodium carbonate has to be prepared and pumped into the system before standards can be injected into the system to perform calibration. Then a 50 mmol/L sulphuric acid of 0.5 mL/ min (8×10^{-9} m^3 s^{-1}) is used as a suppressant. The samples to be analysed must be filtered through a 0.45 µm Millipore filter prior to being injected into the IC system (Edokpayi et al., 2018).

Ion chromatography has become the method of choice for ion analysis in many applications such as commercial product analysis (hair products and juices) and for water analysis (monitoring water quality). For those, single-anion solutions, each anion should be prepared from stock reference standards and then the prepared standard solutions of each anion in question will then be injected into the ion chromatograph to determine the retention times (Phillip et al., 2005). Thereafter, calibration standards are prepared and analysed to obtain corresponding calibration curves for each concentration level. The anions can, then be determined from samples using experimental analytical method data, that is calibration curve and retention times (Phillip et al., 2005). Figure 2.4 below shows a sample of an ion chromatogram.

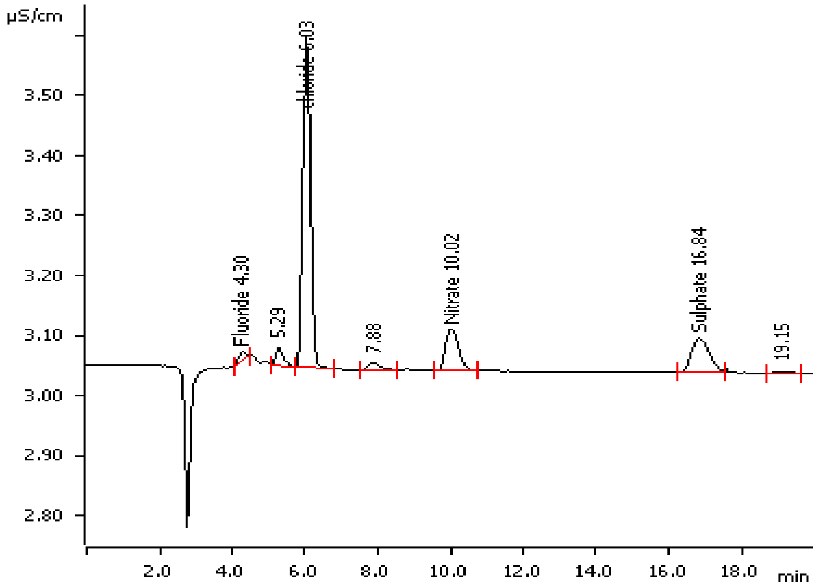


Figure 2.4: A sample of an ion chromatogram

Enitan et al. (2019) used the ion chromatography method (Metrohm 850 Professional IC) to determine the nitrate concentrations in groundwater. Multiple solutions of 1, 5, 10, and 20 mg/L were prepared as standards for the calibration processes according to the manufacturer's instructions and an eluent of 1.0 Mm $NaHCO_{3/3.5}$ Mm Na_2CO_3 was pumped through the ion chromatograph. The standards were then injected into the instrument to perform the calibration. Samples to be analysed were filtered through a 0.41 µm pore size filter before being injected into the sequential injection IC system for analysis.

2.10.2. Inductively coupled plasma (ICP) technologies

Inductively coupled plasma-optical emission spectroscopy (ICP-OES) is used in the determination of metals by injecting samples into a radiofrequency (RF) generator and given a plasma energy to excite the component elements (atoms) of the analysis samples. When the excited elements return to their lower energy position, the spectrum rays (emission rays) are released and the rays that correspond to the photon wavelength are then measured (Ghosh et al., 2013). The element type is determined based on the position of the photon rays. The schematic diagram in Figure 2.5 indicates the layout of major components of a typical ICP-OES instrument.

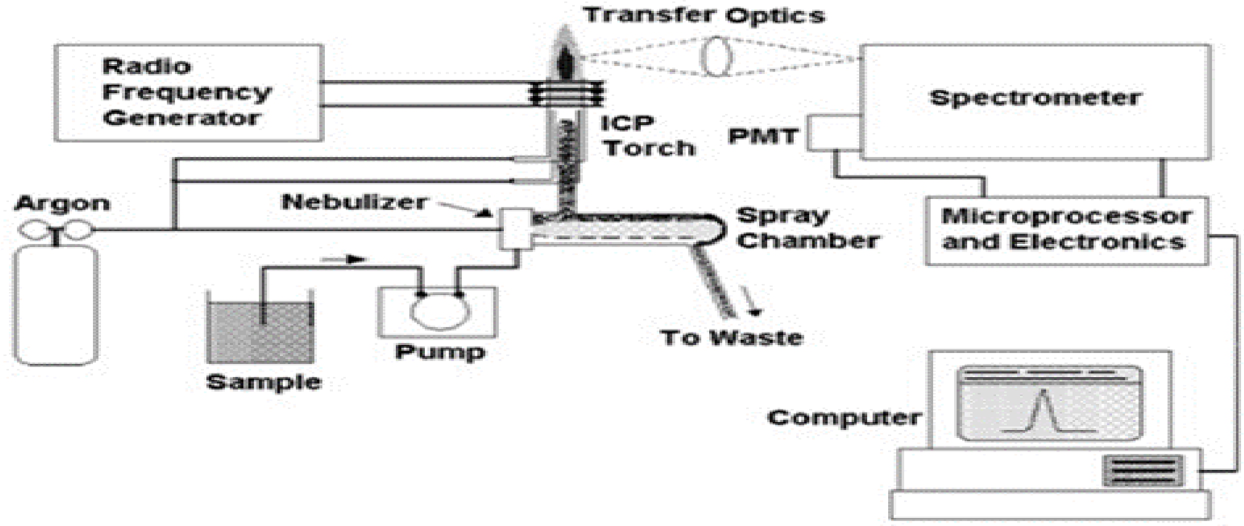


Figure 2.5: Major components of an ICP-OES instrument (Ghosh et al., 2013)

Edokpayi et al. (2018) used ICP-OES (Thermo Scientific) to analyse heavy metals in groundwater. Prior to the measurements, the analytical precision was checked by analysing the standards and blanks frequently. The instrument was standardised with seven standard solutions (multi-point linear fitting) for cadmium, zinc, chromium, iron, manganese, lead, and copper.

The inductively coupled plasma-mass spectrometry (ICP-MS) technique detects and quantifies all elements at concentrations as low as one part in 10^{15} (part per quadrillion) on non-interfered low-background isotopes. The detection is achieved by ionizing the sample using a mass spectrometer to separate and quantify the ions (Anabtawi et al., 2022). A schematic diagram of an ICP-MS instrument is given in Figure 2.6.

Brima (2017) used inductively coupled plasma-mass spectrometry (ICP-MS) for multi-element analysis of water samples where samples were introduced by an autosampler (CETAC™ ASX-S20 with 4 x 60 position sample racks), and a PlasmaLab Software (Version 25.4, Thermo Fisher Scientific) was used to process samples by calibration and running samples (before and after). The external multi-element calibration standards (Claritas PPT® grade CLMS-2) were used for Al, As, Ba, Cd, Co, Cu, Cr, Fe, Mn, Mo, Ni, Pb, Rb, Se, Sr, U, V, and Zn, in which the concentrations ranged from 0 µg/L in the blank sample up to 100 µg/L.

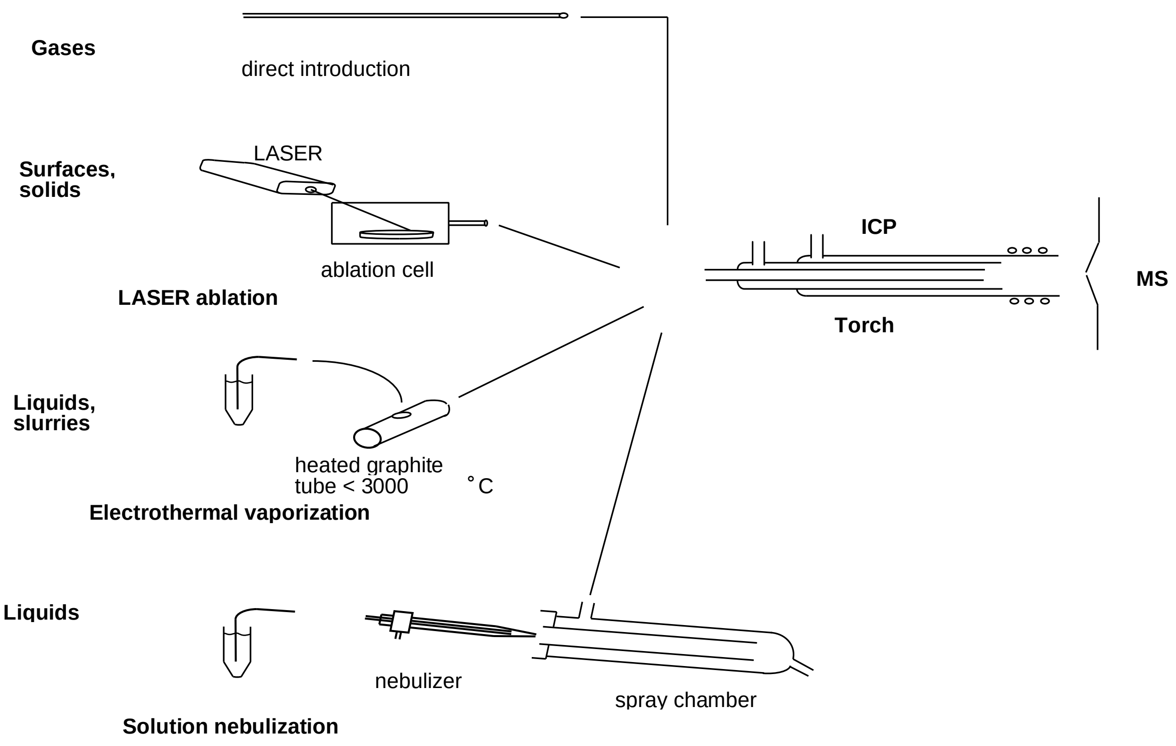


Figure 2.6: Schematic diagram of an ICP-MS instrument (Ammann, 2007)

2.10.3. Atomic absorption spectrometry

Atomic absorption spectrometry (AAS) is an analytical technique that makes use of the wavelengths of light to measure the concentrations of elements and it is so sensitive that it can measure down to parts per million of a sample (Rakshit, 2006). Compared to other methods, It has many uses in different areas of chemistry, including clinical analysis (analysing metals in biological fluids such as blood), pharmaceuticals (the amount of catalyst present during manufacturing processes can be determined), industry (levels of major elements in raw materials can be analysed), mining (the amount of metals, such as gold in rocks can be determined) and environmental analysis (monitoring the various levels of elements for example, in air, drinking water, sea water, rivers, beer, wine, fruit drinks, and petrol).

Edokpayi et al. (2014) used flame atomic absorption spectroscopy (FAAS) (PerkinElmer Flame Atomic Absorption Spectrometer) to analyse the concentration of heavy metals in samples collected from river water. The calibration standards of 1 000 ppm were prepared for each of the metals analysed and the serial dilutions of 0.5 ppm, 1 ppm, 2 ppm, 5 ppm, and 10 ppm were made. Prepared known concentrations of each of the target metals were run by the instrument to show consistency and distilled water was used to bring the instrument to zero before the analysis. The calibration curve was then prepared for each metal to be analysed.

2.11. ANALYTICAL METHODS FOR MICROBIOLOGICAL WATER QUALITY TESTING

Rajapaksha et al. (2018) explained the different methods for the detection of microbial pathogens. The methods included - polymerase chain reaction (PCR), colony counting and culturing, molecular detection methods, flow cytometry, and others. Colony counting and culturing is a similar method to membrane filtration where the method is performed by enumeration of the samples by placing a membrane filter on a 15 mL layer of an agar medium for bacteria (that is, m-*Enterococcus* agar) and incubating it at 37 ºC for 24 hours. The results are read by counting the colour colonies of faecal streptococci.

2.11.1. Culture-based method

This is regarded as a simple, cost-effective, and reliable method of detecting bacteria in water by transferring samples to be analysed into agar plates and incubating these at 37 ºC for 24 h (Tenebe et al., 2020). In a culture-based method, samples are cultured on a medium and kept at 37 ºC for about 1 to 5 days (depending on the type of bacteria) where all the positive cultures will be biochemically identified. To extract the DNA of the microorganisms in the sample, samples have to be centrifuged at 10 000 g and then the precipitate can be dissolved in 1 mL of sterile distilled water and the solution is heated for about 20 min at 85 ºC to kill the organisms and extract their DNA (Khorshidi et al., 2009).

A multiple tube fermentation test (or most probable number (MPN) technique) is used to determine the number of bacteria present in water samples; a series of sterile broth tubes are inoculated with measured amounts of the water sample to be tested and incubated for 24 hours (24 h) at 37 ºC and observed for changes in colour, turbidity, and appearance of gases, where those changes indicate the presence and growth of bacteria (Tenebe et al., 2020).

The most probable number (MPN) technique for routine water microbiology has now largely been replaced by membrane filtration (MF) methods: water samples from different sources are passed through a membrane filter with a pore size of 0.45 µm and the membrane is incubated on an agar plate. Bacterial cells trapped on the membrane will grow into colonies that can be counted. Different filtration volumes of water are used, depending on the sources of the water.

2.11.2. Molecular method

Molecular techniques are used for detecting and categorising of bacteria using 16S rRNA gene sequence analysis, among others. The molecular techniques for identification of microbes are single gene sequencing (for example, by sequencing ribosomal RNA encoding 16S, 23S, and 18S genes, and associated internal transcribed spacer (ITS) markers); multiple gene sequencing (housekeeping and pathogenic genes) and whole-genome sequencing. Molecular techniques are also used to diagnose several viral diseases, generally in the clinical laboratories. They identify the viruses present by detecting the viral messenger RNA (mRNA) using automated devices of non-amplified nucleic acid probes labelled with radioisotopes and enzymes.

2.11.3. Flow cytometry

Flow cytometry is a technology used to measure the relative size of microscopic particles using an optical-to-electronic coupling system that records how a cell or a particle is scattered in a laser light and emits fluorescence, then collected and stored in the computer as data. In the flow cytometry method, microorganisms are suspended in a liquid matrix and passed through a beam of laser-focused light and then the light will be both scattered and absorbed by the organisms present and then the scattered light (with a system of photocells and lenses) can be used to determine the sizes, numbers, and the shapes of microorganisms (Rajapaksha et al., 2018). It is a modern way of analysing thousands of particles per second and can actively separate and isolate microbial particles having specified properties (Shukla, 2018).

2.11.4. Polymerase chain reaction (PCR) method

The polymerase chain reaction (PCR) is a molecular method that can be used to detect the presence of pathogens in water (DeBusk and Hunt, 2014). PCR is a nucleic acid amplification technique that is widely used to identify bacteria by means of isolation, amplification, and quantification of a short segment of DNA (Rajapaksha et al., 2018). The PCR cycle consists of three main steps, namely, denaturation, primer annealing, and primer extension, followed by analysis with electrophoresis. The PCR method is performed by varying the outer primer annealing temperature and primer concentration (Khorshidi et al., 2009).

2.12. HEALTH RISKS ASSOCIATED WITH THE USE OF ROOFTOP-HARVESTED RAINWATER

It is crucial to recognise the human-health risks associated with rooftop-harvested rainwater by gauging them against existing standards for water quality. A health risk can be categorized as either perceived risk (stakeholders and public's perception), estimated risk (application of scientific facts), or actual risk (number of people whose health status have been compromised) (Jiang et al., 2015). Rainwater is likely to contain microorganisms from birds and mammals that live around the catchment area (Zabidi et al., 2020). The roof catchment is open to the environment and accessible to insects, birds, reptiles, and pathogenic organisms through faecal deposits, insects breeding, decay of dead organisms, dust, and other organic debris (Afangideh and Udokp, 2021). Drinking rainwater that is contaminated by heavy metals poses a threat to human health because of their toxicity, and exposure to toxic substances can lead to heavy-metal poisoning; for example, exposure to cadmium affects the kidneys, disturbs the bone metabolism, and affects the human reproductive system, while lead can cause anaemia, damage the reproductive organs in males and trigger miscarriage in pregnant women (Chubaka et al., 2018; Anabtawi et al., 2022).

If the tanks storing harvested rainwater remain open to the environment, there is a high risk of contamination from the environment, people or animals, mosquito breeding and the growth of algae (Struk-Sokolowska et al., 2020). The consumption of such contaminated water and poor hygiene storage practices may cause an outbreak of waterborne diseases that can lead to deaths (Chukwuma et al., 2014). These contaminants may be particulate matter, microorganisms, metals, chemicals, and ionic elements that are detrimental to human health; they can cause people to suffer from asymptomatic infections with symptoms that can go unnoticed but still dangerous to health (Chubaka et al., 2018). There are approximately 2.2 million childhood deaths per annum in developing countries from diarrhoeal disease, cholera, typhoid fever, and dysentery which are due to polluted drinking water (Afangideh and Udokpoh, 2021).

Drinking roof-harvested rainwater with environmental components such as arsenic, lead, fluoride, cadmium, mercury, chloride, and nitrates can lead to diseases such as dental and skeletal fluorosis, memory lapses, renal failure, acute nausea, anaemia, stunted growth, foetal abnormalities, skin rash, diarrhoea, vomiting, poisoning, and bladder cancer (Judeh et al., 2022). The potential health risks associated with the use of rooftop-harvested rainwater (RTHRW) can be minimised by starting the prevention of contamination at the source. This can be done by safe storage, practising good animal husbandry and appropriate roof maintenance systems, (for example, cleaning roof gutters before a rainfall event) (WRC, 2017). Rainwater tanks should be equipped with close-fitting lids which should be kept shut to prevent contamination but will allow access to the tank for cleaning.

CHAPTER THREE: METHODOLOGY

3.1. CHAPTER BACKGROUND

This section describes the research methodology used to achieve the objectives of this study. The chapter also provides information on the study area.

Rooftop-harvested water was collected during six (6) rainfall events in October 2020, December 2020, January and February 2021, October 2021, November 2021, and December 2021. Rooftop-harvested rainwater samples collected in October 2021 were taken as first flush because those samples were collected at the start of a rainfall season after several months of no rain.

Three communities in Vhembe District in the Limpopo Province, South Africa, were used as areas of sample collection of rooftop-harvested rainwater. Those areas included a rural village (Tshikhudini village), an urban area (Sibasa), and an Institution of Higher Learning (the University of Venda). All the communities were found to be suitable and convenient for this research because they consisted of varying land uses – a learning institution, residential area, industrial and agricultural areas, apartments, parking lots, commercial sites, shops, and complexes.

The collection of rainwater samples was done from five different roof types (thatched, steel, slate, concrete, and aluminium) from each community per rainfall event (Figure 3.1). The different roof types used are presented in Figure 3.2. Control samples (samples collected directly from rainfall) were also collected from each of the three communities during each sample collection exercise. With the University of Venda sampling area, the thatched roof type was used for collection, as in other communities, for only the first rainfall event for samples collected in October 2020, thereafter, all other roofs were also sampled for roof-harvested rainwater at the University of Venda for the other rainfall events. A total of 294 samples were collected for six rainfall events occurring over the different months (including first flush), in three different communities with different land uses and locations, and from five different roofing materials.

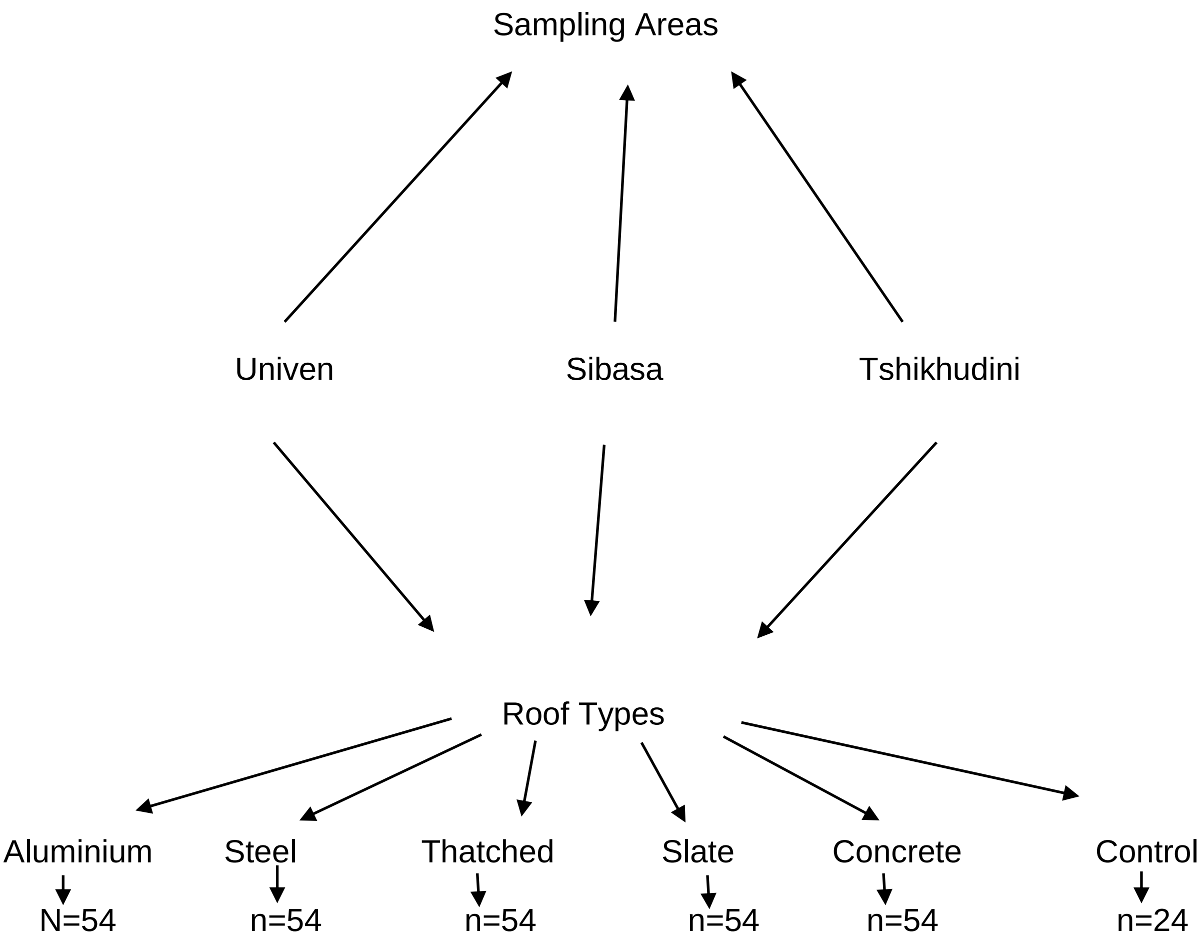


Figure 3.1: A flow chart demonstrating the collection of harvested rainwater from different roofing types, including the control (samples collected directly from rainfall)

Rainwater samples were collected using sterile high-density polyethylene (HDPE) containers and a funnel was used to collect rainwater from the rooftops into the bottles (Figure 3.3). Collected samples were transported to the University of Venda and stored at 4 ºC in the laboratory refrigerator. Rainwater samples collected directly from the atmosphere served as control samples and all other samples were collected from the different rooftops. Samples were then divided into analytical and microbiological samples for further analysis.

Figure 3.2: Different rooftops used to collect samples in this study, where 1 represents, Slate roofing, 2: Aluminium roofing, 3: Steel roofing, 4: Concrete tile roofing, 5: Thatched roofing

3.3. ANALYTICAL METHODS

3.3.1. Physicochemical parameters

Physicochemical parameters that were measured in this study include: pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and turbidity. EC (µs/cm), pH, salinity (mg/L), and TDS (mg/L) were measured using a specialised multimeter. Turbidity (NTU) was measured using the TB200 Benchtop Turbidity Meter. Both meters were calibrated before use, following the guidelines of the manufacturer and at room temperature. The measurements were performed in triplicate to ensure accuracy and precision of the results.

Figure 3.3: A schematic picture of a bottle and a funnel that were used to collect rainwater samples

3.3.2. Heavy metals

Water samples were analysed for heavy metals using inductively coupled plasma mass spectrometer (ICP-MS). The instrument uses an Octopole Reaction System (ORS) that has He as collision gas, and O2/H2 as reaction gas used to remove polyatomic interferences from the analytes of interest. Rainwater samples were digested with nitric acid before analysis with ICP-MS. This was done to slow down the chemical reactions and to prevent the multiplications of microorganisms in the water samples (Enitan et al., 2018). For the analysis, samples were introduced through a 0.4 mL/min (7 × 10−9 m3 s −1) micro-mist nebulizer into a Peltier-cooled spray chamber at 2 ◦C (275.15 K), with a carrier gas flow of 1.05 L/min (1.75 × 10−5 m3 s −1).The metals that were analysed included - aluminium (Al), boron (B), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), lithium (Li), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn).

3.3.3. Microbiological analysis

All samples were analysed for microbial organisms within 6 hours of sample collection. Total coliforms and *E. coli* were analysed using the membrane filtration technique according to U.S. Environmental Protection Agency method (Hach, 2018). The sample cups of the manifold were boiled in a hot-water bath at 100 °C for 30 min and cooled off afterwards. Paper filter disks of 47 mm diameter and 0.45 µm pore size (EMD Millipore, Billerica, MA, USA) were removed from their sterile packages to the surface of the manifold with forceps with an aseptic technique. The filter paper was placed in a sterile petri dish with absorbent pad with 2 mL of selective growth media solution (m-ColiBlue24, EMD Millipore, Billerica, MA, USA). The ready-to-use nutrient medium, m-ColiBlue24® Broth (Cat M00PMCB24) was poured in a specialised petri dish with the samples, and then were incubated at 35 °C for 24 hours before the counting of the colonies (Edokpayi et al., 2018).

3.4. METEOROLOGICAL DATA

Historical rainfall data for Vhembe District of Limpopo Province, South Africa were collected for a time series of 20 years (1996-2020) to track down the availability of rainfall over the study area since the success of harvesting rainwater is dependent on rainfall. The hydrological data were obtained from the South African Department of Water and Sanitation and the South African Weather Service. Temperature does not influence the quality of roof-harvested rainwater, however, for an accurate estimate and design for the collection of rainwater, the temperature, and the rainfall pattern around the area within which the rainwater will be harvested, need to be known. South African rainfall patterns are seasonal, with the Western Cape being a Mediterranean region while other parts of the country receive summer rainfall.

3.5. POTENTIAL HEALTH RISK ASSOCIATED WITH TRACE METALS

Using untreated roof-harvested rainwater for human consumption or other domestic uses may lead to potential public health risks. Risks are mainly associated with factors, such as roofing material, environmental conditions, and animal droppings which may transfer pathogens onto roof rainwater catchment areas. Unfortunately, the presence of pathogens in untreated water may lead to the transmission of water-borne diseases with devastating effects on the population (Tenebe et al., 2020).

The assessment of health risk is normally based on risk estimation classified as ‘non-carcinogenic health hazards. A method adopted from the US EPA Risk Assessment

Guidance for Superfund (RAGS) reported upon by Edokpayi et al., (2018) was used to calculate the human exposure risks which could be through inhalation, ingestion, and dermal absorption. Common human exposure risk pathways for water are dermal absorption and ingestion routes. Equation (3.1) and Equation (3.2) below were used to determine the human health risks through these two pathways:

$$EXPing\,\frac{Cwater \times IR \times EF \times ED}{BW \times AT} - (3.1)$$

$$EXPderm\,\frac{Cwater \times SA \times KP \times ET \times EF \times ED \times CF}{BW \times AT} - - - - - - - - - - - - - (3.2)$$

where:

EXP_{ing} – exposure dose through ingestion (mg/kg·d)

EXP_{derm} - exposure dose through dermal adsorption (mg/kg·d)

C_{water} - average concentration of metals in water

IR - ingestion rate (L/d)

EF- exposure frequency (365 days/year)

ED - exposure duration (years)

AT - average time (days/years)

SA - exposed skin (cm^2)

K_p - dermal permeability coefficient on water (cm/h)

ET - exposure time (h/d) CF - unit conversion factor (0.001 L/cm^3)

BW - average body weight (kg)

Potential non-carcinogenic risks were determined by comparing the calculated contaminant exposure of the two exposure routes using Equation 3.3.

$$HQing/derm\,\frac{EXPing/derm}{RFDing/derm}\text{---}(3.3)$$

where:

$RFD_{ing/derm}$ is ingestion/dermal toxicity reference dose (mg/kg·d)

A hazard quotient (HQ) lower than 1 is safe and significantly non-carcinogenic, but if it is above 1, there may be major potential health concerns. The constants of the equation above are given in the Table 3.1 below.

Table 3.1: Health risk assessment of different exposure through parameter

Parameter	**Unit**	**Child**	**Adult**
Exposure Frequency (EF)	Day/ year	365	365
Body Weight (BW)	Kg	15	70
Ingestion Rate (IR) or Daily intake (DI)	L /day	1.8	2.2
Exposure Duration (ED)	Years	6	70
Skin surface Area (SA)	Cm^3	6600	18 000
Exposure Time (ET)	Hours /day	1	0.58
Conversion Factor (CF)	L / cm^3	0.001	0.001
Averaging Time (AT)	Days	365 × 6	365 × 70

Adapted from USEPA (1989)

3.6. WATER QUALITY INDEX

The Water Quality Index (WQI) is a single numeric value which can be calculated and used to express the overall status of water quality through the integration of microbiological and physicochemical parameters. It measures the degree of contamination and indicates whether a specific water resource produces poor water quality or an excellent water quality (Banda and Kumarasamy, 2020).

In this study, the WQI was calculated in three stages - (1) allocating relative weight to investigated parameters; (2) computing equations to resolve the quality rating scale and (3) using the SANS standards given for each parameter and the quality rating scale to calculate the WQI. The method used by Singh and Hussian (2016) and Banda and Kumarasamy (2020) were adopted.

To calculate the unit weight of the parameter (W_i), the relative weight of the i^{th} parameter (b_i) must be divided by the sum of all the ratings (equation 3.5.)

$$Wi = \frac{bi}{\sum_1^n (bi)} \tag{3.5}$$

where:

b_i is the assigned significance rating of the ith water parameter.

W_i is the unit weight of pollutant; and

n is the total number of rated water quality parameters.

Considering the water quality parameters being monitored, the quality rating of the ith parameter (q_i) was determined as follows (correct Equation. 3.6):

$$Qi = \frac{Ci}{Si} \times 100 \quad (3.6)$$

where:

C_i is the concentration of each chemical parameter (mg/L) in each roof-harvested rainwater sample, and

S_i is the accepted water quality standard for each parameter.

The WQI was then computed using the following equation. The sub-index of the ith parameter (SI_i) is first determined for each parameter, and it is given as:

$$SIi = Wi \times qi \quad (3.7)$$

Then:

$$WQI = \sum_{i=1}^{n} SIi \quad (3.8)$$

where:

SI_i is the sub-index of the ith parameter;

W_i is the relative weight of the ith parameter;

q_i is the quality rating of the ith parameter; and

n is the number of rated water quality parameters.

The results were classified based on the WQI ranges given in Table 3.2.

Table 3.2: Water Quality Index (WQI) ranges

Number	WQI range	Description
1	<50	Excellent water quality
2	50-100	Good water quality
3	100-200	Poor water quality
4	200-300	Very poor water quality
5	>300	Water is unfit for drinking purposes

Source: Singh and Hussian (2016)

3.7. QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA)

Quantitative microbial risk assessment (QMRA) is a modelling technique used to estimate the probability of infection and subsequent illness for a specific population when exposed to pathogenic microorganisms (Charles et al., 1999). The assessment is focused on faecal contamination of water and the faecal indicator organisms include but are not limited to - *Escherichia coli*, *Salmonella, Shigella, Vibrio, Clostridium*, *Campylobacter*, *Cryptosporidium*, and *Giardia* spp. (Evans et al., 2007). Its procedures are based on scientific data and best assumptions which may be used to educate and instil confidence in stakeholders about the benefits of a practice, which in this study was about the usage of rooftop-harvested rainwater (Jiang et al., 2015).

The model of beta-Poisson dose-response was used to calculate the probability of infection (Pi) resulting from the ingestion of 100 mL and 2000 mL (2 L for the pathogens) of rooftop-harvested rainwater, as described by the World Health Organization (Abia et al., 2016). In this study, the QMRA was determined using the pathogenic *E. coli* counts expressed as CFU/100 mL. The probability of infection was calculated assuming that 8% of average *E. coli* counts are pathogenic (Haas et al., 1999).

The equation used for calculating the probability of infection, due to the ingestion of 100 mL and 2000 mL (2 L) of untreated rooftop harvested rainwater based on a single exposure, was given as follows:

$$Pi = 1 - (1+N/\beta)^{-\alpha} \qquad (3.9)$$

Where:

N = number of dose ingested

β and α are organism-specific equation parameters. The β and α parameters for the calculation of Pi for *E. coli* microbial species are given as 2.473 and 0.395, respectively (Haas et al., 1999).

The equation for calculating the probability of infection resulting from multiple exposures of 100 mL and 2000 mL of untreated roof-harvested rainwater, was given using the following formula:

$$Pn = 1 - (1-Pi)^{-n} \qquad (3.10)$$

where n is the number of times exposure occurs.

3.8. QUESTIONNAIRES

3.8.1. Questionnaire data collection

A total of 110 respondents were selected from different groups of people who practice RWH in their households. This include community members, students, workers, farmers and housewives who gave their consent to participate in the study. All respondents that do not practice RWH were excluded from the study. An exception was also made in the case of persons under 20 years of age who were not asked to participate in the survey.

Pilot testing questionnaires were sent to assess the quality and suitability of the questions. The first pretest was a participatory survey administered to 10 participants who were informed it was a pretest phase where they can add comments and suggestions. The second pretest was treated as the real survey and was also administered to 10 participants. Changes were made on designing the set of instructions and on other questions that were unclear and difficult to understand. Face-to-face interviews were conducted with the respondents and the sessions were guided by typed paper questionnaires which were available in English as the first language and in Tshivenda as the most spoken language within the district, (see appendix 1). The questionnaire was administered during the period of the Covid-19 pandemic. All the Covid-19 health protocols were observed during the interviews to minimise the spreading of the virus.

3.8.2. Questionnaire Design and Construction

The questionnaire was developed based on prior studies focusing on public perception on the use of harvested rainwater in different countries and an identification of knowledge gaps. The considerations in constructing the questionnaire included - 1) profile of the respondents, 2) collection of harvested rainwater, 3) storage tank and its condition, 4) potential uses of harvested water, 5) risks associated with the use of harvested rainwater, 6) willingness to pay, and 7) compelling reasons for using harvested rainwater.

3.8.3. Ethical consideration

Ethical clearance was obtained from the University of Venda Research and Ethics Committee, prior to the study (No: SEA/21/HWR/07/1608). The Ethical Clearance Certificate is presented in Appendix 2.

3.9. STATISTICAL ANALYSIS

Both the physicochemical and the microbiological data were coded, processed, and analysed using Microsoft Excel 2016 where averages were calculated, and line charts were also plotted to determine trends. The acquired data was compared with that of existing standards of the quality of roof-harvested rainwater, and with the water quality results of rooftop-harvested rainwater from previous studies.

All the results in this thesis were reported according to their mean and standard deviations. The statistical analysis was conducted using the IBM SPSS statistical analysis software platform to generate analysis of variance (ANOVA). The relationship between physicochemical parameters and mean concentration of bacterial counts in the rooftop-rainwater harvested samples were determined by Pearson's correlation coefficient (r), where $p<0.05$ was considered significant and at a confidence level (95%).

CHAPTER FOUR: THE PERCEPTION AND ACCEPTANCE BY THE PUBLIC OF THE USE OF HARVESTED RAINWATER IN THE VHEMBE DISTRICT MUNICIPALITY OF THE LIMPOPO PROVINCE, SOUTH AFRICA

4.1. CHAPTER BACKGROUND

This chapter presents and discusses the results on the survey carried out on the public who practice, RWH in the VDM. The results of this chapters are based on the first objective of this study - to assess the perception and attitude of people towards the use of roof-harvested water.

4.2. HOUSEHOLD SIZE

Villages in VDM that took part in the questionnaire survey were 28 communities, and they include - Thohoyandou, Malamulele, Sibasa, Ha Mutsha, Shayandima, Lufule, Sidou, Mangoni, Majosi, Maungani, Mbahela, Tshivhilwi, Tswinga, Dimani, Phiphidi, Thengwe, Tshikhudini, Mphego, Muledane, Tshisaulu, Mapate, Ha Mavhunda, Lwamondo, Tsianda, Tshififi, Masea, Ngwenani and Khubvi.

Figure 4.1 shows the number of people in the households of the respondents. The household size varied between one to twenty-one members, with the average numbers ranging between 3-7. The mean highest household size recorded in this study was 6. A South African study in the Kleinmond LCH area of the Western Cape had an average household size of 3.8 (O`Brien, 2014).

4.3. DEMOGRAPHIC CHARACTERISTICS OF THE RESPONDENTS

The survey responses analysed showed that the responses were gender-skewed with majority being males (55.5%, n =61). Several similar studies have recorded higher participation of women than their male counterpart because women are believed to be the ones responsible for household activities, such as the provision of water (Gonzales-Padron et al., 2019; Owusu and Asante, 2020). There was a high age variation among the respondents, which ranged from 20 to 80 years. Most participants were between the age of 20-29 (58.2%, n=64) (Table 4.1).

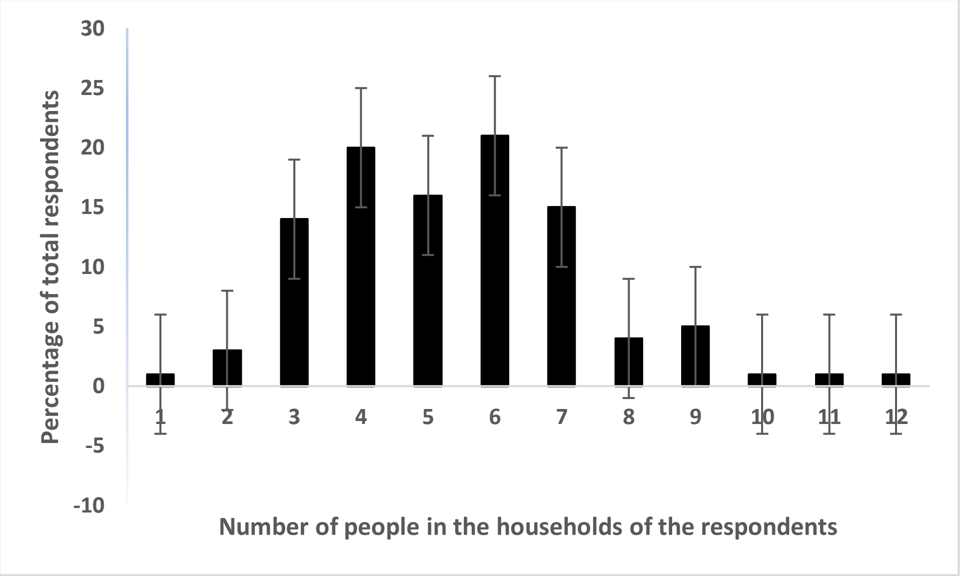


Figure 4.1: Number of people in the households of the respondents

Table 4.1: Demographic picture of the respondents

Age	**N**	**Percentages (%)**	**Equipment used to store collected rainwater**	**N**	**Percentages (%)**
20-29	64	58.18	Store underground	0	0
30-39	19	17.27	Jojo tanks	46	41.82
40-49	16	14.55	Small buckets	60	54.55
50-59	6	4.55	Other water drums	2	1.82
60-69	1	0.91	Other big basins	2	1.82
70-79	2	1.82			
80-89	2	1.82			
Time of rainwater harvesting	**N**	**Percentages (%)**			
Morning	6	5.5			

Afternoon	1	0.9
Evening	3	2.7
Anytime it rains	100	90.9

In terms of employment status, 74.6% (n=28) of the respondents were unemployed and only 25.5% (n=82) were employed. The low socioeconomic status of the unemployed may be a reason why they have largely adopted RWH in their households (Ogbiye et al., 2021). People with high socio-economic status would prefer to drill a borehole when there is limited supply of water to ensure continuous access to meet their needs. Majority of the households in South Africa reported that they depend on government grants for survival (Fisher-Jeffes, 2015). Unlike the present study where majority of people cannot support themselves socio-economically, a study by Karim et al. (2015) reported that the entire population of Bangladesh is characterized by people who are either employed or self-employed, since there are no grants provided by the government.

Majority of those who took the survey were mostly university graduates (32.73%, n=36); (Table 4.2). Ramya et al. (2019) established that most of those who harvest rainwater had no formal education; similarly, the majority of those interviewed by Mannel et al. (2014) in a South African study, had very little education and most stopped schooling at the primary level.

Table 4.2: The respondents' level of education

Level of Education	N	Percentage (%)
No schooling	2	1.82
Primary	0	0
Secondary	14	12.73
Further Education Training (FET)	29	26.36
Higher Education Training (HET)	27	24.55
Graduates	36	32.73

4.4. COLLECTION OF HARVESTED RAINWATER AND FREQUENCY OF USE

A hundred of the 110 respondents in this study reported that they harvest rainwater whenever it rains (Table 4.1). Three of the respondents, however, reported that they harvest rainwater in the evenings because they are usually at work during the morning and afternoon periods. The Water Service Act of South Africa, Section 3 of Chapter 1 states that rainwater can be harvested from one's dwelling place to provide water for basic needs (Kahinda et al., 2014). Almost all the respondents (95%) used their own roof to collect rainwater, while the others collect rainwater from their neighbor's roof catchment. Most of the respondents reported that they often used the harvested rainfall as an alternative source of water since they cannot store the rainwater all through the year. When potable water is available, they often resort to it and return to the harvested rainwater when the taps are shut.

Edokpayi et al., (2018) reported that due to erratic supply of potable water to households in Vhembe Districts, residents have resorted to using water from boreholes, springs, and harvested rainwater. Fifty-one respondents reported that they use the collected harvested rainwater several times in the week, while 29.09% (n=32) reported using the harvested water daily due to the absence of other sources of water at a reasonable distance, while 23.64% (n=26) of the respondents use it less, only when other sources of water are not available.

4.5. STORAGE TANK USED AND ITS CONDITION

The storage tank is the most visible or recognizable component of a RWH system; it is where the captured rainwater is diverted to and stored (Mohammad, 2020). The respondents use various containers to store the harvested rainwater, ranging from open buckets to jojo thanks. 54.55% (n=60) of the respondents uses small buckets as storage containers; 41.82% (n=46) store their harvested rainwater in a 1000-2000L, jojo tanks. No respondent in this survey reported the use of an underground storage tank. Drums and basins were also reported as storage containers in the study area. Some of the storage containers are presented in Figure 4.2 below. In this study, contamination of harvested rainwater was reported due to handling and storage, as the use of open containers for storage creates a higher chance of microbial contamination and biofilm formation.

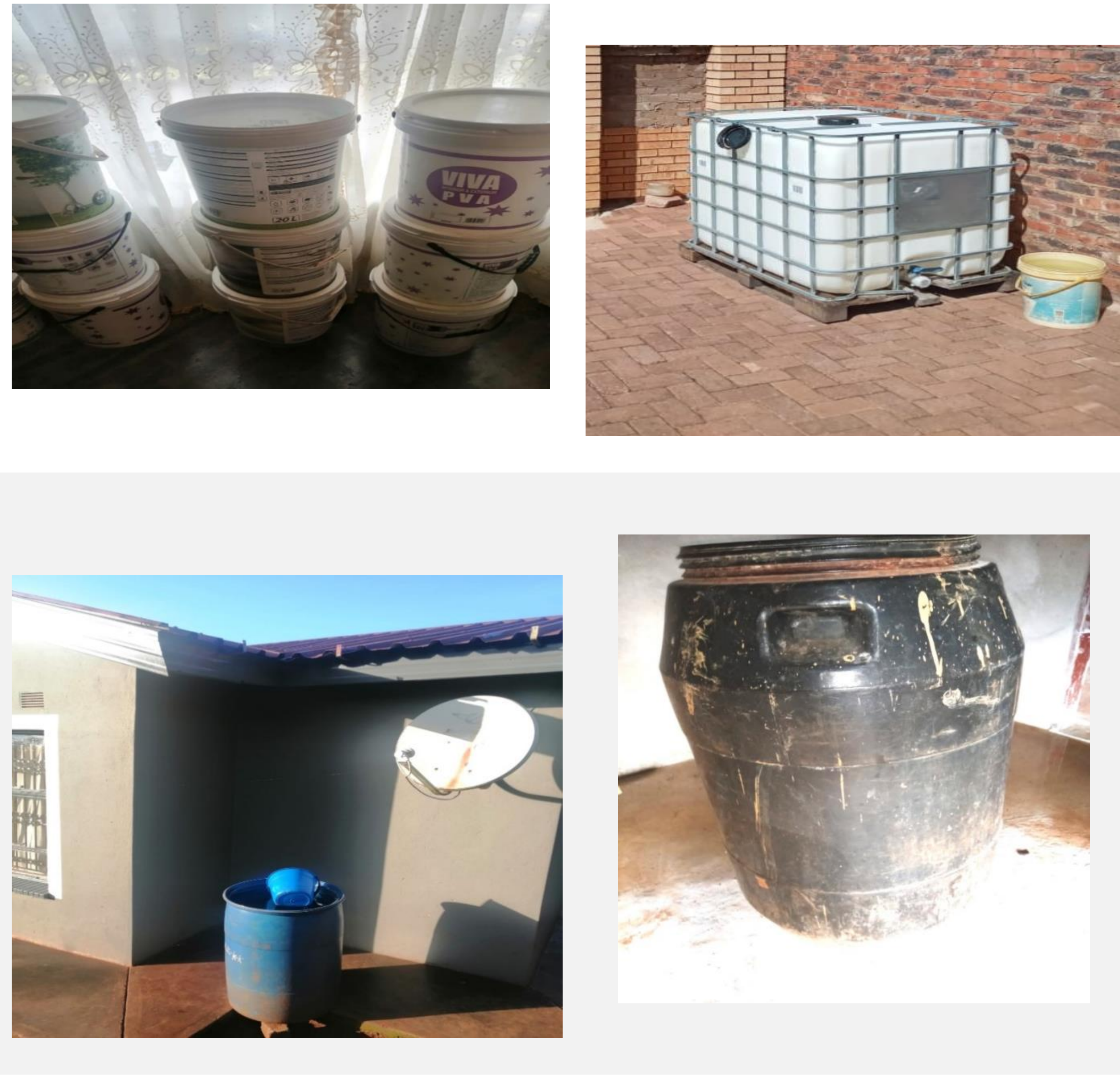


Figure 4.2: Various storages used for harvested rainwater

The socio-economic status played a role in the kind of storage containers used by the households. The storage of harvested rainwater for a long time in an unsuitable container will also increase the risk of contamination. Malambo and Huang (2016) in their study reported that harvested rainwater was stored in PVC bottles, dishes, and buckets. Another study by Asmuni et al. (2016), reported that majority of their respondents (84.4%) preferred to use water drums for the storage of rooftop-harvested rainwater. It is interesting to note that only 51.8% of the respondents store only harvested rainwater in their storage containers while others (48.2%) stored any kind of water in their storage containers, thus, mixing harvested rainwater with borehole water and potable water from the municipality when available.

Some of the respondents noted that their storage containers are not in good condition but due to their socio-economic status they have to continue to use them. Majority of the respondents (62.7%, n=69) however, reported that they feel their storage containers are in good working condition; others (31.8%, n=35) did not answer this question. Some of the respondents (42.7%) reported the cleaning of their storage containers at least once in a month; 20% (n=20) washed their storage containers weekly; about 30% wash their storage containers once in a year, while 7.3% (n=8) had never washed their storage containers. It is vital to keep harvested rainwater's storage tanks clean because they are very prone to contaminants and microbiological contaminates may multiply and disintegrate the quality of harvested rainwater. Other ways to reduce the risk of using harvested rainwater includes, cleaning the catchment and storage tanks during the dry periods, discouraging birds from perching and animals from wandering over the catchment area (Judeh et al., 2022).

Most of the respondents (81.8%, n=90) were willing to pay for the repair of their storage tanks if it is ever required, although a few (18.2%, 20) were not willing to do so. Previous studies have mentioned that RWH system is not a "fit and forget" system, but a system where maintenance is always a requirement to check, clean and replace parts of the system, for example, roof catchment, gutters and storage tank, over time to minimize the contamination of roof-harvested rainwater (Ward et al., 2008). Korsten et al. (2016) reported that many households which practice RWH lack the knowledge that best suits their areas in terms of the best harvesting technique, construction of the catchment and maintenance of the entire system.

Results from this study showed that 44.5% (n=49) of the respondents do not have adequate knowledge of the construction, use and maintenance of a RWH system, although, 55.5% alleged that they have adequate knowledge. It is, however, noteworthy that the respondents (n=36), who indicated that they do not have adequate knowledge of the system are willing to learn how to effectively manage their RWH systems. Judeh et al., (2022) mention that the system of RWH has low running costs, and its construction, operation and maintenance are not labor-intensive.

4.6. CURRENT USES OF HARVESTED RAINWATER

The question on the current uses of the harvested water, respondents were allowed to list all the potential uses of their harvested rainwater. The results obtained showed that they are currently using the harvested rainwater for a variety of domestic purposes, such as for doing the laundry (83.7%), bathing (67.27%), irrigation (64.55%), sanitation (42.73%), drinking (36.36%), washing of dishes (56.36%), cooking (20%) and washing of the compounds (21.82%). Recorded studies have revealed that rainwater can be used for a variety of purposes, without treatment. Most of the respondents do not drink the water as they perceived that the water quality may be compromised, however, the water harvested can be used for a wide variety of purposes which places less burden on the treated water.

Several previous studies have been undertaken to assess the community's perception and the people's preference of the potential uses of their harvested rainwater. Table 4.3 below shows the various uses of harvested rainwater reported in literature and in this study.

Table 4.3: Percentages of the public's different uses of harvested rainwater

Previous Studies	Respondents	Percentages (%) of different uses of previously conducted studies							
		Drinking	Cooking	Bathing	Gardening	Toilet flushing	Washing vehicles	Washing dishes	Washing Clothes
Asmuni et al., (2016)	109	16.51	NR	8.26	80.73	49.34	62.39	15.51	11.01
Ogbiye et al., (2021)	400	6	17	NR	NR	21	9	38	10
Obrien et al., (2014)	410	3	3	20	35	29	NR	13	13
Mannel et al., (2014)	68	24	19	44	46	NR	NR	70	92
Fisher-Jeffes (2015)	NR	15	NR	29	NR	26	NR	2	24
This study	110	36	20	67	65	43	22	56	83

Where NR is not reported

4.7. PERCEIVED WATER QUALITY AND TREATMENT OPTIONS FOR HARVESTED RAINWATER

The use of harvested rainwater, of high quality can reduce the dependence on the municipal's water supply system as the quality of the former has been linked to positive health outcomes. Most of the respondents (98.2%, n= 108) reported to never trying to know the quality of their harvested rainwater, while others judge the water quality on aesthetic reasons, such as turbidity, taste, colour and odour. A number of the respondents never treated the harvested rainwater before use (48.18%, n= 53), however, some reported that they use simple water treatment methods before consumption and for food preparation. The most common methods reported was boiling (38%), addition of bleach (12%), sedimentation (4%) and placing it under the sun for solar disinfection (4%). The methods used are presented in Figure 4.3.

The treatment of harvested rainwater depended on the uses of such water in the various households. The quality of the harvested rainwater is often suitable for irrigation, laundry, and sanitation purposes; however, simple point-of-use water treatment systems can be used to treat the water if it is to be used for drinking purposes. Sheik (2020) reported that, although harvested rainwater can be perceived as relatively clean, visually, treatment is required and Mannel et al., (2014) corroborated by stating that if such water is used for domestic purposes, such as drinking and food preparation, simple water treatments are encouraged. Results from this study differ from those reported by Kim et al., (2016) where ultraviolet radiation and chlorination were the most common treatments used to disinfect harvested rainwater.

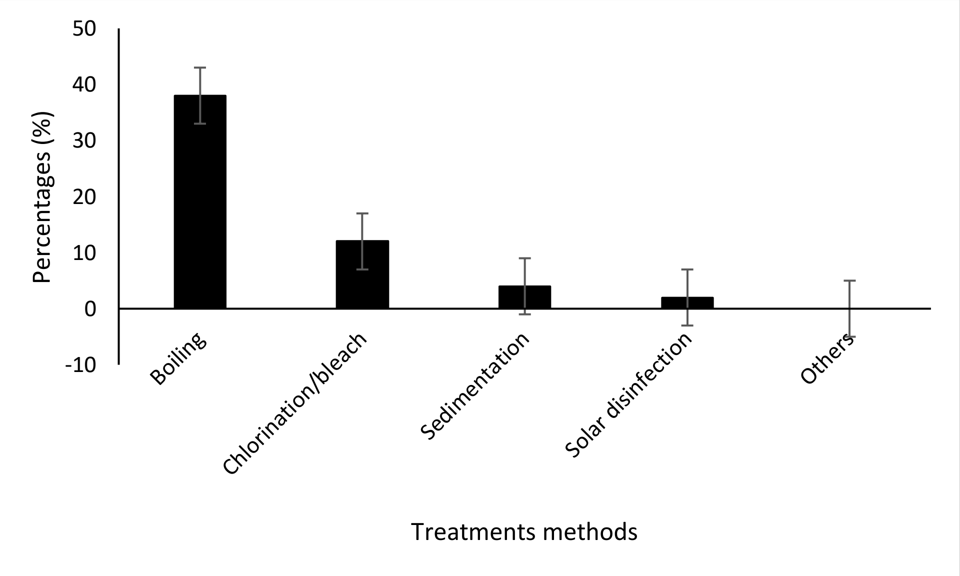


Figure 4.3: Potential RWH treatments and the number of respondents who uses them

Majority of the respondents (93.6%, (n=103)) reported that they have not recorded any adverse effect from the use of the harvested rainwater. Common reported adverse effects from this study include diarrhoea when consumed without treatment and skin irritation when used for bathing. Other studies reported adverse impacts associated with the use of untreated harvested rooftop rainwater included, body rash, nausea and skin infection (Judeh et al., 2022). Some of the respondents reported the presence of visible worms in the harvested rainwater at certain times.

4.8. REASONS FOR PRACTISING RAINWATER HARVESTING

The respondents (35%, (n=38)) reported that one of the reasons for practicing rainwater harvesting is the unavailability of water infrastructure in their area. Others (31%, n=34) reported that they conserve harvested rainwater as an alternative source of water when their main source is not in operation. Some respondents practise rainwater harvesting due to rationing and limited quantity of water often received from their main water supply system, while others are involved in RWH to reduce the amount of money spent on the purchase of potable water. These are valid reasons to engage in rainwater harvesting as the procedure makes water available, most of the time for the people for various uses. The idea of using harvested rainwater as alternative water source is commendable and it reduces the stress, time and energy spent on sourcing water from other locations which may be far from the respondents.

To ascertain the driving force for rainwater harvesting, the respondents were given a list of the possible compelling factors to choose from. Their responses are presented in Table 4.4. The five influences are statistically different ($p < 0.05$) between those who were unsure, sure, not, and those who did not want to answer.

Table 4.4: Factors influencing respondents to use harvested rainwater

In overall, what influenced you to use harvested rainwater?				
	Yes	No	Unsure	Do not want to answer
Not enough water supplied by municipal	101	4.00	2	
Water supply costs	78	18.00	6	1
Rainwater tastes good	38	38.00	20	1
Rainwater free from odours	41	44.00	15	1
Rainwater is clear	41	47.00	10	1

4.9. LEVEL OF SATISFACTION

Majority of the respondents (65%, n=71) reported that the quality of the harvested rainwater is acceptable for their use, 18.18% (n=20) felt the water is excellent, while 17.27% (n=19) felt the water is not of an acceptable quality. There are several factors that can influence the level of satisfaction derived from the use of harvested rainwater. One of which is the water quality, which is linked to the kind of material used as the catchment for harvesting the rainwater, as well as the air quality of the area. Respondents who do not discard the first flush are likely not to feel satisfied with the quality of water harvested during rain events. In a similar study by Sheik (2020), 46% of his respondents were suspicious of the quality of harvested rainwater and they indicated that they did not take the first flush into consideration.

4.10. CONCLUSION

This chapter explored the perception of selected people who use harvested rainwater in the Vhembe District Municipality of the Limpopo Province, South Africa. This is the first study of this kind to be conducted in the Vhembe District region. The practice of RWH is very high in the study area and therefore, shows that VDM has a huge potential of exploiting rainwater harvesting. The residents in the district have a positive perception, are knowledgeable of rainwater harvesting processes and have accept it as an alternative to potable water mainly for domestic purposes.

From the results obtained, a lot of people who reside in communities within the VDM harvest rainwater anytime it rains, and they use their own roofs as the catchment area. They use various kind of containers to store the water, unfortunately, some of the containers are left open which is a source of contamination. There are several potential uses of harvested rainwater reported which include - bathing, cooking, garden irrigation, toilet flushing, washing laundry, washing dishes, as well as washing of parking lots and cars. From this chapter, it can be concluded that RWH is a very useful and a cost-effective technique for the provision of water. It is, however, recommended that the water be treated using simple point-of-use treatments if such water will be consumed.

CHAPTER FIVE: WATER QUALITY RESULTS AND DISCUSSION

5.1. PHYSICOCHEMICAL PARAMETERS

A total of 358 harvested rainwater samples from five (5) different roof types were analysed for physicochemical parameters. Samples were collected in six rainfall events, including first flush. The summarised results of the physicochemical analysis collected in three (3) different regions (in land-use activities, vegetation cover and populations) in the Vhembe District Municipality are presented in Table 5.1.

The physicochemical parameters analysed in this study included, pH, turbidity, electrical conductivity, salinity, and total dissolved solids. The average values and the standard deviations of roof harvested rainwater for different physicochemical parameters analysed in this study are presented with the acceptable South African National Standards (SANS) of drinking water (Table 5.1). These physicochemical results are also given in detail according to the sampling dates on which the rainwater samples were harvested (Appendix 3). The results are presented according to the chosen sampling sites, hence, the mean concentrations and standard deviations are given for Univen, Tshikhudini and Sibasa area, separately.

From a physical observation, all the roof-harvested rainwater samples were odourless and colourless except for samples collected from thatched roofing materials which showed some colour and debris.

The results demonstrated that samples collected from Univen recorded an average pH range of 4.59 from thatched roof type to a range of 5.92 from aluminium roof type. In both Sibasa and Tshikhudini villages, the collected rainwater samples recorded a minimum pH of 4.56 for samples collected from thatched roof type. The maximum measured pH for samples collected from Sibasa and Tshikhudini were 5.67 (from slate roof type) and 5.46 (from concrete roof type), respectively. Rainwater is considered to be acidic when it has a pH of <5.6, and any level below may cause roofs to corrode.

Table 5.1: Physicochemical parameters of rooftop harvested rainwater samples collected in VDM given with Average ± STDEV

Sampling site	**N**	**Roof type**	**pH**	**Turbidity (NTU)**	**EC (µS/cm)**	**Salinity (mg/L)**	**TDS (ppm)**
Univen	18	Slate	5.63±0.53	1.87±2.24	33.87±11.71	30.35±8.14	23.40±6.96
		Aluminium	5.92±0.69	1.75±1.80	38.23±9.54	30.67±5.38	28.15±5.25
		Steel	5.37±0.60	3.37±3.58	46.42±11.46	37.63±5.21	27.97±6.19
		Concrete	5.63±0.61	2.50±2.17	40.05±16.41	29.40±7.83	27.25±14.40
		Thatched	4.59±0.4	7.80±2.8	54.10±4.00	43.50±10.0	31.30±5.7
		Control	6.00±0.55	0.25±0.34	16.95±6.33	22.97±10.20	17.45±10.23
		SANS	5-9.7	<1	≤1700	<1500	≤1200
Sibasa	18	Slate	5.67±0.76	1.91±1.58	34.47±8.73	24.58±5.86	28.83±8.53
		Aluminium	5.55±0.69	2.03±1.51	34.47±8.07	32.95±8.10	27.62±8.46
		Steel	5.39±0.70	1.59±1.55	40.83±7.47	26.17±6.17	29.98±12.61
		Concrete	5.06±0.52	1.34±1.71	34.32±9.67	32.25±7.36	26.58±9.36
		Thatched	4.56±0.45	5.12±1.48	40.93±15.27	32.22±8.87	53.52±25.53
		Control	5.87±0.39	0.18±0.19	16.05±5.55	14.30±6.17	14.10±4.99
		SANS	5-9.7	<1	≤1700	<1500	≤1200
Tshikhudini	18	Slate	5.27±0.56	2.10±2.71	40.15±15.65	51.91±53.68	28.18±4.46
		Aluminium	5.46±0.40	2.92±3.65	60.73±61.80	51.92±38.88	41.35±21.91
		Steel	5.13±0.62	1.49±0.91	38.51±6.29	33.74±6.85	31.68±11.02
		Concrete	5.48±0.79	2.48±2.67	55.12±42.34	44.06±26.35	45.32±26.92
		Thatched	4.56±0.14	5.27±1.41	36.19±19.255	37.56±16.30	50.71±26.01
		Control	5.87±0.41	0.25±0.28	15.48±4.52	15.82±3.82	17.97±5.54
		SANS	5-9.7	<1	≤1700	<1500	≤1200

The pH of rainwater in the samples all complied with the SANS and WHO standards, except for the samples collected from thatched roofs. The reason why thatched roofs recorded a lower pH below 5 may possibly be due to the chemical properties of the thatch materials on the roof. Afangideh and Udokpoh (2021) reported that pH of harvested rainwater is supposed to be acidic in nature, and that acidic rainfall is mostly influenced by atmospheric pollution. According to WHO standards for drinking water, pH in harvested rainwater should be in the range of 6.5-8.5; SANS has a pH standard range of 5-9.7. The acidity of roof-harvested rainwater can affect crops and plant growth if the water is used for irrigation purpose (Edokpayi et al., 2018). Results showed that the pH values of all the samples had a range of 4.56-6.00 which support a statement made by Struk-Sokołowska et al., (2020) that pH in rainwater can range from weak acidic (pH 3.1) to weak alkaline (pH 11.4). From observation of the results, all samples collected from the different research sites (Tshikhudini, Univen and Sibasa) did not show any difference in samples according to the site of the sample collection. This means that pH is not influenced by the atmospheric conditions and the land use of sampling site, but by the material (that is, roofing components) of the sampling catchment.

Turbidity measures the water cloudiness by observing the amount of particles, such as organic matters, silt and biological materials collected from roof-harvested rainwater's runoff (Chukwuma et al., 2014; Olaoye and Olaniyan, 2012). In the present study, the Univen collected rainwater samples recorded an average turbidity concentration range of 1.75 NTU from aluminium roof type to 7.80 NTU from thatched roof type. Sibasa area recorded an average turbidity range value of 1.34 NTU from samples collected from concrete roof type to 5.12 NTU from samples collected from thatched roof type. Tshikhudini area recorded average range of turbidity of 1.49 NTU from rainwater samples collected from steel roof type, to 5.27 NTU from rainwater samples collected from thatched roof type. From all the roof types analysed, thatched roof type recorded the highest average values of turbidity than other roof types, with Univen having the highest average value of turbidity. Univen is an old establishment and the thatched roof types at Univen were likely to have been completed decades ago, therefore, the age of the thatched roof may have played a role in the lack of water clarity. Thatched roofs wither, decay and shrivel with time, and it is easier for thatched particles to be subjected to organic decomposition and accumulate dust.

Higher values of turbidity in any water sample indicate the possibility of the presence of clay, silt and organic matters suspended in water (Edokpayi et al., 2018), hence, rainwater collected from a thatched roof type may contain high sediments runoff and the consumption of rainwater collected from that roof type can pose a health risk when used for household domestic purposes. The results obtained from a study by Friedler et al. (2017) on the quality of roof-harvested water showed a wide range of turbidity values in the range of 0.7-143 NTU. Any level of turbidity of <5 is considered acceptable for human consumption (Morales-Pinzon et al., 2015) and high turbidity could be the result of dust and particles on the roofs. From a study by Mao et al., (2020), there was no difference in the turbidity of all the samples and all the roof types (asphalt, concrete, ceramic tile and galvanized metal) from which rainwater samples was harvested.

Electrical conductivity (EC) measures the ability of water to allow electrical current to pass through (Gonzalez, 2012). Univen-collected rainwater samples recorded an average range of EC values of 33.87 µS/cm (slate roof type) to 54.10 µS/cm (thatched roof type). Sibasa recorded an average range of 34.32 µS/cm (concrete roof type) to 40.93 µS/cm (thatched roof type). Tshikhudini village recorded an average range of EC of 36.19 µS/cm (thatched roof type) to 60.73 µS/cm (aluminium roof type). EC standards that compile with those of SANS and WHO values are <1700 µS/cm and 600.01 µS/cm, respectively. This parameter permits the presence of certain ions such as carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium in water. From the results obtained, all roof-harvested rainwater samples, from all the three sample collection sites and the different roof catchments recorded the EC levels below the recommended limits. There is similarity between the average EC levels of Struk-Sokołowska et al., (2020) and this study.

Univen area, Sibasa and Tshikhudini villages recorded average maximum salinity values in roof harvested rainwater of 43.50 mg/L (thatched roof type), 32.95 mg/L (aluminium roof type) and 59.92 mg/L (aluminium roof type). From the present study, the average values of salinity varied slightly. From a study by Madilonga et al., (2021), they mentioned that salinity may cause eye irritation in humans and chlorosis in animals. All samples in the current study recorded mean concentrations of salinity that were within the permissible SANS standard of <1500 mg/L. This was also similar with the total dissolved solids (TDS) which all recorded mean concentrations below the standard concentration in the collected rainwater samples. The thatched roof catchment recorded the highest concentrations of TDS in all samples from the different sites with average concentrations of 31.30 ppm, 53.52 ppm and 50.71 ppm, for Univen, Sibasa and Tshikhudini sampling area, respectively (Table 5.1). The presence of TDS in harvested rainwater may be the results of pollution on the roofs that gets washed out with rainwater runoff.

Most of roof-harvested rainwater samples collected in October recorded the highest concentrations of physicochemical indicators. This could be because the month of October is the first month of rainy seasons, so it may be regarded as the month of the first flush rainfall. Physicochemical parameters in this study were analysed from the three sites with different land-use activities; a difference could only be observed in the mean concentrations from one roof type to the other. The land use activity, vegetation cover and the population of the three sites differs, indicating that different land uses in areas of the sample collection did not have an impact on the physicochemical quality of rooftop-harvested rainwater.

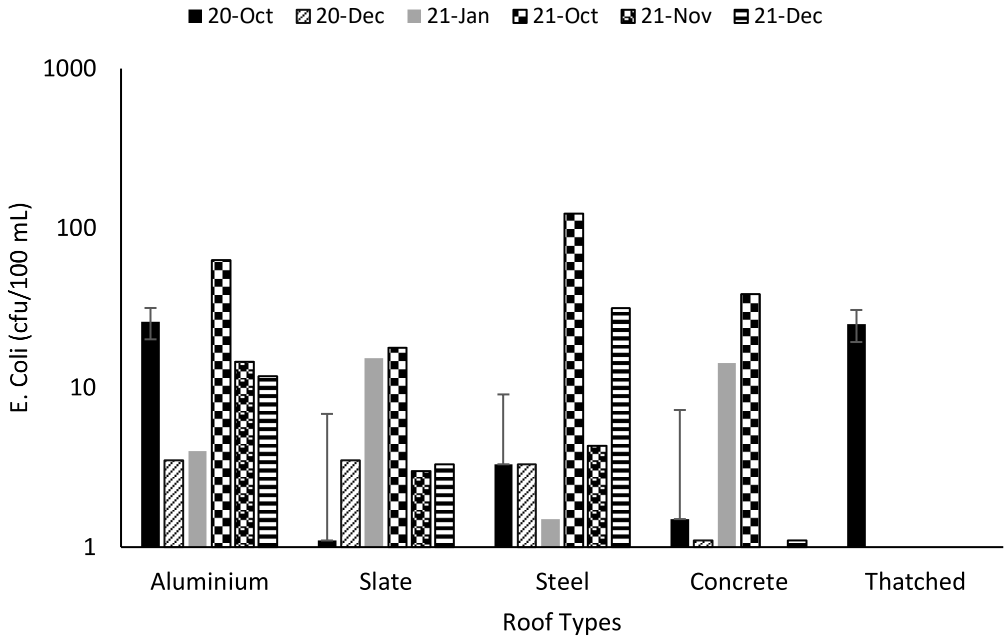
5.2. MICROBIOLOGICAL QUALITY

The microbiological pathogens analysed in this study were *E. coli* and total coliform; no microbes should be detected in drinking water as they present an acute health risk to humans.

The mean average *E. coli* concentrations for the Univen samples ranged from 7.33 cfu /100 mL from the slate roof type to 25 cfu /100 mL on the thatched roof type. In Sibasa samples, *E. coli* concentrations ranged 11.12 cfu /100 mL (steel roof type) to 31.6 cfu /100 mL (thatched roof type). For samples collected in Tshikhudini area, *E. coli* ranged from 4.31 cfu /100 mL (aluminium roof type) to 63.7 cfu /100 mL (thatched roof type). Rooftop rainwater samples collected from Tshikhudini research area, especially for thatched roof type recorded higher average *E. coli* values compared with the other two sampling areas. This could be the result of land use in Tshikhudini since it is a village which is characterized by residents who sweeps the floor causing dust to accumulate on top of roofs. Rural areas are characterized by domestic animals and unpaved roads that increase the accumulation of dusts.

Rainwater collected from the thatched roof type during all sampling events recorded the highest levels of *E. coli* and total coliform. Microbial levels in the rainwater collected from the various rooftops of Univen are presented in Figure 5.1. *E. coli* concentration in rainwater collected from a thatched roof in Univen is recorded for the month of October 2020 only because after the first set of sample collection, thatched roofing infrastructures were demolished in Univen area, hence, after that there were no samples collected for *E. coli* analysis, however, the month of October (first flush) recorded the highest levels of *E. coli* (Figure 5.2a). The levels of *E. coli* recorded were not so high and the water can be made suitable for drinking by using simple water treatment methods. The microbial levels showed that the water is suitable for irrigation and aquaculture. The trend from the average levels of *E. coli* for roof harvested rainwater was, slate < concrete < aluminium < steel < thatched, in Univen-collected samples.

E. coli represents the faecal pollution in water from humans and animal wastes (Mohammad, 2020). In a study by Bello and Nike (2015), all roof-harvested rainwater samples demonstrated poor microbiological quality which made the rainwater unsuitable for human consumption without treatment. The feacal matters in roof-harvested rainwater samples could be from animal droppings on the roofs and gutters (Korsten et al., 2016).



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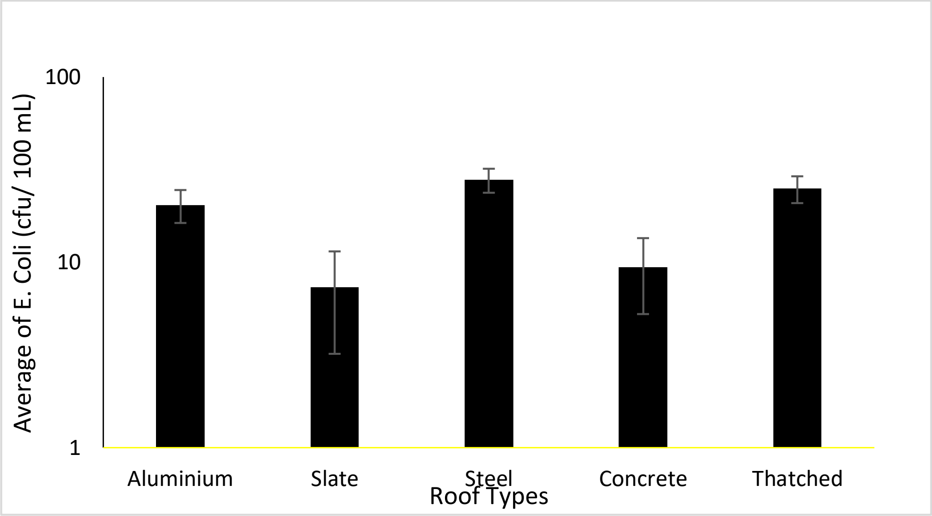
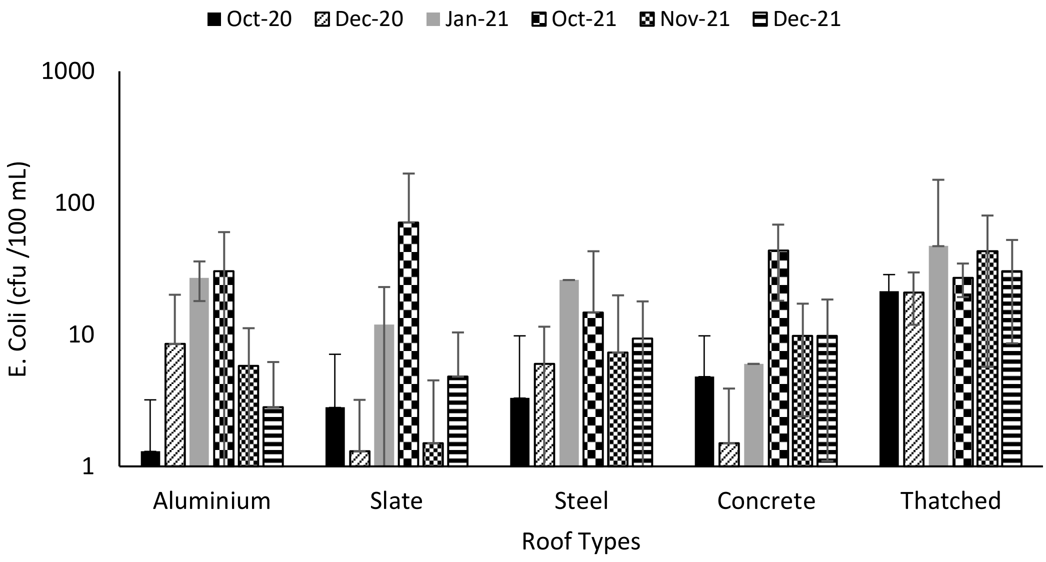


B.

Figure 5.1: A: *E. coli* levels in the different roof types in Univen study site, B: Average E. coli levels during the study for each of the roof types (n =18)



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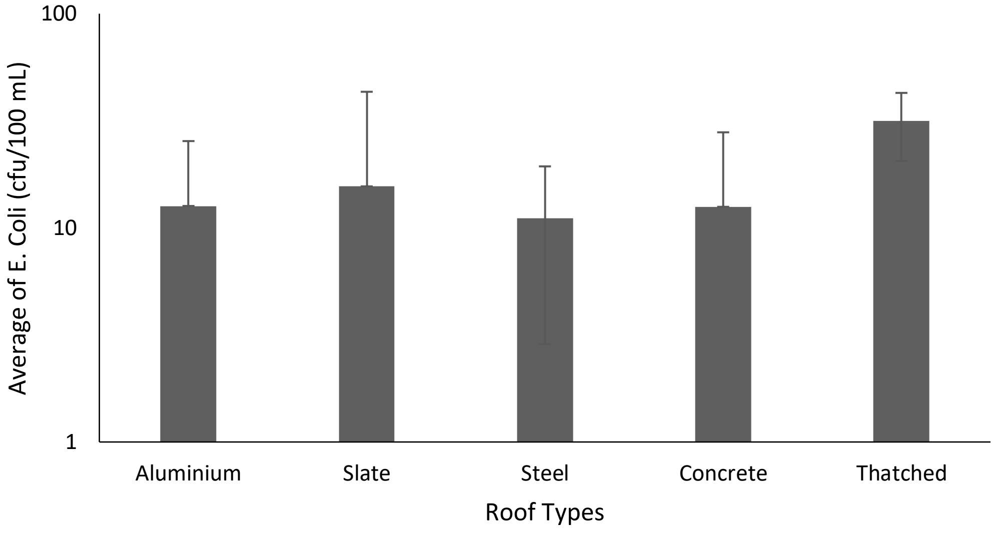

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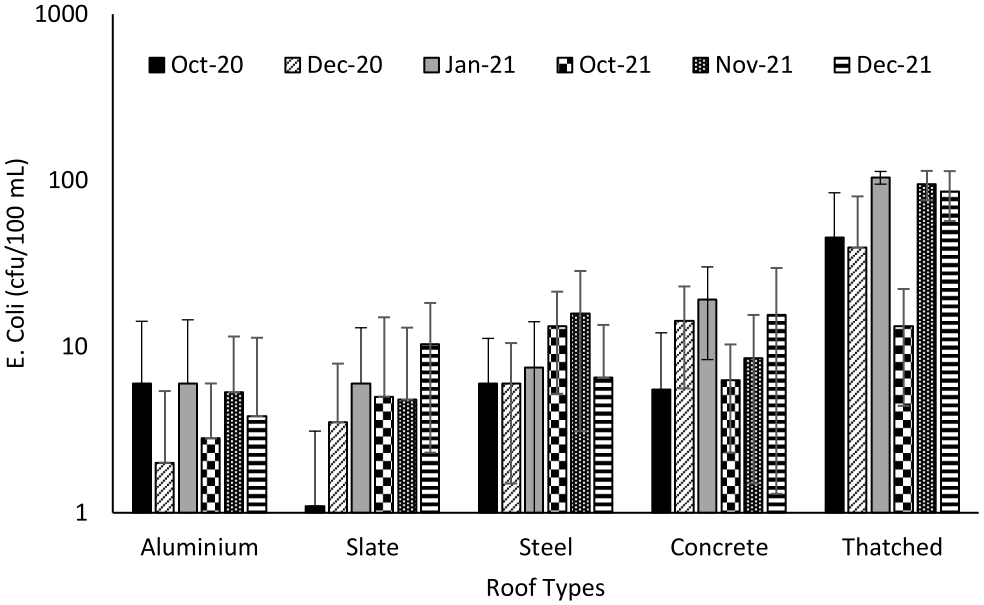
Figure 5.2: A: *E. coli* levels in the different roof types in Sibasa study site (n=3), B: Average *E. coli* levels during the study for each of the roof types (n =18)



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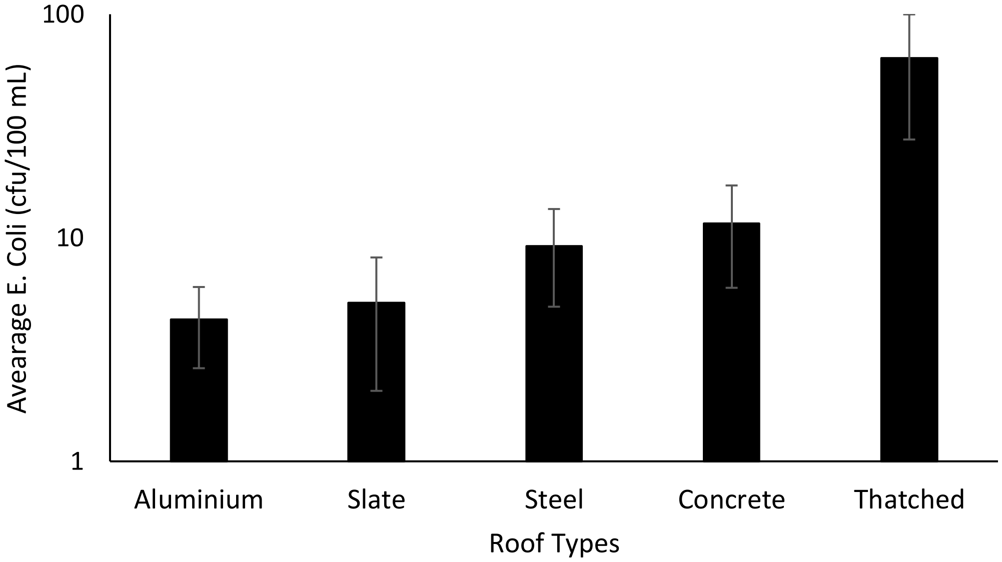


B.

Figure 5.3: A: *E. coli* levels in the different roof types in Tshikhudini study site (n=3), B: Average *E. coli* levels during the study for each of the roof types (n =18)

In both Tshikhudini and Sibasa, in the collected roof rainwater, higher concentrations of *E. coli* were recorded in rainwater collected from a thatched roof catchment (Figures 5.2-5.3). As in the Univen collected samples, rainwater samples collected in the first flush (October 2021) recorded the highest concentrations of *E. coli.* A similar study about the quantity of microorganisms in harvested rainwater in Queensland, recorded *E. coli* concentration in the range of <1- 3060 CFU/ 100 mL (Chubaka et al., 2018).

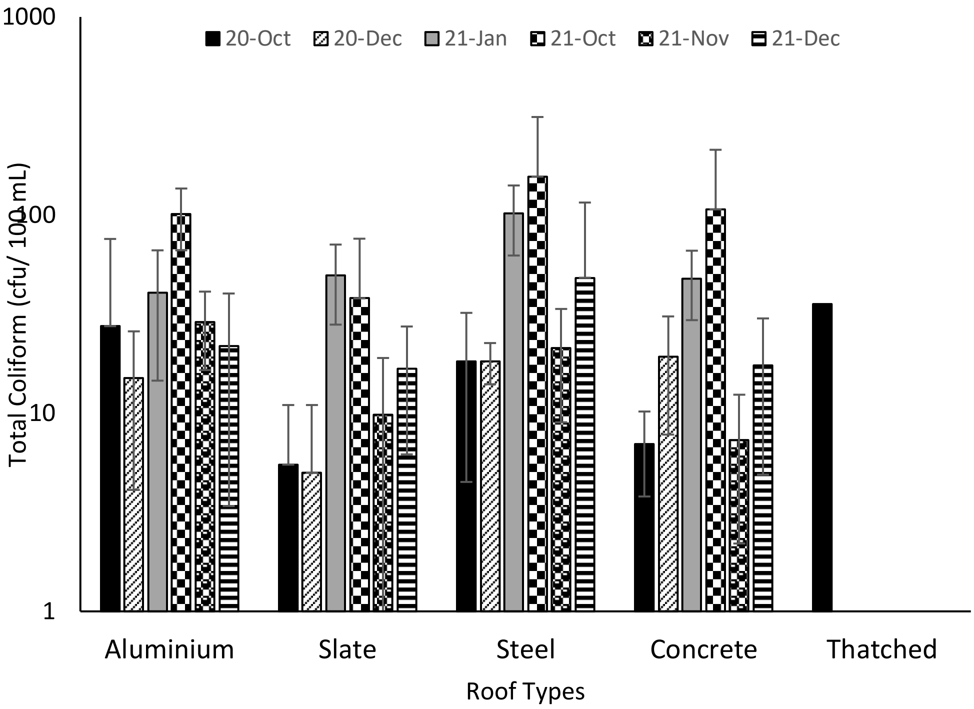
In general, this study recorded higher total coliform concentrations in rooftop-harvested rainwater samples than *E. coli.* The average total coliform concentrations for rooftop-harvested rainwater from Univen ranged from 20.77 cfu//100 mL collected from slate roof type to 60.72 cfu/100 mL for samples collected from steel roofs. Sibasa samples recorded an average range of total coliform of 26.87 cfu/100 mL (steel roof type) to 122.93 cfu/100 mL (thatched roof type). Tshikhudini samples recorded an average range of 19.83 cfu/100 from an aluminium roof type to cfu /100 mL (aluminium roof type) to 129.08 cfu/100 mL (thatched roof type).

Many types of coliform bacteria are harmless, but some may cause health problems such as nausea, vomiting, cramps, and diarrhoea (Gonzales, 2012). The other coliforms analysed in this study was total coliform. A study by Sazakli et al., (2007) reported that total coliform was detected in 80.3% of their roof-harvested rainwater samples. From Figures 5.4.A and 5.5.A, it can be observed that October 2021 (first flush) recorded the highest levels of total coliforms. First flush is often associated with high pollutant loads being washed out on the roof catchment (Korsten et al., 2016).

In this study, excessive microbiological pollutants were recorded in roof rainwater samples harvested from thatched roofing, except for Univen samples. Figure 5.4 A and B below show that the highest total coliform recorded for Univen samples were obtained from steel roof types.

The average total coliforms recorded in this study exceeded the SANS and WHO standards for drinking water. Mendez et al., (2010) also recorded total coliforms concentrations of up to 648 CFU/ 100 mL in their sampled rooftop harvested rainwater.

Appendix 4 shows the relationships among the roofing materials, from the three research areas. The levels of *E. coli* collected from the three different roof types did not vary significantly (P>0.05) in Univen.



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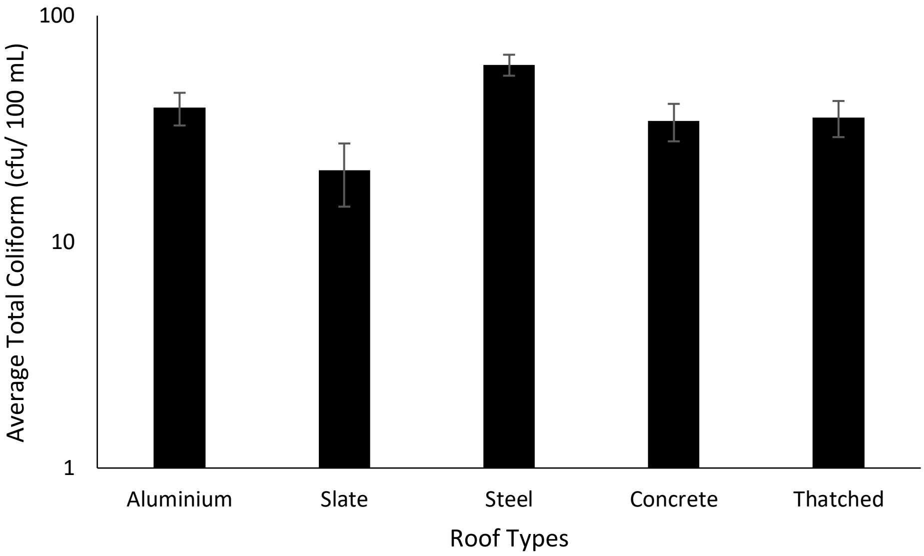


B.

Figure 5.4: A: Total coliform levels in the different roof types in the Univen (site n=3), B: Average total coliform levels for each of the roof types (n=18)

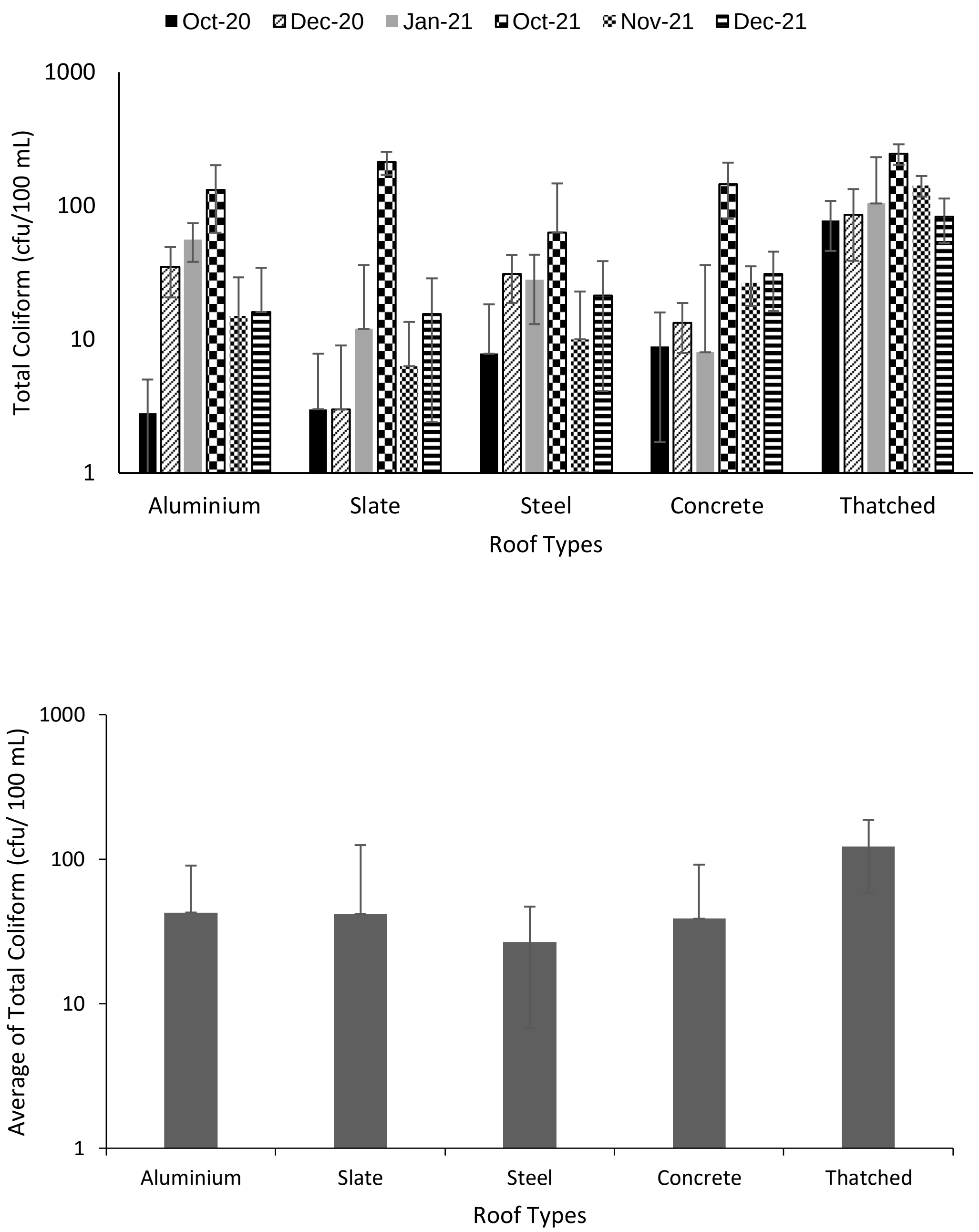
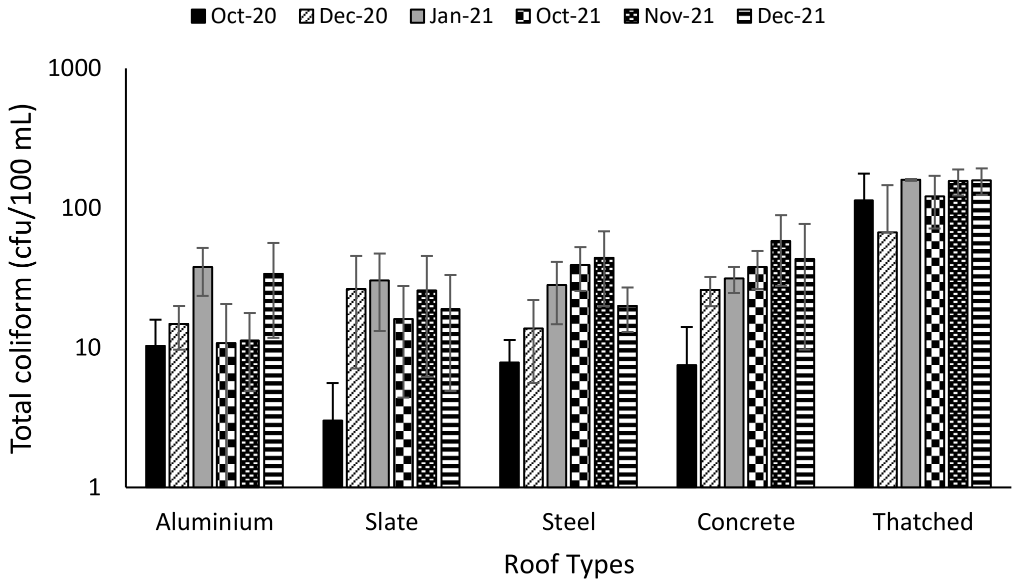


Figure 5.5: A: Total coliform levels in the different roof types in Sibasa (site n=3), B: Average total coliform levels during the study for each of the roof types (n=18)



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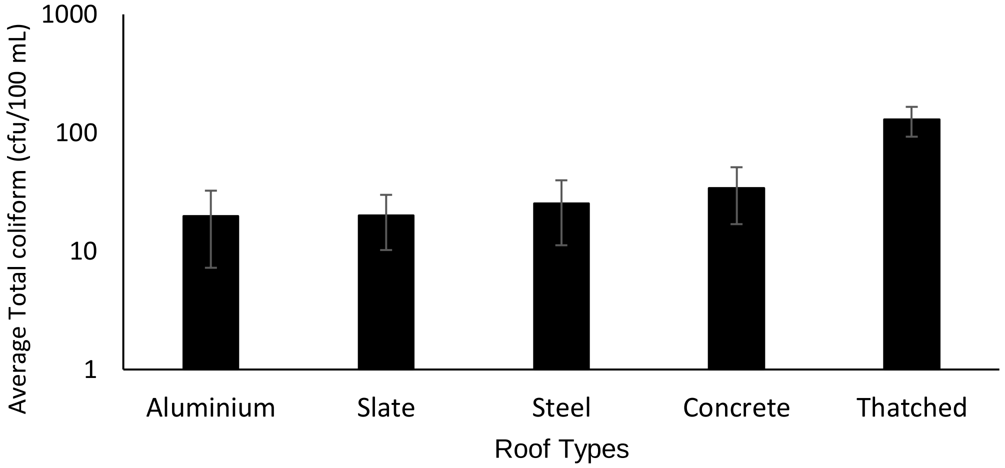

B.

Figure 5.6: A: Total coliform levels in the different roof types in Tshikhudini (site n=3), B: Average total coliform levels during the study for each of the roof types (n=18)

From roof type harvested rainwater samples collected from the Sibasa sampling area, the levels of *E. coli* in the various rooftops only vary significantly ($P< 0.05$) between the thatched roof type and the others. The correlation relationship of *E. coli* and total coliform between roofing materials from the three sampling areas are presented in Appendix 5. Hence from the results recorded the thatched roof type cannot be recommended for harvesting water for domestic purposes but water harvested from it can be used for other purposes such as irrigation and ground washing.

5.3. HEAVY METALS

The heavy metals analysed in this study to determine the quality of roof-harvested rainwater from the three areas (Univen, Tshikhudini and Sibasa), included Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Cd, Sn, Sb, and Pb. The detailed results are given in Appendices 6 to 10. The mean concentrations of most of the heavy metals analysed were within the permissible limits of SANS and the WHO. This is similar to a study by Struk-Sokołowska et al., (2020) in various parts of Europe, where all the concentration of all heavy metals (Ca, Cd, Cr, Cu, Fe, pb, Mg, Mn, Ni, K and Zn) analysed in roof-harvested rainwater (tile and ceramic roofs) did not exceed that of the permissible standards.

The aesthetic metals analysed in this study included Al, Fe and Mn. Aluminium ranged from 9.04 µg/l -51.91 µg/l for rooftop rainwater samples collected from Univen sampling area. For Sibasa and Tshikhudini aluminium values also ranged between 15.16 µg/l-136.35 µg/l and 11.29 µg/l- 39.24 µg/l, respectively. The drinking water quality standards for Aluminium according to the SANS is ≤300 µg/l. High levels of aluminium in drinking water can cause Alzheimer’s disease and renal failure among others (Edokpayi et al., 2018). All the samples recorded compiled with the acceptable standards. Steel rooftop sample recorded the highest mean concentrations of aluminium in roof harvested rainwater with the mean concentrations of 138.35 µg/l in Sibasa and 98.28 µg/l in Univen samples. From recorded average values ranged from 11.51 to 33.96 µg/l for rooftop rainwater samples collected from Univen, a range of 6.30 to 50.01 µg/l for Sibasa roof harvested rainwater samples, while a range of 7.31 to 36.87 µg/l for rooftop rainwater samples collected from Tshikhudini. Fe has regulatory standards of ≤2000 µg/l for chronic health and ≤300 µg/l for aesthetic purposes (SANS, 2015). In this study, Fe levels ranged between 6.95 and 50.01 µg/l. The steel roof type recorded the highest levels of Fe in this study.

Madilonga et al., (2021) also mentioned that higher concentrations of Fe and Mn give a certain taste to water and influence the aesthetic properties of water. Mn was also recorded to be higher in steel roof type for samples collected from Univen and Sibasa areas with mean concentrations of 26.54 and 15.12 µg/l, respectively. Tshikhudini, however, recorded higher levels of Fe and Mn in the thatched roof type. The concrete roof type consistently recorded the lowest levels of Fe and Mn in all the study areas.

The most hazardous heavy metals analysed in this study included, As, Pb and Cd. The concentration of As in rooftop rainwater samples collected from Univen, Sibasa and Tshikhudini research areas were in the range of 0.04 µg/l- 0.13 µg/l, 0.06 µg/l – 0.12 µg/l, and 0.05 µg/l- 7.01 µg/l, respectively. As can damage the central nervous system and impair human cardiologic system (Chubaka et al., 2018). It can also cause corrosion and an adverse pregnancy outcome. Cadmium is toxic for the kidneys and also affects the human reproductive and endocrine systems (Chubaka et al., 2018). The mean concentrations of Cd recorded in this study ranged from 0.02 µg/l to 0.13 µg/l from samples collected from all the sampling areas. Rainwater samples collected from steel roof catchment recorded higher concentrations of Cd than any other roof type in samples collected from Univen area. Lead can trigger personal and mental disorder in children and anaemia in adults (Chubaka et al., 2018). If consumed, it also has other wide range of effects including, various neurodevelopmental effects, mortality, impaired renal function, hypertension, and impaired fertility (Mohammad, 2020). From the rainwater samples collected in this study, Pb was recorded to be below detention limit in most samples. Lead contamination in water is mostly influenced by industrial applications, such as in water distribution pipes, in paints, in batteries, among others. In this study, Pb was recorded at the lowest levels compared to the other metals and compared with regulatory standards.

Trace metals known as ‘micronutrients’ include Zn, Cu and Al. Zn is a metallic element which is highly soluble in water at acidic pH. In this study, Zn recorded the highest levels compared to the other metals analysed with a minimum mean concentration of 4.96 µg/l and maximum mean concentration of 601.82 µg/l for samples collected from Univen sampling area, a minimum mean concentration of 39.65 µg/l and a maximum mean concentration of 1263.19 µg/l for samples collected from Sibasa sampling area, and a minimum mean concentration of 15.38 µg/l and a maximum concentration of 1801. 66 µg/l for samples collected from Tshikhudini sampling area. Lower levels of Zn were recorded from concrete roof types from Univen and Tshikhudini samples. High levels of Zn in thatched roof collected rainwater samples may be because of the chemical components in thatched materials.

Cu in high concentration can be dangerous since when exposed into the environment can become bioaccumulates in certain plants. The levels of Cu in Univen and Tshikhudini ranged from bdl to 4.05 µg/l (steel roof type) and 12.40 µg/l (concrete roof type). In Sibasa, Cu levels ranged from 1.25 µg/l (thatched roof type) to 6.63 µg/l (aluminium roof type).

Heavy metals such as V, Mo, As, Ni, Co, Cr, Sn and Sb were also analysed and the results were that their mean concentrations in roof-harvested rainwater were all within the permissible standards. This is in line with Chubaka et al., (2018) assertion that contamination of heavy metals in harvested rainwater is expected to be high in more industrialised areas.

Struk-Sokołowska et al., (2020) reported that three metals (Zn, Pb and Ni) were recorded in high levels in roof-harvested rainwater samples from north-west Poland, Europe. All the rainwater samples analysed for Ni in this study recorded mean concentrations below that of the standard concentration of 70 µg/l (Table 5.2). In comparison with the other roof rainwater catchment considered in this study, aluminium roof catchment had the highest recorded values of nickel from all the three sites but complied with the regulatory standards.

5.4 METEOROLOGICAL DATA

Climate variability, unpredictable weather conditions and droughts are major concerns for the adoption of RWH systems (Amos et al., 2016). The meteorological data was obtained from the South African Weather Services. The average precipitation data for the period of 1996 to 2020 was used which was the most recent information available (Figure 5.7; Appendix 11).

From the data presented, it can be observed that rainfall usually occurs from October and extends to April, the following year. The highest recorded precipitation was obtained in January. It can be concluded that each year has a uniform rainfall pattern as the subsequent years.

Table 5.2: Mean trace metals levels in various roof types in samples from the study area

A: Univen Samples

Metals						**WHO, 2011 (µg/l)**	**SANS, 2015 (µg/l)**
	Aluminium	**Slate**	**Steel**	**Concrete**	**Thatched**		
Al	9.04 (5.11)	10.97 (5.49)	98.28(61.13)	16.18(12.99)	51.91(42.33)		≤300
V	0.32 (0.17)	0.15 (0.10)	0.50 (0.33)	0.42 (0.14)	0.28 (0.20)		200
Cr	0.70 (0.53)	0.73 (0.27)	0.78 (0.10)	0.55 (0.14)	0.77 (0.14)	50	≤50
Mn	11.14 (9.87)	3.17 (1.47)	26.54(24.74)	7.49 (6.09)	11.08(15.69)	500	≤100
Fe	13.37 (13.37)	12.55 (10.59)	33.96(25.15)	11.51 (8.90)	14.00 (9.30)		≤300
Co	0.19 (0.09)	0.08 (0.04)	0.90 (0.82)	0.12 (0.08)	0.27 (0.36)	10	500
Ni	0.94 (0.85)	0.41 (0.12)	0.97 (0.58)	0.33 (0.19)	0.44 (0.20)	70	≤70
Cu	1.69 (0.84)	Bdl	4.05 (2.49)	Bdl	2.49 (1.24)	2000	≤2000
Zn	601.82(135.50)	75.26(103.99)	67.28(21.03)	4.96 (1.12)	154.56(115.49)	3000	≤5000
As	0.10 (0.06)	0.04 (0.02)	0.13 (0.07)	0.06 (0.04)	0.07 (0.09)		≤10
Mo	0.05 (0.02)	0.02 (0.01)	0.03 (0.01)	0.02 (0.00)	0.03 (0.02)		10
Cd	0.02 (0.01)	0.06 (0.03)	0.07 (0.07)	0.02 (0.01)	0.05 (0.03)	3	≤3
Sn	0.10 (0.07)	0.06 (0.02)	0.05 (0.03)	0.07 (0.04)	0.04 (0.02)		
Sb	1.10 (0.09)	1.02 (0.13)	0.86 (0.21)	0.95 (0.11)	0.76 (0.06)		≤20
Pb	1.03 (0.99)	Bdl	0.69 (0.35)	Bdl	0.10 (0.05)	10	≤10

*Values in parenthesis are the associated standard deviations

Bdl = below detection limit

B: Sibasa Samples

Metals						WHO, 2011 (µg/l)	SANS, 2015 (µg/l)
	Aluminium	**Slate**	**Steel**	**Concrete**	**Thatched**		
Al	28.13 (14.06)	15.16(9.25)	136.35(68.18)	17.12(11.37)	17.07(4.26)		≤300
V	0.22 (0.19)	0.24 (0.18)	0.17 (0.10)	0.94 (0.97)	0.31 (0.10)		200
Cr	3.89 (3.02)	0.77 (0.15)	0.91 (0.21)	0.63 (0.16)	0.87 (0.06)	50	≤50
Mn	2.61 (1.34)	6.02 (4.45)	15.12 (21.65)	1.82 (0.29)	7.34 (2.55)	500	≤100
Fe	6.95 (4.58)	10.14(9.97)	50.01 (94.46)	6.30 (3.39)	15.19(4.80)		≤300
Co	0.11 (0.05)	0.20 (0.10)	0.41 (0.63)	0.09 (0.05)	0.22 (0.09)	10	500
Ni	0.70 (0.37)	0.54 (0.32)	0.55 (0.39)	0.56 (0.22)	0.63 (0.08)	70	≤70
Cu	6.63 (3.32)	2.31 (1.16)	5.49 (2.74)	4.07 (2.61)	1.25 (0.73)	2000	≤2000
Zn	1263.19(935.44)	1176.47(996.62)	435.06(262.11)	621.68(1103.97)	39.65(2.14)	3000	≤5000
As	0.12 (0.08)	0.06 (0.02)	0.07 (0.04)	0.08 (0.04)	0.06 (0.04)		≤10
Mo	0.06 (0.04)	0.12 (0.07)	0.03 (0.01)	0.03 (0.02)	0.04 (0.03)		10
Cd	0.04 (0.03)	0.13 (0.11)	0.07 (0.07)	0.02 (0.01)	0.09 (0.06)	3	≤3
Sn	0.16 (0.12)	0.08 (0.04)	0.05 (0.03)	0.04 (0.02)	0.06 (0.02)		
Sb	2.19 (0.84)	1.13 (0.20)	0.85 (0.11)	1.02 (0.10)	0.73 (0.05)		≤20
Pb	0.08 (0.04)	0.28 (0.16)	0.69 (0.34)	0.10 (0.04)	0.05 (0.03)	10	≤10

*Values in parenthesis are the associated standard deviations

C: Tshikhudini Samples

Metals						WHO, 2011 (µg/l)	SANS, 2015 (µg/l)
	Aluminium	**Slate**	**Steel**	**Concrete**	**Thatched**		
Al	11.29 (6.63)	39.24 (35.58)	11.72(5.86)	14.24(10.32)	34.37(32.88)		≤300
V	0.41 (0.29)	0.31 (0.41)	0.25 (0.17)	0.21 (0.20)	0.63 (0.35)		200
Cr	0.54 (0.14)	0.81 (0.20)	0.87 (0.10)	0.60 (0.08)	1.45 (0.78)	50	≤50
Mn	3.72 (4.35)	5.47 (2.46)	3.34 (3.23)	2.13 (1.46)	14.78(17.68)	500	≤100
Fe	10.82 (6.00)	7.31 (2.93)	12.20 (9.72)	7.33 (4.51)	36.87(26.07)		≤300
Co	0.11 (0.12)	0.13 (0.05)	0.10 (0.07)	0.05 (0.02)	0.38 (0.36)	10	500
Ni	0.59 (0.17)	0.58 (0.31)	0.57 (0.13)	0.57 (0.27)	1.00(0.47)	70	≤70
Cu	4.80 (3.89)	Bdl	Bdl	12.40 (6.20)	6.07 (3.74)	2000	≤2000
Zn	141.99(140.26)	1801.66(2096.57)	284.39(150.86)	15.38 (9.34)	26.12(14.92)	3000	≤5000
As	0.13 (0.06)	0.05 (0.02)	0.08 (0.05)	0.06 (0.03)	7.01 (9.66)		≤10
Mo	0.12 (0.07)	0.05 (0.02)	0.03 (0.02)	0.02 (0.01)	0.05 (0.04)		10
Cd	0.02 (0.02)	0.10 (0.12)	0.04 (0.01)	0.06 (0.05)	0.09 (0.07)	3	≤3
Sn	0.09 (0.05)	0.06 (0.03)	0.07 (0.04)	0.06 (0.03)	0.08 (0.04)		
Sb	1.35 (0.43)	0.97 (0.13)	0.77 (0.12)	1.02 (0.11)	0.86 (0.03)		≤20
Pb	0.11 (0.05)	0.08 (0.05)	Bdl	Bdl	0.12 (0.06)	10	≤10

*Values in parenthesis are the associated standard deviations

Bdl = below detection limit

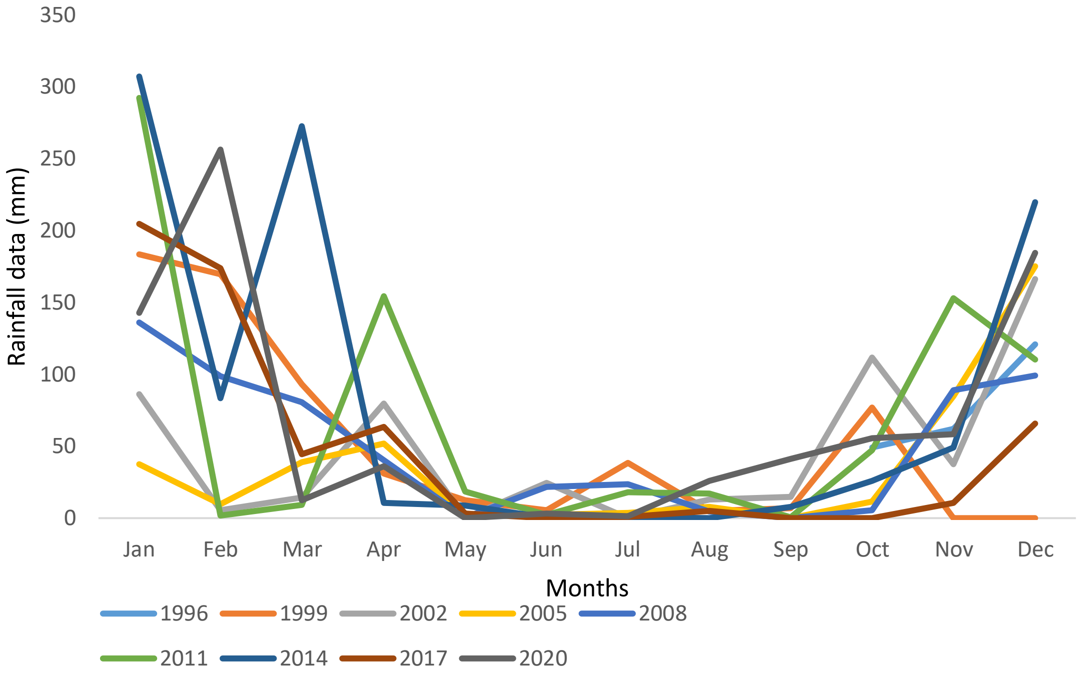

Figure 5.7: VDM monthly average rainfall data (1996-2020)

5.5 ESTIMATION OF WATER QUALITY INDEX

Water quality index gives a single value from combining the measures of several water quality parameters as a representative of quality impairments or suitability of use (Chukwuma et al., 2014). Not all the water quality parameters analysed in this study were included in the computation of the water quality index, however, Yogendra and Puttaiah (2008) mentioned that index does not necessarily have to include all the parameters but just some important parameters to provide a simple indicator. The weights of each parameter were adapted from a study by Madilonga et al. (2021).

The South African National Standards were used for the calculation of WQI and the parameters used to compute the WQI in this study were pH, EC, Salinity, TDS, Fe, Cd, Pb, Al, Cr and Zn. Table 5.3 below shows how the WQI was determined for each roof type.

Table 5.3: WQI computed from physicochemical parameters and metals for all the roof types selected and for all the areas: A. Univen, B. Sibasa and C. Tshikhudini.

A.

Site	Parameter	Average value (Ci)	Desirable value (Si)	Weight of each parameter (wi)	Relative weight (Wi)	Quality rating (qi)	WQI
Aluminium	pH	5.92	6.9-9.5	4	0.07	72.20	5.16
	EC	38.23	1700 µs/cm	4	0.07	2.25	0.16
	Salinity	30.67	1500 mg/l	3	0.05	2.04	0.11
	TDS	28.15	1200 ppm	4	0.07	2.35	0.17
	Fe	13.37	300 µg/l	3	0.05	4.46	0.24
	Cd	0.02	4 µg/l	5	0.09	0.50	0.04
	Pb	1.03	10 µg/l	5	0.09	10.30	0.92
	Al	9.04	300 µg/l	3	0.05	3.01	0.16
	Cr	0.7	50 µg/l	5	0.09	1.40	0.13
	Zn	1.82	5000 µg/l	4	0.07	0.04	0.00
	Mn	11.14	100 µg/l	3	0.05	11.14	0.60
	Ni	0.94	70 µg/l	3	0.05	1.34	0.07
	As	0.1	10 µg/l	5	0.09	1.00	0.09
	Turbidity	1.75	1 NTU	5	0.09	175.00	15.63
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 23.5$
Slate	pH	5.63	6.9-9.5	4	0.07	68.66	4.90
	EC	33.87	1700 µs/cm	4	0.07	1.99	0.14
	Salinity	30.35	1500 mg/l	3	0.05	2.02	0.11
	TDS	23.4	1200 ppm	4	0.07	1.95	0.14
	Fe	12.55	300 µg/l	3	0.05	4.18	0.22
	Cd	0.06	4 µg/l	5	0.09	1.50	0.13
	Pb	0	10 µg/l	5	0.09	0.00	0.00
	Al	10.97	300 µg/l	3	0.05	3.66	0.20
	Cr	0.73	50 µg/l	5	0.09	1.46	0.13
	Zn	75.26	5000 µg/l	4	0.07	1.51	0.11
	Mn	3.71	100 µg/l	3	0.05	3.71	0.20
	Ni	0.41	70 µg/l	3	0.05	0.59	0.03
	As	0.04	10 µg/l	5	0.09	0.40	0.04
	Turbidity	1.87	1 NTU	5	0.09	187.00	16.70
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 23$
Steel	pH	5.37	6.9-9.5	4	0.07	65.49	4.68
	EC	46.42	1700 µs/cm	4	0.07	2.73	0.20
	Salinity	37.63	1500 mg/l	3	0.05	2.51	0.13
	TDS	27.97	1200 ppm	4	0.07	2.33	0.17
	Fe	33.96	300 µg/l	3	0.05	11.32	0.61
	Cd	0.07	4 µg/l	5	0.09	1.75	0.16
	Pb	0.69	10 µg/l	5	0.09	6.90	0.62
	Al	98.28	300 µg/l	3	0.05	32.76	1.76
	Cr	0.78	50 µg/l	5	0.09	1.56	0.14
	Zn	67.28	5000 µg/l	4	0.07	1.35	0.10

	Mn	26.54	100 µg/l	3	0.05	26.54	1.42
	Ni	0.97	70 µg/l	3	0.05	1.39	0.07
	As	0.13	10 µg/l	5	0.09	1.30	0.12
	Turbidity	3.37	1 NTU	5	0.09	337.00	30.09
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 40.2$
Concrete	pH	5.63	6.9-9.5	4	0.07	68.66	4.90
	EC	40.05	1700 µs/cm	4	0.07	2.36	0.17
	Salinity	2.5	1500 mg/l	3	0.05	0.17	0.01
	TDS	27.25	1200 ppm	4	0.07	2.27	0.16
	Fe	11.51	300 µg/l	3	0.05	3.84	0.21
	Cd	0.02	4 µg/l	5	0.09	0.50	0.04
	Pb	0	10 µg/l	5	0.09	0.00	0.00
	Al	16.18	300 µg/l	3	0.05	5.39	0.29
	Cr	0.55	50 µg/l	5	0.09	1.10	0.10
	Zn	4.96	5000 µg/l	4	0.07	0.10	0.01
	Mn	7.49	100 µg/l	3	0.05	7.49	0.40
	Ni	0.33	70 µg/l	3	0.05	0.47	0.03
	As	0.06	10 µg/l	5	0.09	0.60	0.05
	Turbidity	2.5	1 NTU	5	0.09	250.00	22.32
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 28.7$
Thatched	pH	4.59	6.9-9.5	4	0.07	55.98	4.00
	EC	54.1	1700 µs/cm	4	0.07	3.18	0.23
	Salinity	43.5	1500 mg/l	3	0.05	2.90	0.16
	TDS	31.3	1200 ppm	4	0.07	2.61	0.19
	Fe	14	300 µg/l	3	0.05	4.67	0.25
	Cd	0.05	4 µg/l	5	0.09	1.25	0.11
	Pb	0.1	10 µg/l	5	0.09	1.00	0.09
	Al	51.91	300 µg/l	3	0.05	17.30	0.93
	Cr	0.77	50 µg/l	5	0.09	1.54	0.14
	Zn	154.56	5000 µg/l	4	0.07	3.09	0.22
	Mn	11.08	100 µg/l	3	0.05	11.08	0.59
	Ni	0.44	70 µg/l	3	0.05	0.63	0.03
	As	0.07	10 µg/l	5	0.09	0.70	0.06
	Turbidity	7.8	1 NTU	5	0.09	780.00	69.64
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 76.6$

B.

Site	Parameter	Average value (Ci)	Desirable value (Si)	Weight of each parameter (wi)	Relative weight (Wi)	Quality rating (qi)	WQI
Aluminium	pH	5.55	6.9-9.5	4	0.07	67.68	4.83
	EC	34.47	1700 µs/cm	4	0.07	2.03	0.14
	Salinity	32.95	1500 mg/l	3	0.05	2.20	0.12
	TDS	27.62	1200 ppm	4	0.07	2.30	0.16
	Fe	6.95	300 µg/l	3	0.05	2.32	0.12
	Cd	0.04	4 µg/l	5	0.09	1.00	0.09
	Pb	0.08	10 µg/l	5	0.09	0.80	0.07
	Al	28.13	300 µg/l	3	0.05	9.38	0.50
	Cr	3.89	50 µg/l	5	0.09	7.78	0.69
	Zn	1263.19	5000 µg/l	4	0.07	25.26	1.80
	Mn	2.61	100 µg/l	3	0.05	2.61	0.14
	Ni	0.7	70 µg/l	3	0.05	1.00	0.05
	As	0.12	10 µg/l	5	0.09	1.20	0.11
	Turbidity	2.03	1 NTU	5	0.09	203.00	18.13
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 26.97$
Slate	pH	5.67	6.9-9.5	4	0.07	69.15	4.94
	EC	34.47	1700 µs/cm	4	0.07	2.03	0.14
	Salinity	24.58	1500 mg/l	3	0.05	1.64	0.09
	TDS	28.83	1200 ppm	4	0.07	2.40	0.17
	Fe	10.14	300 µg/l	3	0.05	3.38	0.18
	Cd	0.13	4 µg/l	5	0.09	3.25	0.29
	Pb	0.28	10 µg/l	5	0.09	2.80	0.25
	Al	15.16	300 µg/l	3	0.05	5.05	0.27
	Cr	0.77	50 µg/l	5	0.09	1.54	0.14
	Zn	1176.47	5000 µg/l	4	0.07	23.53	1.68
	Mn	6.02	100 µg/l	3	0.05	6.02	0.32
	Ni	0.54	70 µg/l	3	0.05	0.77	0.04
	As	0.06	10 µg/l	5	0.09	0.60	0.05
	Turbidity	1.91	1 NTU	5	0.09	191.00	17.05
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 25.6$
Steel	pH	5.39	6.9-9.5	4	0.07	65.73	4.70
	EC	40.83	1700 µs/cm	4	0.07	2.40	0.17
	Salinity	26.17	1500 mg/l	3	0.05	1.74	0.09
	TDS	29.98	1200 ppm	4	0.07	2.50	0.18
	Fe	50.01	300 µg/l	3	0.05	16.67	0.89
	Cd	0.07	4 µg/l	5	0.09	1.75	0.16
	Pb	0.69	10 µg/l	5	0.09	6.90	0.62
	Al	136.35	300 µg/l	3	0.05	45.45	2.43
	Cr	0.91	50 µg/l	5	0.09	1.82	0.16
	Zn	435.06	5000 µg/l	4	0.07	8.70	0.62
	Mn	15.12	100 µg/l	3	0.05	15.12	0.81
	Ni	0.55	70 µg/l	3	0.05	0.79	0.04
	As	0.07	10 µg/l	5	0.09	0.70	0.06
	Turbidity	1.59	1 NTU	5	0.09	159.00	14.20

				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 25.1$
Concrete	pH	5.06	6.9-9.5	4	0.07	61.71	4.41
	EC	34.32	1700 µs/cm	4	0.07	2.02	0.14
	Salinity	32.25	1500 mg/l	3	0.05	2.15	0.12
	TDS	26.58	1200 ppm	4	0.07	2.22	0.16
	Fe	6.3	300 µg/l	3	0.05	2.10	0.11
	Cd	0.02	4 µg/l	5	0.09	0.50	0.04
	Pb	0.1	10 µg/l	5	0.09	1.00	0.09
	Al	17.12	300 µg/l	3	0.05	5.71	0.31
	Cr	0.63	50 µg/l	5	0.09	1.26	0.11
	Zn	621.68	5000 µg/l	4	0.07	12.43	0.89
	Mn	1.82	100 µg/l	3	0.05	1.82	0.10
	Ni	0.56	70 µg/l	3	0.05	0.80	0.04
	As	0.08	10 µg/l	5	0.09	0.80	0.07
	Turbidity	1.74	1 NTU	5	0.09	174.00	15.54
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 22.1$
Thatched	pH	4.56	6.9-9.5	4	0.07	55.61	3.97
	EC	40.93	1700 µs/cm	4	0.07	2.41	0.17
	Salinity	32.22	1500 mg/l	3	0.05	2.15	0.12
	TDS	53.52	1200 ppm	4	0.07	4.46	0.32
	Fe	15.19	300 µg/l	3	0.05	5.06	0.27
	Cd	0.09	4 µg/l	5	0.09	2.25	0.20
	Pb	0.05	10 µg/l	5	0.09	0.50	0.04
	Al	17.07	300 µg/l	3	0.05	5.69	0.30
	Cr	0.87	50 µg/l	5	0.09	1.74	0.16
	Zn	39.65	5000 µg/l	4	0.07	0.79	0.06
	Mn	7.34	100 µg/l	3	0.05	7.34	0.39
	Ni	0.63	70 µg/l	3	0.05	0.90	0.05
	As	0.06	10 µg/l	5	0.09	0.60	0.05
	Turbidity	5.12	1 NTU	5	0.09	512.00	45.71
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 51.8$

C.

Site	Parameter	Average value (Ci)	Desirable value (Si)	Weight of each parameter (wi)	Relative weight (Wi)	Quality rating (qi)	WQI
Aluminium	pH	5.46	6.9-9.5	4	0.07	66.59	4.76
	EC	60.73	1700 µs/cm	4	0.07	3.57	0.26
	Salinity	51.92	1500 mg/l	3	0.05	3.46	0.19
	TDS	41.35	1200 ppm	4	0.07	3.45	0.25
	Fe	10.82	300 µg/l	3	0.05	3.61	0.19
	Cd	0.02	4 µg/l	5	0.09	0.50	0.04
	Pb	0.11	10 µg/l	5	0.09	1.10	0.10
	Al	11.29	300 µg/l	3	0.05	3.76	0.20
	Cr	0.54	50 µg/l	5	0.09	1.08	0.10
	Zn	141.99	5000 µg/l	4	0.07	2.84	0.20

	Mn	3.72	100 µg/l	3	0.05	3.72	0.20
	Ni	0.59	70 µg/l	3	0.05	0.84	0.05
	As	0.13	10 µg/l	5	0.09	1.30	0.12
	Turbidity	2.92	1 NTU	5	0.09	292.00	26.07
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 32.7$
Slate	pH	5.27	6.9-9.5	4	0.07	64.27	4.59
	EC	40.15	1700 µs/cm	4	0.07	2.36	0.17
	Salinity	51.91	1500 mg/l	3	0.05	3.46	0.19
	TDS	28.18	1200 ppm	4	0.07	2.35	0.17
	Fe	7.31	300 µg/l	3	0.05	2.44	0.13
	Cd	0.1	4 µg/l	5	0.09	2.50	0.22
	Pb	0.08	10 µg/l	5	0.09	0.80	0.07
	Al	39.24	300 µg/l	3	0.05	13.08	0.70
	Cr	0.81	50 µg/l	5	0.09	1.62	0.14
	Zn	1801.66	5000 µg/l	4	0.07	36.03	2.57
	Mn	5.47	100 µg/l	3	0.05	5.47	0.29
	Ni	0.58	70 µg/l	3	0.05	0.83	0.04
	As	0.05	10 µg/l	5	0.09	0.50	0.04
	Turbidity	2.1	1 NTU	5	0.09	210.00	18.75
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 28.1$
Steel	pH	5.13	6.9-9.5	4	0.07	62.56	4.47
	EC	38.51	1700 µs/cm	4	0.07	2.27	0.16
	Salinity	33.74	1500 mg/l	3	0.05	2.25	0.12
	TDS	31.68	1200 ppm	4	0.07	2.64	0.19
	Fe	12.2	300 µg/l	3	0.05	4.07	0.22
	Cd	0.04	4 µg/l	5	0.09	1.00	0.09
	Pb	0	10 µg/l	5	0.09	0.00	0.00
	Al	11.72	300 µg/l	3	0.05	3.91	0.21
	Cr	0.87	50 µg/l	5	0.09	1.74	0.16
	Zn	284.39	5000 µg/l	4	0.07	5.69	0.41
	Mn	3.34	100 µg/l	3	0.05	3.34	0.18
	Ni	0.57	70 µg/l	3	0.05	0.81	0.04
	As	0.08	10 µg/l	5	0.09	0.80	0.07
	Turbidity	1.49	1 NTU	5	0.09	149.00	13.30
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 19.6$
Concrete	pH	5.48	6.9-9.5	4	0.07	66.83	4.77
	EC	55.12	1700 µs/cm	4	0.07	3.24	0.23
	Salinity	44.06	1500 mg/l	3	0.05	2.94	0.16
	TDS	45.32	1200 ppm	4	0.07	3.78	0.27
	Fe	7.33	300 µg/l	3	0.05	2.44	0.13
	Cd	0.06	4 µg/l	5	0.09	1.50	0.13
	Pb	0	10 µg/l	5	0.09	0.00	0.00
	Al	14.24	300 µg/l	3	0.05	4.75	0.25
	Cr	0.6	50 µg/l	5	0.09	1.20	0.11
	Zn	15.38	5000 µg/l	4	0.07	0.31	0.02
	Mn	2.13	100 µg/l	3	0.05	2.13	0.11
	Ni	0.57	70 µg/l	3	0.05	0.81	0.04
	As	0.06	10 µg/l	5	0.09	0.60	0.05

	Turbidity	2.48	1 NTU	5	0.09	248.00	22.14
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 28.4$
Thatched	pH	4.56	6.9-9.5	4	0.07	55.61	3.97
	EC	36.19	1700 µs/cm	4	0.07	2.13	0.15
	Salinity	37.56	1500 mg/l	3	0.05	2.50	0.13
	TDS	50.71	1200 ppm	4	0.07	4.23	0.30
	Fe	36.87	300 µg/l	3	0.05	12.29	0.66
	Cd	0.09	4 µg/l	5	0.09	2.25	0.20
	Pb	0.12	10 µg/l	5	0.09	1.20	0.11
	Al	34.37	300 µg/l	3	0.05	11.46	0.61
	Cr	1.45	50 µg/l	5	0.09	2.90	0.26
	Zn	26.12	5000 µg/l	4	0.07	0.52	0.04
	Mn	14.78	100 µg/l	3	0.05	14.78	0.79
	Ni	1	70 µg/l	3	0.05	1.43	0.08
	As	7.01	10 µg/l	5	0.09	70.10	6.26
	Turbidity	5.27	1 NTU	5	0.09	527.00	47.05
				$\sum wi = 56$	$\sum Wi = 1$		$\sum WQI = 60.6$

Univen rainwater-harvested samples recorded water quality indices in the ranges of 23 (slate roof type) to 76.6 (thatched roof type). The WQI ranges of rainwater collected from Sibasa were 22.1 for concrete roof type to 51.8 thatched roof type. Tshikhudini sampling area recorded a WQI range of 19.6 (steel roof type) to 60.6 (thatched roof type). All the roof top harvested rainwater samples collected in the VDM, from the three sampling areas had an excellent water quality in terms of the physicochemical and the metals' quality indicators except from the thatched roof type which showed good water quality. Water from thatched roof, therefore, can be used for many purposes including domestic purposes, such as laundry, floor washing, car washing, among others.

This study went further to calculate the water quality index including *E. coli* as one of the parameters to compute the WQI. The rooftop-harvested rainwater recorded the presence of *E. coli,* it can, hence, be argued that it is necessary to include it as one of the parameters to compute WQI. The results showed that the inclusion of *E. coli* as a parameter to compute WQI will result in high water quality index value, thereby, proving that pathogenic microorganism play a major role in reducing the quality of water. Without inclusion of *E. coli* parameter, the WQI rating system was calculated and it gave an excellent description range, but with the system included the water quality index ranges for water collected from Univen, the rating moved to a good quality index range with water collected from slate roof type to very poor quality index range for water collected from thatched roof type. Water collected from Sibasa area all had poor water quality index range values. For Tshikhudini samples, the ranges were from good water quality index range for samples collected from an aluminium roof type to very poor water quality index range for rooftop rainwater harvested from thatched roof type, which makes it very unfit for drinking purposes.

Table 5.4: WQI computed with *E. coli* physicochemical parameters and metals for all the roof catchments for all the areas: A. Univen, B. Sibasa and C. Tshikhudini.

Sites	**WQI with *E. coli* included**				**WQI ranges**	
	Univen	Sibasa	Tshikhudini		Range	Description
Aluminium	189.0	128.5	65.4		<50	Excellent
Slate	81.2	151.6	67.8		50-100	Good
Steel	265.4	114.2	93.3		100-200	Poor
Concrete	103.2	123.0	120.9		200-300	Very poor
Thatched	329.4	306.6	577.8		>300	Unfit

5.6 HEALTH RISK ASSESSMENT

If metals are present in water in higher concentrations than recommended, it may expose the users to health risks if the water is not treated prior to use (Igbinosa et al., 2017). The USEPA model of health risk assessment was used to evaluate the risk of heavy metals analysed in this study on humans, through direct ingestion and dermal absorption of roof harvested rainwater samples. The hazard quotient (HQ) value represents the single element within a single health risk exposure of each element (Edokpayi et al., 2018).

The USEPA considered an overall non-carcinogenic hazard index (HI) value of less than 1 as an acceptable threshold (USEPA, 1989). The Hazard Quotient (HQ) values for some trace elements analysed in this study through the ingestion and dermal routes were computed for both adults and children and are given in Tables 5.5 to 5.8. Both the overall HI and the HQ through ingestion and dermal exposure for both children and adult groups in roof-harvested rainwater in VDM from all the three different sites, with different land use activities, did not exceed the threshold limit of 1.

This implies that there is no potential non-carcinogenic health risk for children and adults from trace elements via ingestion of roof harvested rainwater. The occurrence of acute illness is, however, expected due to the levels of microbial contaminants.

Table 5.5: Summary of HQ values of Cr, Mn, Fe, Ni and Cu for children

Children		Cr		Mn		Fe		Ni	
	(µg/L)	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**
Univen	Aluminium	2.80E-02	8.21E-03	5.57E-02	5.11E-03	2.29E-03	4.20E-05	5.64E-03	1.53E-05
	Slate	2.92E-02	8.57E-03	1.59E-02	1.45E-03	2.15E-03	3.94E-05	2.46E-03	6.68E-06
	Steel	3.12E-02	3.11E-01	1.33E-01	1.22E-02	5.82E-03	1.07E-04	5.82E-03	1.58E-05
	Concrete	2.20E-02	6.45E-03	3.75E-02	3.43E-03	1.97E-03	3.62E-05	1.98E-03	5.38E-06
	Thatched	3.08E-02	9.03E-03	5.54E-02	5.08E-03	2.40E-03	4.40E-05	2.64E-03	7.17E-06
Sibasa	Aluminium	1.56E-01	4.56E-02	1.31E-02	1.20E-03	1.19E-03	2.18E-05	4.20E-03	1.14E-05
	Slate	3.08E-02	9.03E-03	3.01E-02	2.76E-03	1.74E-03	3.19E-05	3.24E-03	8.80E-06
	Steel	3.64E-02	1.07E-02	7.56E-02	6.93E-03	8.59E-03	1.57E-04	3.30E-03	8.96E-06
	Concrete	2.52E-02	7.39E-03	9.10E-03	8.34E-04	1.08E-03	1.98E-05	3.36E-03	9.13E-06
	Thatched	3.48E-02	1.02E-02	3.67E-02	3.36E-03	2.60E-03	4.77E-05	3.78E-03	1.03E-05
Tshikhudini	Aluminium	2.16E-02	6.34E-03	1.86E-02	1.71E-03	1.85E-03	3.40E-05	3.54E-03	9.61E-06
	Slate	3.24E-02	9.50E-03	2.74E-02	2.51E-03	1.25E-03	2.30E-05	3.48E-03	9.45E-06
	Steel	3.48E-02	1.02E-02	6.10E-02	5.59E-03	2.09E-03	3.83E-05	3.42E-03	9.29E-06
	Concrete	2.40E-02	7.04E-03	3.67E-02	3.36E-03	1.26E-03	2.30E-05	3.42E-03	9.29E-06
	Thatched	5.80E-02	1.70E-02	1.84E-01	1.69E-02	6.32E-03	1.16E-04	6.00E-03	1.63E-05

Table 5.6: Summary of HQ values for Zn, Mo, Cd and Pb in children

Children		Mo		Cd		Pb		Cu	
	(µg/L)	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**
Univen	Aluminium	1.20E-03	8.80E-04	4.80E-03	3.52E-04	8.83E-02	4.32E-03	5.07E-03	9.30E-05
	Slate	4.80E-04	3.52E-04	1.44E-02	1.06E-03	0	0	0	0
	Steel	7.20E-04	5.28E-04	1.68E-02	1.23E-03	5.91E-02	2.89E-03	1.22E-02	2.23E-04

	Concrete	4.80E-04	3.52E-04	4.80E-03	3.52E-04	0	0	0	0
	Thatched	7.20E-04	5.28E-04	1.20E-02	8.80E-04	8.57E-03	4.19E-04	7.47E-03	1.37E-04
Sibasa	Aluminium	1.44E-03	1.06E-03	9.60E-03	7.04E-04	6.86E-03	3.35E-04	1.99E-02	3.65E-04
	Slate	2.88E-03	2.11E-03	3.12E-02	2.29E-03	2.40E-02	1.17E-03	6.93E-03	1.27E-04
	Steel	7.20E-04	5.28E-04	1.68E-02	1.23E-03	5.91E-02	2.89E-03	1.65E-02	3.02E-04
	Concrete	7.20E-04	5.28E-04	4.80E-03	3.52E-04	8.57E-03	4.19E-04	1.22E-02	2.24E-04
	Thatched	9.60E-04	7.04E-04	1.68E-02	1.58E-03	4.29E-03	2.10E-04	3.75E-03	6.88E-05
Tshikhudini	Aluminium	2.88E-03	2.11E-03	4.80E-03	3.52E-03	9.43E-03	4.61E-04	1.44E-02	2.64E-04
	Slate	1.20E-03	8.80E-04	2.40E-02	1.76E-03	6.86E-03	3.35E-04	0	0
	Steel	7.20E-04	5.28E-04	4.80E-03	7.04E-04	0	0	0	0
	Concrete	4.80E-04	3.52E-04	1.44E-02	1.06E-03	0	0	3.72E-02	1.36E-04
	Thatched	1.20E-03	8.80E-04	1.08E-02	1.58E-03	1.03E-02	5.03E-04	1.82E-02	6.68E-05

Table 5.7: Summary of HQ values for Cr, Mn, Fe, Ni, and Cu in adults

Adults		Cr		Mn		Fe		Ni	
	(µg/L)	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**
Univen	Aluminium	7.33E-03	2.78E-03	3.65E-01	6.92E-05	6.00E-04	1.42E-05	1.48E-03	5.19E-06
	Slate	7.65E-03	2.90E-03	1.04E-01	1.97E-05	5.63E-04	1.34E-05	6.44E-04	2.26E-06
	Steel	8.17E-03	3.10E-03	8.69E-01	1.65E-04	1.52E-03	3.62E-05	1.52E-03	5.36E-06
	Concrete	5.76E-03	2.19E-03	2.45E-01	4.65E-05	5.17E-04	1.23E-05	5.19E-04	1.82E-06
	Thatched	8.07E-03	3.06E-03	3.63E-01	6.89E-05	6.29E-04	1.49E-05	6.91E-04	2.43E-06
Sibasa	Aluminium	4.08E-02	1.55E-02	8.54E-02	1.62E-05	3.12E-04	7.40E-06	1.10E-03	3.87E-06
	Slate	8.07E-03	2.82E-03	1.97E-01	3.74E-05	4.55E-04	1.08E-05	8.49E-04	2.98E-06
	Steel	9.53E-03	3.62E-03	4.95E-01	9.40E-05	2.25E-03	5.34E-05	8.64E-04	3.04E-06
	Concrete	6.60E-03	2.51E-03	5.96E-02	1.13E-05	2.83E-04	6.71E-06	8.80E-04	3.09E-06

	Thatched	9.11E-03	3.46E-03	2.40E-01	4.56E-05	6.82E-04	1.62E-05	9.90E-04	3.48E-06
Tshikhudini	Aluminium	5.66E-03	2.15E-03	1.22E-01	2.31E-05	4.86E-04	1.15E-05	9.27E-04	3.26E-06
	Slate	8.49E-03	3.22E-03	1.79E-01	3.40E-05	3.28E-04	7.79E-06	9.11E-04	3.20E-06
	Steel	9.11E-03	3.46E-03	3.99E-01	7.58E-05	5.48E-04	1.30E-05	8.96E-04	3.15E-06
	Concrete	6.29E-03	2.39E-03	2.40E-01	4.56E-05	3.29E-04	7.81E-06	8.96E-04	3.15E-06
	Thatched	1.52E-02	5.77E-03	1.21E-00	2.29E-04	1.66E-03	3.93E-05	1.57E-03	5.52E-06

Table 5.8: Summary of Zn, Mo, Cd and Pb in adults

	(µg/L)	Mo		Cd		Pb		Cu	
		HQ ing	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**	**HQ ing**	**HQ der**
Univen	Aluminium	3.14E-04	2.98E-04	1.26E-03	1.19E-04	2.31E-02	1.46E-03	1.33E-03	3.15E-05
	Slate	1.26E-04	1.19E-04	3.77E-03	3.58E-04	0	0	0	0
	Steel	1.89E-04	1.79E-04	4.40E-03	4.18E-04	1.55E-02	9.80E-04	3.18E-03	7.55E-05
	Concrete	1.26E-04	1.19E-04	1.26E-03	1.19E-04	0	0	0	0
	Thatched	1.89E-04	1.79E-04	3.14E-03	2.98E-04	2.24E-03	1.42E-04	1.96E-03	4.64E-05
Sibasa	Aluminium	3.77E-04	3.58E-04	2.51E-03	2.39E-04	1.80E-03	1.14E-04	5.21E-03	1.24E-04
	Slate	7.54E-04	7.76E-04	8.17E-03	7.76E-04	6.29E-03	3.98E-04	1.82E-03	4.31E-05
	Steel	1.89E-04	1.79E-04	4.40E-03	4.18E-04	1.55E-02	9.80E-04	4.31E-03	1.02E-04
	Concrete	1.89E-04	1.79E-04	1.26E-03	1.19E-04	2.24E-03	1.42E-04	3.20E-03	7.59E-05
	Thatched	2.51E-04	2.39E-04	5.66E-03	5.37E-04	1.12E-03	7.10E-05	9.82E-04	2.33E-05
Tshikhudini	Aluminium	7.54E-04	7.16E-04	1.26E-03	1.19E-04	2.47E-03	1.56E-04	3.77E-03	8.95E-05
	Slate	3.14E-04	2.98E-04	6.29E-03	5.97E-04	1.80E-03	1.14E-04	0	0
	Steel	1.89E-04	1.79E-04	1.26E-03	5.97E-06	0	0	0	0
	Concrete	1.26E-04	1.19E-04	3.77E-03	3.58E-04	0	0	9.74E-03	2.31E-04
	Thatched	3.14E-04	2.98E-04	5.66E-03	5.37E-04	2.69E-03	1.70E-04	4.77E-03	1.13E-04

5.7 Quantitative Microbial Risk Assessment (QMRA)

5.7.1. Average *E. coli* concentrations in roof-harvested rainwater samples

All the samples collected were analysed for *E. coli.* Table 5.9 below shows the mean concentrations of *E. coli* counts recorded during the entire study for the 6 different rainfall events. The concentrations were then used to compute the health risk due to pathogenic *E. coli.*

Roof harvested rainwater collected from thatched roof recorded the highest *E. coli* concentrations compared with the other roof types used for sample collection in the present study, however, these concentrations differ from one area to another. This may be due to difference in land use activities. The mean concentrations of *E. coli* ranged from 4.29 cfu/100 mL for rainwater sample collected from an aluminium roofing material to 63.67 cfu/100 mL for rainwater sample collected from thatched roofing material.

Table 5.9: Average *E. coli* concentrations (±standard deviation) that were used to calculate the microbial risk

	Univen (CFU/ 100 mL)	**Sibasa (CFU/ 100 mL)**	**Tshikhudini (CFU/ 100 mL)**
Slate	7.25 ± 7.29	7.88 ± 37.22	5.08 ± 3.08
Concrete	9.33 ± 15.17	11.75 ± 8.96	11.54 ± 5.58
Aluminium	20.42 ± 22.39	10.25 ± 10.18	4.29 ± 1.71
Steel	27.83 ± 48.12	9.63 ± 9.72	9.17 ± 4.27
Thatched	25.00 ± 9.9	33.17 ± 37.15	63.67 ± 36.18

5.7.2. Dose (N) calculations

The dose in this study was calculated by assuming that 8% of *E. coli* is pathogenic (Haas et al., 1999). The dose calculated for both the ingestion of 100 mL and of 2000 mL of roof harvested rainwater samples is presented in Table 5.10. The WHO recommends 2L of drinking water per person, per day and that is why it is essential to calculate microbial risk based on volume of ingestion. The dose-response was used to compute the health risk through both single and multiple exposures.

Table 5.10: Average *E. coli* dose of microbial results

	100 mL	2000 mL	100 mL	2000 mL	100 mL	2000 mL
	Univen		**Sibasa**		**Tshikhudini**	
Slate	0.58	11.60	0.63	12.60	0.41	8.13
Steel	2.23	44.53	0.77	15.40	0.73	14.67
Concrete	0.75	14.93	0.94	18.80	0.92	18.47
Aluminium	1.63	32.67	0.82	16.40	0.34	6.87
Thatched	2.00	40.00	2.65	53.07	5.09	100.00

5.7.3. Probability of infection with *E. coli*

The probability that a person will be infected given a certain dose of roof harvested rainwater is estimated. Table 5.11 summarises the results for infection through a single exposure. Both types of exposure were quantified by ingestion per 100 mL and per 2000 mL (2 L). Figures 5.8 to 5.11 present the probability of infection through multiple exposures with an average *E. coli* counts for 100 mL and 2000 mL of untreated roof harvested rainwater.

Based on the single exposure of dose of both 100 mL and 2000 mL, risk was detected in all samples analysed. For Univen-collected samples, the percentage ranges of health risk resulting from single exposure is 7.99% from slate roof type, to 22.40% from samples collected from a steel roof type, and 49.68 % for samples collected from a slate roof type to 68.75% for samples collected from thatched roof type for 100 mL and 2000 mL, respectively. Considering an ingestion of 2000 mL of the untreated roof harvested rainwater, all the sites also recorded a positive health risk; meaning if someone consumes that water, there is the possibility that they may get infection or may get sick.

For samples collected in Sibasa sampling area, the probability of infection through single exposure was calculated and ranged from 5.57% for samples collected from a slate roof type to 25.02% for samples collected from thatched roof type for ingestion of 100 mL. For a 2000mL single exposure ingestion, the probability of infection ranged from 51.03% from a slate roof type to 70.74 from a thatched roof type. For samples collected in Tshikhudini sampling area, the probability of infection through single exposure from ingesting both 100 mL and 2000 mL of rooftop harvested rainwater ranged from 5.01% from an aluminium roof type to 35.71% from a thatched roof type and from 40.84% from an aluminium roofing to 77.03% from a thatched roof type.

Table 5.11: Probability of infection (Pi and Pn) with average *E. coli* counts of both 100 mL and 2000 mL of untreated roof-harvested rainwater.

Average Conc.				**Pi = 1-(1+N/β) ^-α**	
		100 mL		**2000 mL**	
Univen			**%**		**%**
Slate		0.08	7.99	0.50	49.68
Steel		0.22	22.40	0.69	68.75
Concrete		0.10	9.90	0.54	53.74
Aluminium		0.18	18.15	0.65	64.95
Thatched		0.21	20.87	0.67	67.47
Sibasa			**%**		**%**
Slate		0.09	8.57	0.51	51.03
Steel		0.10	10.15	0.54	54.22
Concrete		0.12	11.95	0.57	57.26
Aluminium		0.11	10.70	0.55	55.19
Thatched		0.25	25.02	0.71	70.74
Tshikhudini			**%**		**%**
Slate		0.06	5.84	0.44	43.74
Steel		0.10	9.75	0.53	53.45
Concrete		0.12	11.78	0.57	56.99
Aluminium		0.05	5.01	0.41	40.84
Thatched		0.36	35.71	0.77	77.03

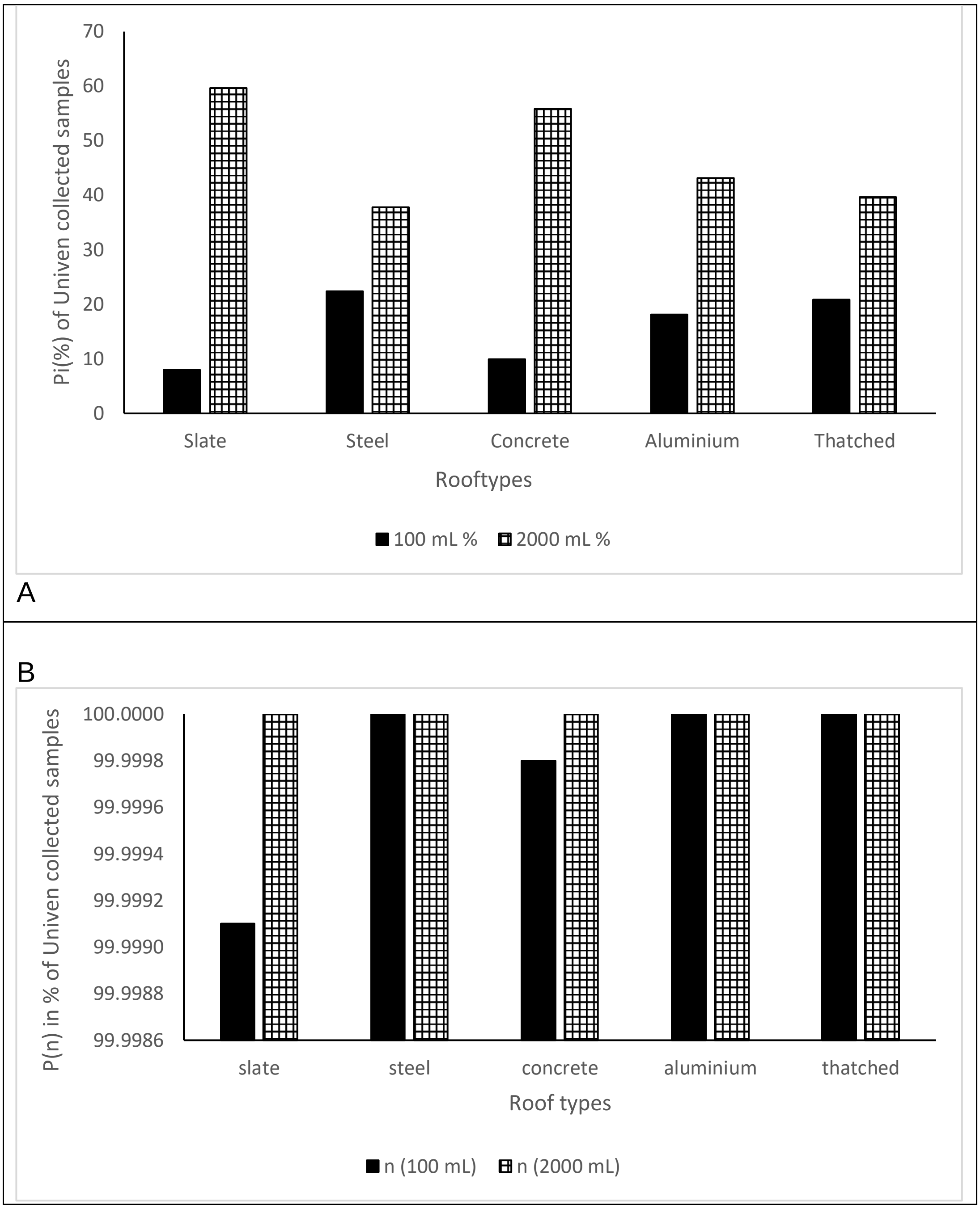

Figure 5.8: Probability of infection through both single exposure (A) and multiple exposures (B) ingested of 100 mL and 2000 mL of Univen roof-harvested rainwater

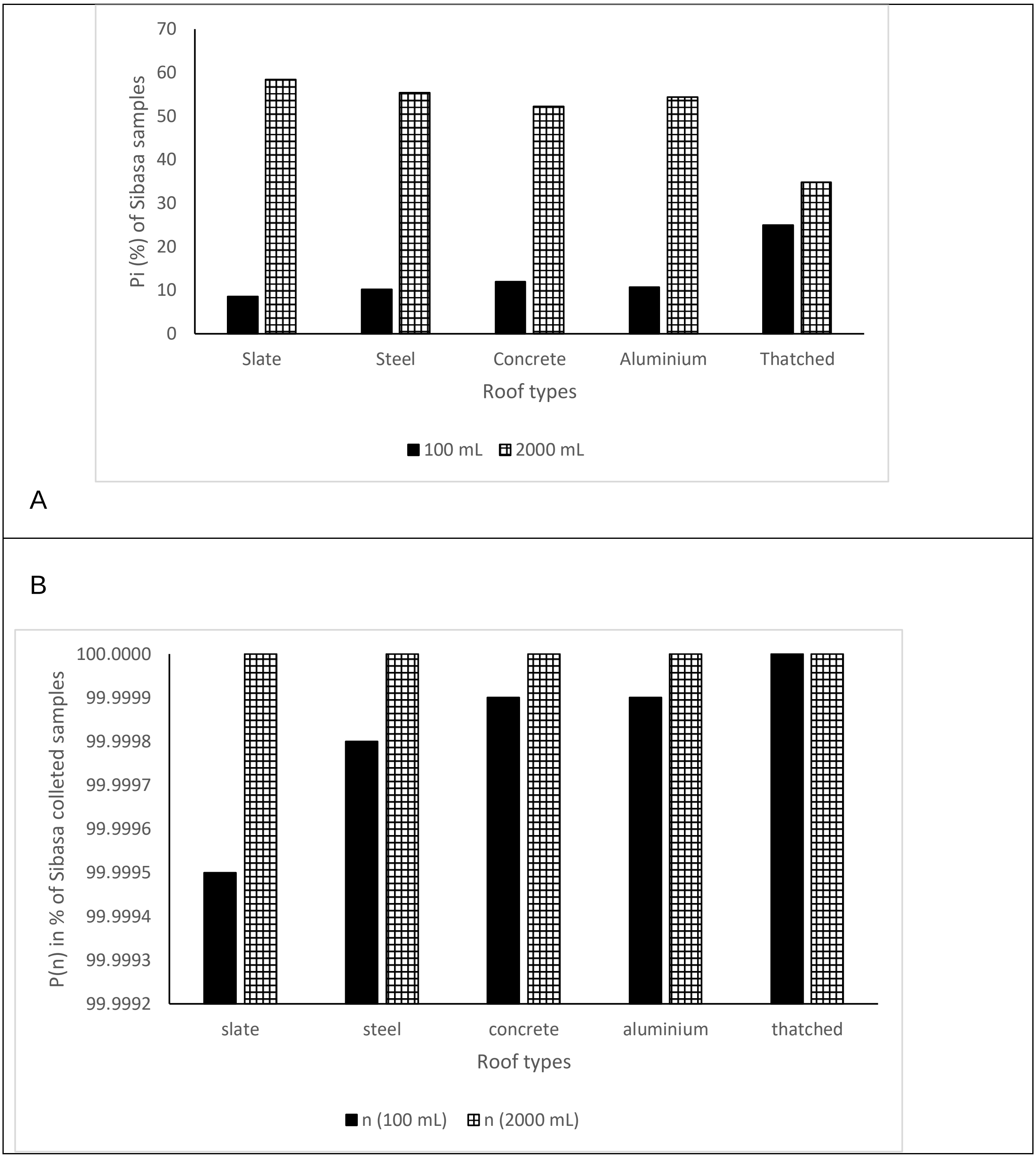

Figure 5.9: Probability of infection through both single exposure (A) and multiple exposures (B) ingested for 100 mL and 2000 mL of Sibasa roof-harvested rainwater.

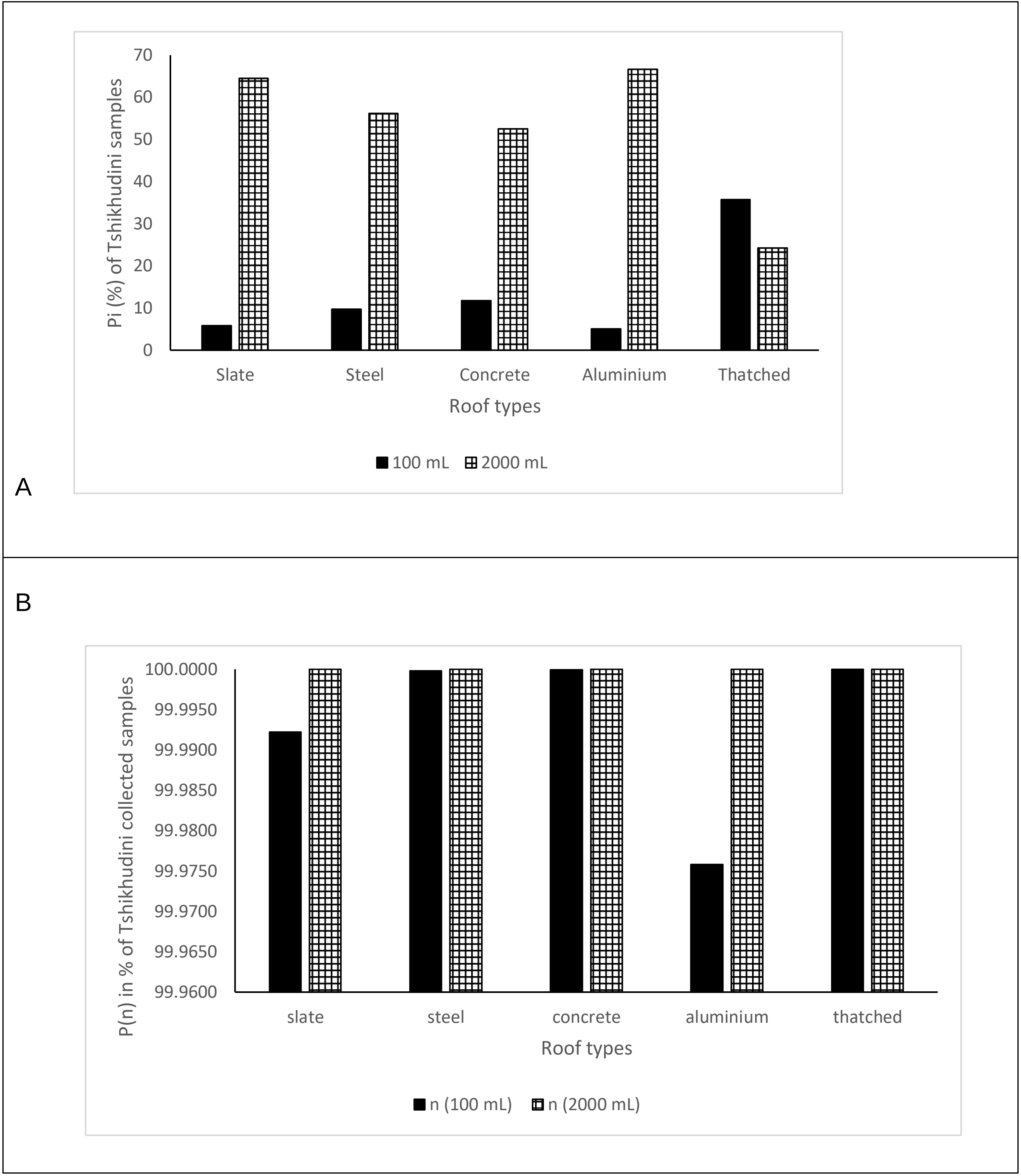

Figure 5.10: Probability of infection through both single exposure (A) and multiple exposures (B) ingested for 100 mL and 2000 mL of Tshikhudini roof-harvested rainwater

The probability of infection through multiple exposures of rooftop harvested rainwater for all the three sampling sites of this study were recorded with ranges of 99.97% to 100% through both the exposure to 100 mL and 2000 mL. This means that continuous consumption of rooftop-harvested rainwater without any treatment could pose a great risk to human health, therefore, it can be advised that people practise at least one treatment method prior consumption of rooftop harvested rainwater.

The quality of microbiological pathogens is of most concern when it comes to rainwater being in contact with humans via bathing, consumption, and toilet flushing (Jiang et al., 2015). The quantified potential health risk of microbial pathogens in this study were assessed using QMRA.

All the samples collected in this study showed a health risk from ingestion of roof harvested rainwater with *E. coli* pathogenic microorganism for both 100 mL and 2000 mL of exposure to rooftop-harvested rainwater in the Vhembe District, South Africa. There are severe public health consequences in ingestion of microbiologically contaminated water. The QMRA revealed that there is a high risk for the populations using this water. A study by Ahmed et al. (2010) recorded the risk of infection from consuming roof harvested rainwater in the range 0-7% for *E. coli.*

Thatched roof type recorded the highest probability of infection than any other roof type in this study. It is expected for untreated rooftop harvested rainwater to have very high levels of microbiological estimated risk from waterborne pathogens because they are linked with zoonosis in birds and other animals that inhabit or transit on roofs (Hora et al., 2018). Aryal et al. (2022) mentioned that roofs are subjected to more contaminants which are the results of the accumulation of tree litters, atmospheric deposits, and animal faeces (birds, and other animals). The accumulation of contaminates may be higher in thatched roof, therefore, thatched roof type cannot be recommended for the collection of roof-harvested rainwater for domestic use, to minimize the risk of infection.

The results obtained in a study by John et al., (2021) show the necessity of applying disinfection method (alum, chlorination, boiling, among others.) as ways of eliminating any harmful threats by *E. coli* in roof harvested rainwater. A study by Ahmed et al., (2010) reported that *E. coli* poses low risk level of infection if rooftop harvested rainwater was for non-potable usage, therefore, rooftop harvested rainwater can be recommended for non-potable uses such as, irrigation and toilet flushing.

Jiang et al., (2015) reported that QMRA measures the estimated risk, therefore, the actual risk can be more than the estimated risk. Prior treatment of roof harvested rainwater is, thus, recommended before the use of such water for domestic use. John et al., (2021) used QMRA to assess the health risk of roof harvested rainwater in the Ikorodu area of

Lagos state, Nigeria. The findings demonstrated that there is a maximum risk of *E. coli* exposure from the consumption of roof harvested rainwater.

5.8 Conclusion

The physicochemical parameters analysed in this study were pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and turbidity. From the results obtained, all roof harvested rainwater were within the recommended SANS and WHO standards. Similarly, all the heavy metals analyzed in this study also had average values that were below the standard limits. The average *E. coli* and total coliform counts were higher than the permissible SANS and WHO standards with an overall range of 4.31 cfu /100 mL (aluminium roof type) to 63.7 cfu /100 mL (thatched roof type) and 20.77 cfu//100 mL (slate roof type) to 129.08 cfu/100 mL (thatched roof type).

The QMRA calculations all showed the possibility of risk in consumption of rooftop harvested rainwater. This means that continuous consumption of rooftop harvested rainwater, without any treatment could pose a great risk to human health, therefore, it is advised that people practise at least one treatment method prior to consumption of rooftop harvested rainwater.

Using *E. coli* as one of the parameters to compute, the WQI ranged from 19.6 (excellent water quality) from sample collected from a steel roof type to 76.6 (good water quality) from sample collected from thatched roof type. Very poor water quality was recorded in WQI computed with an inclusion of *E. coli* as one of the parameters. Without *E. coli*, the quality of water was calculated to be excellent, but with it, the status of the water collected from Univen moved to good quality from slate roof type to very poor quality for water collected from thatched roof type.

All the HQ values and the overall non-carcinogenic sum of HI calculated in this study for health risk, through both ingestion and dermal adsorption of roof harvested rainwater samples from the VDM, were recorded to be less than 1, therefore, no potential non-carcinogenic risk associated with the use of RHRWT.

CHAPTER SIX CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

Water scarcity has become an issue of concern globally, especially with the rapid increase in population. Rooftop rainwater harvesting is a very old technology for collecting and storing rainwater from roof catchments for human, plant, and animal consumption. In South Africa, the use of RTRWH is currently supported by both the government and non-governmental organisations. The people of Vhembe District Municipality also practise rainwater harvesting as an alternative source of domestic water source, but its quality is not well documented.

The study set out to explore and give the perceptions of those individuals who collect, store, and use harvested rainwater in the Vhembe District Municipality of the Limpopo Province, South Africa. This is the first study of this kind to be conducted in the Vhembe District region. The practice of RWH is very high in the study area and the reason for its adoption was communities not having enough water supplied by municipality, and the majority of the respondents being also satisfied with the quality of roof harvested rainwater.

From the data gathered in the study, the water quality parameters were within the permissible limit of the SANS and WHO's guidelines for drinking water. There was an exception, however, of the microbiological quality as *E. coli* and total coliforms levels were above the recommended SANS and WHO drinking water quality guidelines.

Of all the roof types - slate, steel, aluminium, concrete and thatched - investigated in this study, thatched roof type impacted negatively in terms of physicochemical and microbiological quality of the collected rainwater. With roof harvested rainwater being highly polluted with microbiological organisms, using untreated rainwater would pose a high potential risk of infection. The risk of infection from roof harvested rainwater through both single and multiple exposures would lead to elevated risk to the users, therefore, the use of various simple water-treatment technologies are recommended.

The Water Quality Index was established by some of the essential physicochemical parameters analysed in this study. All the roof harvested rainwater samples collected had an excellent water quality in terms of the physicochemical and the metal water quality indicators from roof types of slate, steel, aluminium and concrete. There was an exception, however, from samples collected from thatched roof type, in all the three areas that recorded water quality index that showed good water quality. WQI with an inclusion of *E. coli* as one of the parameters used resulted in a reduction of the quality. There was no non-carcinogenic risk (HQ<1) associated with the consumption of roof harvested rainwater by both children and adults based on the levels of trace metals recorded from the study.

6.2. LIMITATIONS OF THE STUDY

This study only looked at rooftop harvested rainfall practices in three regions of the Vhembe District from 2020-2021. Secondly, the questionnaires were distributed to 774 residents in dispersed villages of the District.

6.3. RECOMMENDATIONS FOR FUTURE RESEARCHES AND REAL-LIFE APPLICATIONS

Based on the results of the study, the following recommendations are made:

1. More regions in the VDM can be included in future studies.
2. Rooftop harvested rainwater must be properly treated using one of the various simple point-of-use water treatment technology before potable use.
3. More research is necessary to investigate the management of the first flush system.
4. There should be educational interventions aimed at creating awareness about the installation, maintenance and repair of rooftop rainwater harvesting systems.
5. There is a need to conduct a detailed analysis of organics that could be a result of pollution or as leachate components from the thatching material.

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APPENDICES

Appendix 1: RTRWH questionnaire administered to the rainwater collected and users of the VDM

Administered Questionnaire Surveys and Consent

A QUESTIONNAIRE ADAPTED FROM PREVIOUS QUESTIONNAIRES FOR THE PEOPLE WHO COLLECT, STORE AND USE HARVESTED RAINWATER IN THE VHEMBE DISTRICT OF LIMPOPO PROVINCE, SOUTH AFRICA

Consent to Participate in Research

Hello!

I am a Master's Student at the University of Venda and would like to ask you to help me with a study I am doing of Rainwater Harvesting. I want to learn what the community members of Vhembe District Municipality think about collecting rainwater and how they use it.

I would like to talk to you, as a community member, about this for about 15 to 20 minutes by asking you questions on this form and writing your answers in the form.

This study will not be used to tell the University of Venda or the government about what you do with your water, how you feel about water supply, or what you think about collecting rainwater. For this reason, I will not write your name or your address anywhere on this form.

Before we begin, please answer the following questions by ticking "Yes" or "No"

Do you understand what I have explained to you?	Yes	No
Do you understand that nobody except me will know what you tell me today?		
Do you understand that you can stop answering my questions at any time?		
Do you have any questions that you want to ask me before we start?		
Can I start asking you the questions on the form?		

I have explained the project and the implications of being interviewed to the respondent and I believe that the consent is informed and that she/he understands the implications of participation.

Name of Interviewer: Vele Livhuwani

Signature: ________________

Province and District____

Date______________________________

Name of community____

Number of people in the household______________________________________

1. Gender
   ☐Male ☐Female

2. Age
   ☐20-29 ☐30-39 ☐40-49 ☐50-59

   ☐60-69 ☐70-79 ☐80-89 ☐>90

3. Employment Status
   ☐Employed ☐Unemployed

4. Educational Level
   ☐No Schooling ☐Primary ☐Secondary ☐FET

   ☐HET ☐Graduate

5. Do you harvest rainwater?
   Yes ☐ No ☐
6. When do you harvest rainwater?

☐Morning

☐ Afternoon

☐Evening

☐Anytime it rains

7. What do you use as a catchment to collect rainwater from?

☐Own roof

☐Other households' roof

☐Others, specify____

8. What kind of storage are you using to store collected rainwater?

☐Store underground

☐JoJo tank

☐Small buckets

☐Others, specify____

9. Is it only rainwater that is stored in the tank?
☐Yes ☐No

If No, what other sources of water are stored together with rainwater?

____

10. Why are you storing rainwater?
- ☐To reduce water costs
- ☐Lack of water sources
- ☐To save water
- ☐Limited supplied water for use
- ☐Others, specify____

11. Do you test the quality of the harvested rainwater?

☐Yes

☐No

If yes, specify____

12. What are you using harvested rainwater for? *(You can tick more than one)*

- ☐Drinking
- ☐Toilet and flush tank
- ☐Bathing
- ☐Washing clothes
- ☐Washing dishes
- ☐Cooking
- ☐Irrigating backyard garden
- ☐Washing parking lot and car
- ☐Others, ____

13. How often do you use your collected rainwater?
- ☐Daily
- ☐Few times a week
- ☐Less often in a week
- ☐Never

14. Rate the quality of harvested rainwater

☐Satisfactory

☐Acceptable

☐Unsatisfactory

15. In what condition is your rain storage tank?
    ☐Good working condition

    ☐Neither good nor bad

    ☐Damaged

16. How often do you wash the storage tank?
    ☐Once weekly

    ☐Once in a month

    ☐Once in a year

    ☐Never

17. Do you treat rainwater before use?
    ☐Yes

    ☐No

    If yes, what type of treatment?

☐Boiling ☐Sedimentation ☐Solar disinfection

☐Others ____

18. Has any of your household member experienced any kind of problem by using stored rainwater?

☐Yes ☐No

If yes, what type of a problem? ____

19. Do you have knowledge concerning the operation and maintenance of a tank?
    ☐Yes
    ☐No
    If No, will you be willing to learn? __________________________
20. If repair is required for your tank will you be willing to pay for it?
    ☐Yes
    ☐No
21. What is your level of satisfaction in using Harvested Rainwater?
    ☐Extremely Satisfied
    ☐Satisfied
    ☐Slightly Satisfied

☐Not Satisfied

22. What influenced you to use harvested rainwater?

	Yes	No	Unsure	Do not want to answer
Not enough water supplied by municipal				
Water supply costs				
Rainwater tastes good				
Rainwater free from odours				
Rainwater is clear				

MBUDZISO DZA VHATHU VHA NO KELELA, U VHULUNGA NA U SHUMISA MADI A MVULA KHA TSHITIRIKI TSHA VHEMBE KHA VUNDU LA LIMPOPO PROVINCE, SOUTH AFRICA

Thendelo Ya Uvha Murado Kha Mbudziso Idzi

Aa!

Ndi mugudiswa wa Univestity ya Venda, ndi khou humbela thuso kha zwine nda khou gudela zwa u kelelwa ha madi a mvula. Ndi toda u guda uri sa mirado ya community kha tshiriki tsha Vhembe vha humbula mini nga u kelela madi a mvula na uri vha a shumisa hani.

Ndinga takalela u amba navho sa murado wa community nga mithethe I sa fhidzi ya fumbili nga u vha vhudzisa mbudziso dzo nwalwaho afha kha form uri vhai dadze.

Ngudo heino a I nga shumiswi u vhudza vha University ya Venda kana Muvhuso nga ha uri vha itani nga madi avho, vha dipfa hani nga u diswa ha madi, kana vha humbula mini nga u kelela madi a mvula. Zwo ralo, ahu nga nwalwi madzina kana hune vha dzula hone hunwe fhethu kha form iyi.

Ri saathu thoma, ndi humbela vha fhindule mbudziso dzi tevhelaho nga u tikha “Ee” kana “Hai”

Vha a pfesesa zwe nda vha talutshedza?	Ee	Hai
Vha a pfesesa uri a huna munwe muthu ane a do divha nga zwine vhakhou mbudza namusi?		
Vha a pfesesa uri vha nga litsha u fhindula yshifhinga tshinwe na tshinwe?		
Vha na mbudziso ine vha vha nayo ri sa athu thoma?		
Nd inga thoma u vhudzisa zwo nwalwaho kha form?		

Ndo talutshedza project na mvelele dza u vhudziswa kha mufhinduli ndi tenda uri thendelo yo vha hone na uri o pfesesa mvelele dza u shela mulenzhe.

Dzina la muvhudzisi: Vele Livhuwani

Signature: ____________________

Phurovinsi na Tshitiriki____

Duvha____________________________________

Dzina la community____

Nomboro ya vhathu vhane vha dzula navho_________________________

1. Mbeu
   ☐Munna ☐Mufumakadzi
2. Minwaha
   ☐20-29 ☐30-39 ☐40-49 ☐50-59
   ☐60-69 ☐70-79 ☐80-89 ☐>90

3. Mushumo

☐Ndi a shuma ☐A thi shumi

4. Zwa tshikolo

☐A thongo dzhena ☐Primary ☐Secondary ☐FET

☐HET ☐Graduate

5. Vha a kelela madi a mvula?

Ee ☐ Hai☐

6. Madi a mvula vha a kelela a tshi bva kha mini?

☐Thanga ya hayani

☐Thanga dza minwe midi

☐Zwinwevho____

7. Madi a mvula vha a kelelela kha mini?

☐U a panga fhasi ha mavu

☐JoJo tank

☐Ma bucket matuku

☐Zwinwevho____

8. Ndi ngani vha tshi vhulunga madi a mvula?

☐U fhungudza mbadelo dza madi

☐a huna hune nda wana madi

☐U vhulunga madi

☐Madi a re hone a si mazhi

☐Zwinwevho____

9. Vha a test quality ya madi a mvula o kelelwaho?

☐Ee

☐Hai

Arali hu Ee avha
talutshedze____

10. Vha shumisa madi a mvula u itani? *(Vha nga nanga zwi no fhirisa tshithihi)*

☐U nwa
☐Bunga na u gwedzha

☐U tamba

☐U kuvha zwiambaro

☐U tanzwa dziphulethi

☐U bika

☐U sheledza

☐U tanzwa fhasi na dzigoloi

☐Zwinwevho,

____

11. Vha shumisa madi a mvula lungafhani?

☐Duvha linwe na linwe

☐lunzhi kha vhege

☐Zwituku nga vhege

☐A thi shumisi

12. Vha vhonisa hani quality ya madi a mvula o kelelwaho?

☐A a fusha

☐A a tanganedzea

☐Ha fushi

13. Nzulele ya hune vha vhea hone madi a mvula ku nga ndilade?

☐Hu a shumisea zwavhudi

☐Hu vhukati

☐Ho tshinyala

14. Hune vha vhea hone madi vha hu tanzwisa hani?

☐Luthihi nga vhege

☐Luthihi nga nwedzi

☐Luthihi nga nwaha

☐A hu tambi

15. Vha a tanzwa madi vha sa athun shumisa?

☐Ee

☐Hai

Arali hu Ee vha zwi itisa hani?

____

16. Munwe ane vha dzula nae o no lwala nga nthani ha u shumisa madi a mvula o kelelwaho?

☐Ee ☐Hai

Arali hu Ee avha talutshedze _______

____

17. Vha a divha nga kushumisele na ku tanzwele kwa tannge?

☐Ee
☐Hai
Arali hu hai vha a toda u guda? __________________________

18. Arali tannge litshi toda u lugiswa, vha nga zwi badelela?

☐Ee
☐Hai
19. Vha fushea hani nga madi o kelelwaho a mvula?

☐U fushea lwo kalulaho
☐U fushea
☐U fushea nyana
☐Ha fushi

20. Nga u angaredza ndi mini tsho vha itisaho u kelela madi a mvula?

	Ee	Hai	Athina vhutanzi	Athi todi u fhindula
Madi a masipala a si mazhi				
Mutengo wa madi				
Madi a mvula a a difha				
Madi a mvula ha na munukho				
Madi a mvula ndi avhudi				

Appendix 2: Ethical Clearance Certificate

ETHICS APPROVAL CERTIFICATE RESEARCH AND INNOVATION
OFFICE OF THE DIRECTOR

NAME OF RESEARCHER/INVESTIGATOR:
Ms L Vele
STUDENT NO:
15002097

PROJECT TITLE: <u>Water Quality: Assessment of Roof Harvested Rainwater and Evaluation of Potential Uses in Vhembe District Municipality.</u>

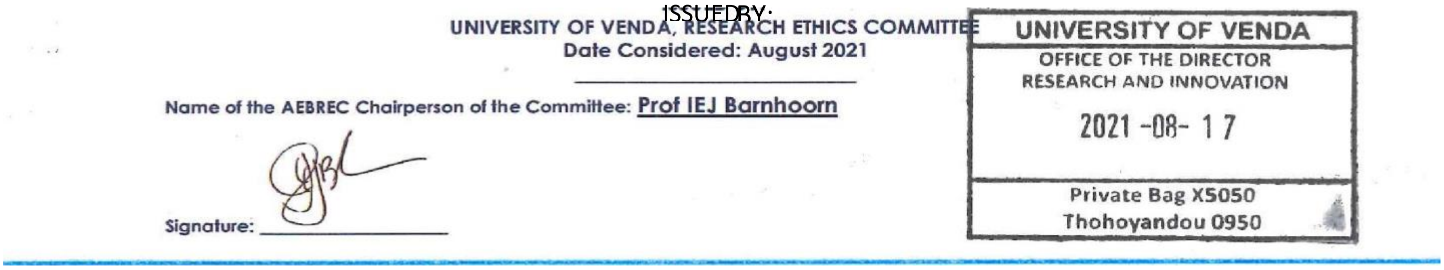
ETHICAL CLEARENCE NO: SEA/21 /HWR/07/1608

SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS

NAME	INSTITUTION & DEPARTMENT	ROLE
Dr J.N Edokpayi	University of Venda	Supervisor
Dr E Ubomba-Jaswa	WRC	Co - Supervisor
MS L Vele	University of Venda	Investigator — Student

Type: Masters Research
Risk: Minimal risk to humans, animals or environment (Category 2)
Approval Period: August 2021 August 2023

ISSUED BY:



UNIVERSITY OF VENDA, RESEARCH ETHICS COMMITTEE
Date Considered: August 2021

Name of the AEBREC Chairperson of the Committee: <u>Prof IEJ Barnhoorn</u>

Signature:

UNIVERSITY OF VENDA
OFFICE OF THE DIRECTOR
RESEARCH AND INNOVATION
2021 -08- 17
Private Bag X5050
Thohoyandou 0950

Appendix 3: Physicochemical parameters results of roof harvested rainwater samples in the VDM given with Average ± STDEV

First Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate	5.1± 1.0	0.7± 0.1	38.9± 1.0	35.4± 2.7	19.2± 10.4
		Aluminum	4.6± 0.2	1.4± 1.9	55.7± 21.8	35.7± 3.5	24.4± 10.2
		Steel	4.2± 0.5	1.7± 1.6	40.9± 26.9	35.8± 3.4	19.2± 10.4
		Concrete	5.0± 0.9	2.9± 1.2	45.1± 10.0	31.8± 4.6	19.3± 6.2
		Thatched	4.6± 0.4	7.8± 2.8	54.1± 4.0	43.5± 10.0	31.3± 5.7
		Control	5.59	0.5	16.2	18	11..8
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Sibasa	18	Slate	5.1± 0.3	2.6± 0.4	48.6± 0.4	33.8± 0.2	24.7± 1.9
		Aluminum	4.8± 0.3	2.2± 3.5	50.9± 4.8	38.9± 6.6	26.8± 5.4
		Steel	4.4± 0.3	1.3± 2.2	47.7± 0.5	34.0± 0.6	24.9± 3.7
		Concrete	4.6± 0.3	1.5± 1.4	45.2± 7.4	33.8± 0.3	24.6± 1.7
		Thatched	4.5± 0.3	3.6± 2.8	90.7± 8.3	42.6± 5.7	31.0± 4.0
		Control	5.47	0.2	18	7.7	10.5
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Tshikhudini	18	Slate	4.4± 0.3	0.6± 0.3	48.4± 0.1	33.8± 0.2	23.0± 0.1
		Aluminum	5.4± 0.9	1.6± 1.2	50.8± 5.2	38.9± 6.6	28.8± 10.7
		Steel	4.2± 0.8	0.9± 0.3	48.6± 0.9	34.0± 0.6	25.1± 2.4
		Concrete	4.0± 0.6	2.9± 1.2	48.7± 0.4	33.8± 0.3	23.7± 1.7
		Thatched	4.3± 0.5	2.9± 2.2	46.7± 26.1	42.6± 5.7	69.3± 17.3
		Control		0.1	10.8	11	14.2
		SANS		<1	≤1700	<1500	≤1200

5.6
6.9-9.5

*All values recorded are in quadruplicate

Second Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate	6.3± 0.4	0.5± 0.4	55.7± 16.5	40.7± 0.7	24.1± 6.5
		Aluminum	6.1± 0.6	0.2± 0.1	29.7± 13.9	38.1± 7.9	36.8± 22.1
		Steel	5.7± 0.7	1.4± 1.0	55.6± 4.7	40.3± 0.4	29.9± 17.0
		Concrete	6.4± 0.7	0.7± 0.9	70.8± 11.0	43.6± 4.2	51.0±34.8
		Control	5.24	0.01	16	31.6	35.8
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Sibasa	18	Slate	7.1± 0.6	1.8± 3.6	48.2± 7.4	30.2± 2.7	18.5± 4.6
		Aluminum	6.2± 0.7	2.4± 0.4	41.8± 18.2	39.3± 5.8	29.4± 4.4
		Steel	5.0± 1.0	1.1± 0.4	39.6± 14.7	36.4± 7.4	28.3± 9.9
		Concrete	5.7± 0.8	0.5± 0.4	55.5± 12.1	30.3± 9.3	23.4± 5.2
		Thatched	5.3± 0.5	3.7± 2.4	89.2± 7.6	53.8± 2.0	36.5± 14.1
		Control	5.71	0.25	21.2	14.7	11.3
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Tshikhudini	18	Slate	5.4± 1.3	1.5± 1.2	26.7± 3.7	26.8± 2.8	22.9± 7.1
		Aluminum	6.1± 0.8	2.9± 1.3	34.3± 13.5	45.1± 7.3	21.7± 12.2
		Steel	5.2± 1.1	0.9± 0.6	37.8± 16.1	32.2± 5.2	18.9± 5.4
		Concrete	6.1± 0.5	1.4± 1.0	38.3± 3.5	43.4±17.0	21.5± 8.8
		Thatched	4.5± 1.1	4.6± 1.5	69.7± 8.3	67.4±13.2	32.4± 12.7
		Control	5.91	0.29	22.2	12.1	12.7
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200

Third Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate	5.9± 0.5	4.8± 1.4	28.4± 4.8	24.6± 2.2	19.0± 3.3
		Aluminum	6.0± 0.8	4.8± 1.8	32.5± 7.9	31.6± 2.9	21.3± 4.7
		Steel	5.9± 0.7	5.6± 1.3	50.7±	32.3± 7.8	32.9± 11.1
		Concrete	6.2± 0.8	4.7± 1.0	14.6	28.5± 7.0	15.9± 3.3
		Control	6.03	0.06	33.9± 9.8	20.1	17.7
		SANS	6.9-9.5	<1	12.3	<1500	≤1200
					≤1700		
Sibasa	18	Slate	5.29±	1.27± 0.91	38.6±	17.1± 39.4	38.5± 36.7
		Aluminum	5.34	0.29± 2.7	27.4	32.7± 16.5	
		Steel	6.18±	0.51± 0.6	38.8±	18.2± 16.9	27.5± 22.3
		Concrete	6.09	0.73± 1.49	47.9	30.6± 34.7	
		Thatched	5.02± 6	5.23± 7.08	5.5± 37.3	32.5± 24.7	49.1± 12.9
		Control	4.88±	0.08	19.8± 68	19.8	
		SANS	5.64	<1	26.9±	<1500	23.6± 17.8
			4.15±		20.5		
			4.28		20		86± 81.4
			5.59		≤1700		20.2
			6.9-9.5				≤1200
Tshikhudini	18	Slate	5.1± 0.3	0.9± 0.8	34.4±	27.9± 6.2	33.7± 6.3
		Aluminum	5.1± 0.2	0.8± 0.1	10.1	29.4± 5.7	
		Steel	5.2± 0.8	1.4± 0.2	32.2± 1.2	28.4± 3.8	38.6± 11.6
		Concrete	5.8± 0.8	0.9± 0.4	42.6± 5.8	22.5± 12.7	
		Thatched	4.7± 0.7	6.0± 1.5	33.8±	23.5± 9.0	38.0± 7.6
		Control	6.05	0.18	10.8	15.3	
		SANS	6.9-9.5	<1	19.1± 5.9	<1500	39.8± 20.9
					15.6		
					≤1700		48.0± 2.7
							19.8
							≤1200

Fourth Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate	5.2±	4.7± 0.2	27.5± 1.3	19.1± 0.8	15.2± 2.9
		Aluminum	0.2	3.0± 0.7	38.3± 12.9	25.6± 10.1	29.4±
		Steel	6.4±	9.7± 0.1	45.1± 31.3	32.2± 21.3	23.0
		Concrete	0.7	5.4± 0.5	27.8± 6.9	21.7± 1.7	21.1±
		Control	5.6±	0.83	15.2	17.2	15.4
		SANS	0.9	<1	≤1700	<1500	14.8± 3.5
			5.7±				12.6
			0.7				≤1200
			6.71				

			6.9-9.5				
Sibasa	18	Slate	5.4± 0.2	4.9± 1.5	28.3± 8.0	20.6± 3.9	18.0± 8.7
		Aluminum	5.7± 0.1	4.7± 0.2	31.9± 5.8	22.2± 4.0	14.9± 2.8
		Steel	6.2± 0.7	4.7± 0.4	41.8± 5.5	23.4± 3.6	15.3± 4.2
		Concrete	5.5± 0.3	4.7± 1.1	29.1± 6.7	20.4± 4.7	15.1± 4.1
		Thatched	4.3± 0.7	7.5± 1.4	39.8± 13.0	19.0± 4.6	28.9± 6.8
		Control	6.13	0.5	18.8	19.9	20.4
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Tshikhudini	18	Slate	6.0± 0.5	7.6± 1.0	67.7± 86.8	161.2± 19.2	30.9± 39.4
		Aluminum	5.2± 0.4	10.2± 7.6	185.9± 3.6	130.5± 2.6	84.0± 5.1
		Steel	5.2± 1.2	3.3± 1.2	36.5± 27.5	33.7± 18.4	23.4± 9.9
		Concrete	5.2± 0.7	7.7± 4.4	140.7± 85.8	95.7± 57.4	65.6± 35.6
		Thatched	4.6± 0.4	6.8± 0.9	33.4± 12.0	37.4± 19.5	18.3± 1.5
		Control	6.25	0.8	19.5	16.8	27.5
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200

Fifth Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate	5.2± 0.6	0.3± 0.2	25.8± 7.2	26.8± 8.0	29.5± 11.6
		Aluminum	5.9± 0.9	0.5± 0.2	32.2± 5.8	27.7± 4.2	28.3± 6.3
		Steel	5.4± 0.3	1.0± 0.7	28.9± 8.7	39.6± 3.4	33.1± 15.6
		Concrete	4.9± 0.3	0.7± 0.3	27.1± 2.7	23.5± 0.9	38.1± 12.9
		Control	6.5	0.02	12.6	11.9	6.4
		SANS	6.9-9.5	<1	≤1700	<1500	≤1200
Sibasa	18	Slate	5.2± 0.4	0.4± 0.4	38.0± 4.3	22.4± 3.5	35.4± 3.0
		Aluminum	5.8± 0.6	1.3± 1.0	41.1± 4.7	30.9± 7.8	38.0± 6.4
		Steel		1.1± 0.5	43.8± 8.6	21.7± 3.2	35.2± 11.2
		Concrete		0.1± 0.1	36.7± 10.0	32.0± 8.7	40.2± 7.8
		Thatched		6.0± 0.8		29.7± 4.3	

		Control SANS	5.6± 1.0 4.4± 0.4 4.2± 0.3 6.53 6.9-9.5	0.01 <1	27.0± 3.1 10.8 ≤1700	5.8 <1500	73.2± 7.3 9 ≤1200
Tshikhudini	18	Slate Aluminium Steel Concrete Thatched Control SANS	5.0± 0.1 5.2± 0.3 4.8± 0.3 5.8± 0.4 4.7± 0.4 5.88 6.9-9.5	1.1±0.3 1.0± 0.2 1.2± 0.4 1.1± 0.2 6.2± 2.0 0.06 <1	36.6± 8.1 32.3± 4.0 34.8± 5.7 31.5± 4.9 20.3± 3.4 12.4 ≤1700	26.2± 5.1 35.3± 4.7 27.6± 1.1 29.5± 7.2 27.7± 5.5 18.8 <1500	30.8± 3.1 37.0± 8.0 36.7± 10.0 89.6± 117.8 45.3± 5.8 19.5 ≤1200

Sixth Sampling

Sampling site	N	Roof type	pH	Turbidity	EC	Salinity	TDS
Univen	18	Slate Aluminum Steel Concrete Control SANS	6.1± 0.1 6.5± 0.4 5.4± 0.4 5.6± 1.0 5.94 6.9-9.5	0.2± 0.3 0.6± 0.4 0.8± 0.3 0.6± 0.7 0.06 <1	26.9± 2.8 41.0± 17.0 27.3± 9.2 35.6± 2.0 29.4 ≤1700	35.5± 9.2 25.3± 8.1 45.6± 4.2 27.3± 6.6 39 <1500	33.4± 8.7 28.7±7.1 31.6± 10.1 24.4± 3.7 20.4 ≤1200
Sibasa	18	Slate Aluminum Steel Concrete Thatched Control	5.9± 0.5 4.6± 0.2	0.7± 0.9 1.3± 0.2 0.8± 0.5 0.5± 0.9 4.7± 2.8 0.02	36.9± 5.9 41.6± 11.5 40.9± 7.1 40.0± 8.5 20.1± 1.3	26.8± 3.9 27.9± 13.7 27.5± 7.7 33.3± 5.5 37.3± 3.3 17.9	35.2± 10.5 34.8± 4.2 36.3± 5.3 35.4± 11.6 69.6± 30.0 13.2

		SANS	6.1± 0.4 5.3± 0.9 4.9± 1.0 5.81 6.9-9.5	<1	7.5 ≤1700	<1500	≤1200
Tshikhudini	18	Slate Aluminum Steel Concrete Thatched Control SANS	5.7± 0.4 5.8± 0.3 6.1± 0.9 6.0± 0.9 4.6± 0.7 6.24 6.9-9.5	0.9± 0.9 1.0± 0.8 1.3± 1.2 0.9± 0.1 5.1± 1.2 0.08 <1	27.1± 10.6 29.9± 8.5 30.7± 3.8 37.7± 19.0 27.9± 5.3 12.4 ≤1700	35.5± 3.9 32.3± 8.6 46.6± 12.5 39.5± 9.6 26.8± 7.8 20.9 <1500	27.8± 6.4 38.0± 3.7 48.0± 17.9 31.7± 4.6 90.9± 43.7 14.1 ≤1200

Appendix 4: The correlation relationship of *E. coli* and total coliform between roofing materials from the three sampling areas

Target Organisms	Univen samples		Sibasa samples		Tshikhudini samples	
	Order	P	Order	P	Order	P
E. coli	Slate vs aluminum	0.203	Slate vs aluminum	0.816	Slate vs aluminum	0.587
	Slate vs steel	0.326	Slate vs steel	0.710	Slate vs steel	0.087
	Slate vs concrete	0.771	Slate vs concrete	0.816	Slate vs concrete	0.033
	Steel vs concrete	0.391	Slate vs thatched	0.217	Slate vs thatched	0.003
	Steel vs aluminum	0.739	Thatched vs aluminum	0.021	Thatched vs aluminum	0.002
	Concrete vs aluminum	0.340	Thatched vs steel	0.005	Thatched vs steel	0.009
			Thatched vs concrete	0.034	Thatched vs concrete	0.006
			Concrete vs aluminum	0.989	Concrete vs aluminum	0.013
			Concrete vs steel	0.847	Concrete vs steel	0.427
			Steel vs aluminum	0.810	Steel vs aluminum	0.027

Total coliform	Slate vs aluminum	0.248	Slate vs aluminum	0.983	Slate vs aluminum	0.972
	Slate vs steel	0.133	Slate vs steel	0.676	Slate vs steel	0.464
	Slate vs concrete	0.457	Slate vs concrete	0.938	Slate vs concrete	0.114
	Steel vs concrete	0.368	Slate vs thatched	0.089	Slate vs thatched	0.000
	Steel vs aluminum	0.435	Thatched vs aluminum	0.034	Thatched vs aluminum	0.000
	Concrete vs aluminum	0.816	Thatched vs steel	0.006	Thatched vs steel	0.000
			Thatched vs concrete	0.033	Thatched vs concrete	0.000
			Concrete vs aluminum	0.892	Concrete vs aluminum	0.133
			Concrete vs steel	0.619	Concrete vs steel	0.367
			Steel vs aluminum	0.468	Steel vs aluminum	0.486

Appendix 5: The correlation relationship of *E. coli* and total coliform between the different roof types of different sampling areas

Target Organisms	Order	P
E. coli	Univen slate vs Sibasa slate	0.49
	Univen slate vs Tshikhudini slate	0.50
	Sibasa slate vs Tshikhudini slate	0.38
	Univen steel vs Sibasa steel	0.42
	Univen steel vs Tshikhudini steel	0.37
	Sibasa steel vs Tshikhudini steel	0.62
	Univen concrete vs Sibasa concrete	0.73
	Univen concrete vs Tshikhudini concrete	0.75
	Sibasa concrete vs Tshikhudini concrete	0.89
	Univen aluminum vs Sibasa aluminum	0.48
	Univen aluminum vs Tshikhudini aluminum	0.11
	Sibasa aluminum vs Tshikhudini aluminum	0.14
	Univen Thatched vs Sibasa Thatched	0.06
Total coliform	Univen slate vs Sibasa slate	0.56
	Univen slate vs Tshikhudini slate	0.94
	Sibasa slate vs Tshikhudini slate	0.54
	Univen steel vs Sibasa steel	0.20
	Univen steel vs Tshikhudini steel	0.17
	Sibasa steel vs Tshikhudini steel	0.89
	Univen concrete vs Sibasa concrete	0.87
	Univen concrete vs Tshikhudini concrete	0.99
	Sibasa concrete vs Tshikhudini concrete	0.84
	Univen aluminum vs Sibasa aluminum	0.88
	Univen aluminum vs Tshikhudini aluminum	0.19
	Sibasa aluminum vs Tshikhudini aluminum	0.28
	Univen Thatched vs Sibasa Thatched	0.84

Appendix 6: Heavy metals results for aluminium roofing in mg/L

	Univen 1	**Univen 2**	**Univen 3**	**Univen 4**	**Sibasa 1**	**Sibasa 2**	**Sibasa 3**	**Sibasa 4**	**Tshikhudini 1**	**Tshikhudini 2**	**Tshikhudini 3**	**Tshikhudini 4**
B	BDL	25.46	BDL	24.58	13.46	BDL	BDL	BDL	BDL	7.45	BDL	6.28
Al	5.86	11.62	BDL	9.64	28.13	BDL	BDL	BDL	BDL	14.82	6.56	6.56
V	0.19	0.31	0.22	0.56	0.50	0.09	0.19	0.09	0.13	0.51	0.22	0.77
Cr	0.40	0.54	1.49	0.38	0.54	7.88	3.40	3.73	0.39	0.73	0.49	0.53
Mn	1.81	22.03	3.84	16.89	1.70	2.00	4.60	2.16	0.41	10.11	1.96	2.40
Fe	4.07	13.44	3.71	32.25	13.01	7.96	3.46	3.34	2.95	11.00	11.77	17.54
Co	0.13	0.29	0.10	0.24	0.07	0.18	0.08	0.10	0.03	0.29	0.04	0.08
Ni	0.42	2.19	0.35	0.78	1.11	0.90	0.44	0.34	0.56	0.80	0.38	0.60
Cu	BDL	BDL	BDL	1.69	6.63	BDL	BDL	BDL	BDL	2.95	2.34	9.11
Zn	626.23	431.41	588.84	760.80	152.40	1634.80	932.80	2332.78	327.12	56.82	12.98	171.03
As	BDL	0.07	BDL	0.13	0.16	BDL	0.07	BDL	0.09	0.21	0.10	0.11
Se	0.07	0.11	BDL	0.10	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Mo	0.06	0.05	0.03	0.06	0.12	0.05	0.04	0.02	0.04	0.19	0.09	0.16
Cd	0.04	0.02	0.01	0.02	0.01	0.07	0.03	0.05	0.01	0.05	0.02	0.01
Sn	0.05	0.15	0.03	0.16	0.26	0.27	0.08	0.03	0.04	0.12	0.07	0.14
Sb	0.97	1.09	1.18	1.16	1.13	2.19	2.29	3.17	1.09	1.99	1.07	1.26
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Pb	BDL	2.00	BDL	0.06	0.08	BDL	BDL	BDL	BDL	0.11	BDL	BDL

Appendix 7: Heavy metals results for Concrete roofing in mg/L

	Univen 1	**Univen 2**	**Univen 3**	**Univen 4**	**Sibasa 1**	**Sibasa 2**	**Sibasa 3**	**Sibasa 4**	**Tshikhudini 1**	**Tshikhudini 2**	**Tshikhudini 3**	**Tshikhudini 4**
B	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	7.71
Al	BDL	7.00	30.34	11.22	BDL	6.59	23.39	21.37	21.88	6.60	BDL	BDL
V	0.29	0.39	0.38	0.62	0.15	0.07	1.88	1.67	0.50	0.14	0.12	0.08
Cr	0.41	0.59	0.48	0.72	0.50	0.49	0.77	0.78	0.68	0.64	0.55	0.52
Mn	1.86	15.03	9.76	3.30	2.24	1.77	1.67	1.60	4.22	2.01	0.98	1.29
Fe	BDL	6.41	7.02	21.11	1.84	9.73	7.88	5.76	14.03	4.26	5.21	5.81
Co	BDL	0.14	0.17	0.04	0.07	0.04	0.13	0.13	0.08	0.05	0.03	0.05
Ni	BDL	0.30	BDL	0.36	0.31	0.47	0.82	0.63	0.50	0.48	0.96	0.35
Cu	BDL	BDL	BDL	BDL	BDL	1.75	5.25	5.21	BDL	BDL	12.40	BDL
Zn	5.20	3.85	4.38	6.41	2276.86	97.72	22.47	89.68	17.50	27.67	9.29	7.06
As	BDL	0.04	0.05	0.10	0.04	0.07	0.06	0.14	0.06	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL	0.09	0.10	BDL	0.12	BDL	BDL	BDL	BDL
Mo	0.02	0.02	0.02	0.02	0.03	BDL	0.04	0.02	0.03	0.02	BDL	0.02
Cd	BDL	BDL	0.01	0.02	0.04	0.02	0.01	0.02	BDL	0.12	0.04	0.02
Sn	0.07	0.14	0.04	0.05	BDL	0.04	0.05	0.03	0.06	0.04	0.10	0.05
Sb	0.91	0.86	0.92	1.10	0.89	1.01	1.11	1.07	1.14	1.06	1.01	0.89
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	0.15	0.07	0.12	0.06	BDL	BDL	BDL	BDL

Appendix 8: Heavy metals results for Slate roofing in mg/L

	Univen 1	**Univen 2**	**Univen 3**	**Univen 4**	**Sibasa 1**	**Sibasa 2**	**Sibasa 3**	**Sibasa 4**	**Tshikhudini 1**	**Tshikhudini 2**	**Tshikhudini 3**	**Tshikhudini 4**
B	10.57	BDL	BDL	BDL	22.75	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Al	10.97	BDL	BDL	BDL	11.49	BDL	18.83	BDL	BDL	72.85	5.62	BDL
V	0.25	0.07	0.23	0.05	0.48	0.09	0.25	0.13	0.12	0.93	0.12	0.07
Cr	0.64	0.60	1.13	0.55	0.87	0.69	0.92	0.60	0.82	1.06	0.77	0.59
Mn	3.39	1.82	5.15	2.32	12.37	2.27	5.66	3.79	8.60	5.50	2.58	5.22
Fe	12.66	5.59	27.49	4.48	24.56	4.42	8.98	2.62	8.87	9.92	3.26	7.19
Co	0.05	0.07	0.08	0.14	0.33	0.14	0.22	0.10	0.17	0.12	0.18	0.07
Ni	0.37	0.32	0.58	0.38	1.01	0.36	0.48	0.32	0.71	0.43	0.59	BDL
Cu	BDL	BDL	BDL	BDL	2.31	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Zn	15.94	22.34	230.94	31.82	542.64	1532.33	2413.80	217.10	2675.75	65.65	4358.37	106.86
As	0.04	BDL	BDL	BDL	0.09	0.04	0.05	0.08	0.05	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Mo	0.03	0.02	0.02	BDL	0.04	0.20	0.16	0.07	0.07	0.05	0.04	0.03
Cd	BDL	0.03	0.05	0.08	0.21	0.24	0.06	0.02	0.08	0.05	0.28	0.01
Sn	0.06	0.03	0.06	0.07	0.14	0.08	0.04	0.05	0.04	0.08	0.10	0.03
Sb	0.88	0.95	1.16	1.09	0.94	1.38	1.18	1.00	0.94	0.98	0.82	1.14
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	0.17	0.36	0.30	BDL	0.07	BDL	0.10	BDL

Appendix 9: Heavy metals results for Steel roofing in mg/L

	Univen 1	**Univen 2**	**Univen 3**	**Univen 4**	**Sibasa 1**	**Sibasa 2**	**Sibasa 3**	**Sibasa 4**	**Tshikhudini 1**	**Tshikhudini 2**	**Tshikhudini 3**	**Tshikhudini 4**
B	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	6.85	BDL	BDL	BDL
Al	BDL	129.59	47.31	117.94	BDL	BDL	136.35	BDL	11.72	BDL	BDL	BDL
V	0.09	0.73	0.38	0.79	0.16	0.14	0.31	0.07	0.18	0.18	0.13	0.50
Cr	0.70	0.69	0.84	0.87	0.62	1.03	1.11	0.90	0.86	0.78	0.82	1.01
Mn	1.43	28.69	16.37	59.67	6.17	3.48	47.53	3.29	7.04	0.73	0.55	5.05
Fe	5.40	64.36	24.21	41.86	3.68	2.65	191.70	2.00	20.40	BDL	BDL	4.00
Co	0.04	1.02	0.58	1.97	0.09	0.09	1.35	0.10	0.14	0.05	0.04	0.18
Ni	BDL	0.85	0.64	1.42	0.32	0.40	1.13	0.34	0.44	0.59	0.74	0.52
Cu	BDL	4.38	2.14	5.63	BDL	BDL	5.49	BDL	BDL	BDL	BDL	BDL
Zn	75.83	69.28	37.57	86.43	531.59	220.47	762.21	225.97	258.94	410.27	387.06	81.31
As	BDL	0.13	0.10	0.15	0.08	BDL	0.07	BDL	BDL	0.08	0.04	0.11
Se	BDL	BDL	0.08	0.10	BDL	BDL	0.09	BDL	BDL	BDL	BDL	BDL
Mo	0.02	0.03	0.03	0.05	BDL	BDL	BDL	0.03	0.03	BDL	BDL	0.04
Cd	0.01	0.05	0.06	0.17	0.04	0.03	0.17	0.03	0.05	0.06	0.04	0.03
Sn	BDL	0.03	0.06	0.06	BDL	0.05	BDL	BDL	0.09	BDL	BDL	0.04
Sb	1.13	0.64	0.91	0.76	0.69	0.92	0.94	0.83	0.91	0.72	0.63	0.81
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Pb	BDL	0.70	0.79	0.57	BDL	BDL	0.69	BDL	BDL	BDL	BDL	BDL

Appendix 10: Heavy metals results for thatched roofing in mg/L

	Univen 1	**Univen 2**	**Univen 3**	**Univen 4**	**Sibasa 1**	**Sibasa 2**	**Sibasa 3**	**Sibasa 4**	**Tshikhudini 1**	**Tshikhudini 2**	**Tshikhudini 3**	**Tshikhudini 4**
B	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	10.76	6.09
Al	BDL	15.30	BDL	88.52	21.70	13.77	19.66	13.14	12.68	13.04	29.50	82.27
V	0.13	0.29	0.14	0.56	0.35	0.16	0.36	0.36	0.32	0.37	1.06	0.78
Cr	0.72	0.74	0.65	0.98	0.80	0.85	0.88	0.94	1.01	0.79	2.53	1.45
Mn	0.34	6.00	3.63	34.36	11.04	5.71	6.99	5.62	6.14	6.11	5.59	41.30

Fe	BDL	12.29	7.50	22.21	8.44	15.46	19.56	17.31	16.20	17.57	41.99	71.70
Co	0.04	0.13	0.09	0.81	0.33	0.14	0.25	0.16	0.20	0.17	0.23	0.91
Ni	0.36	0.36	0.31	0.74	0.53	0.58	0.70	0.70	0.78	0.45	1.36	1.42
Cu	BDL	BDL	BDL	2.49	1.14	BDL	1.36	BDL	BDL	BDL	7.65	4.49
Zn	325.27	93.10	123.63	76.22	37.62	41.27	41.73	38.00	43.75	31.97	9.53	19.23
As	0.08	0.06	0.07	0.06	0.08	BDL	0.05	0.05	0.04	BDL	19.72	1.26
Se	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.07
Mo	0.02	0.04	BDL	0.03	0.02	BDL	0.06	0.02	BDL	0.02	0.09	0.04
Cd	0.02	0.05	0.04	0.08	0.06	0.14	0.02	0.16	0.19	0.05	0.05	0.06
Sn	BDL	0.03	BDL	0.04	0.03	0.06	0.06	0.08	0.06	0.04	0.10	0.13
Sb	0.67	0.83	0.76	0.78	0.74	0.67	0.79	0.71	0.83	0.83	0.89	0.87
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	0.10	BDL	BDL	0.05	BDL	BDL	BDL	BDL	0.12

Appendix 11: VDM monthly average rainfall data (1996-2020)

Months	**VDM rainfall data records in different months (mm)**								
	1996	1999	2002	2005	2008	2011	2014	2017	2020
Jan		183.5	86	37.3	136.1	292.3	307.2	204.7	142.6
Feb		169.7	5.3	9.6	98.9	2	83.6	174	256.4
Mar		93.1	14.5	38.7	80.6	9.2	272.5	44.6	12.6
Apr		31	79.5	52.1	40.1	154.6	10.4	63.7	36.2
May		12.7	0	1.9	0.2	18.4	8.7	3.1	0
Jun		5.6	24.4	2.4	21.9	2.4	0.2	0	3.2
Jul		38.3	0	3.7	23.8	18.1	0.7	1	1.2
Aug		5	12.9	7.6	4.6	17.1	0	5.2	25.8
Sep		7.1	14.7	0	0.1	0.6	7.7		41.4
Oct	49.2	76.8	111.7	11.7	5.4	47.3	25.7		55.6
Nov	61.9	0	37.6	84.6	89	153	49.2	10.8	58.2
Dec	120.9	0	166.3	175.2	99	110.5	219.7	66	184.4
Annual	-	622.8	552.9	424.8	599.7	825.5	985.6	573.1	817.6