VULNERABILITY OF ZAMBEZI BASIN HEADWATERS TO PONTETIAL CONTAMINATES: A CASE STUDY OF IKELENGE DISTRICT, NORTH-WESTERN PROVINCE, ZAMBIA

By

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DECLARATION

This thesis was submitted in accordance with the rules and regulations governing the award of the Masters of Science in Integrated Water Resources Management of the University of Zambia. I Further declare that the thesis has neither in part nor in whole been presented as substance, for the award of any degree, either to this or any other University. Where other people's work has been drawn upon, acknowledgement has been made.

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ABSTRACT

Vulnerability refers to the degree to which human and environmental systems are likely to experience harm due to perturbation or stress. This study investigates the vulnerability of Zambezi headwaters in Ikelenge District, North-Western Province of Zambia, to potential contaminants using Geographic Information Systems (GIS), remote sensing (RS), Analytical Hierarchy Process (AHP), literature reviews, surveys and ground truthing. Experts from various sectors were consulted, contributing to weighting factors for vulnerability parameters.

Key vulnerability factors identified include land use, precipitation, slope and groundwater depth. High vulnerability was found at Lwiinga and Chinyazhi tributaries, largely due to extensive agricultural activities. Moderate vulnerability was observed at Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji, and Jimbe tributaries, whereas the Zambezi Source and Kangwadi Tributary showed low vulnerability due to substantial forest cover. By assessing the slope, which indirectly reflects drainage patterns, the study captures how natural topography and land use interact to influence runoff and water infiltration, contributing to overall vulnerability.

The study identified low pH, low dissolved oxygen and high levels of fecal and total coliforms as major contaminants in the Zambezi headwaters. These issues arise from factors such as land use, precipitation, surface slope and depth to groundwater. Water quality indices indicated moderate to good quality, with significant seasonal variations. Measures by the Zambian Government, Private Sector, and Non-Governmental Organisations are essential for protecting the Zambezi headwaters and maintaining ecological balance. Additionally, the study recommends that academic and research institutions, such as the University of Zambia, conduct comprehensive research on groundwater, surface water, climate change, and biodiversity in the region to enhance public awareness of their interrelationships and environmental impacts.

DEDICATION

To my loving mum, Delia Njobvu,

You are not only my mother, but also my guiding light, my pillar of strength, and the embodiment of unconditional love. Throughout my journey, you have been my constant source of inspiration and support, always cheering me on with unwavering belief in my abilities.

Your selflessness, kindness, and boundless affection have shaped me into the person I am today. Your wisdom and encouragement have propelled me to overcome challenges and reach for the stars.

You have sacrificed so much for my well-being and success, and I am forever grateful for the countless sacrifices you have made to ensure my happiness and fulfilment.

In every triumph and every setback, you have stood by my side, offering comfort, understanding, and reassurance. Your unwavering faith in me has given me the strength to persevere and the confidence to chase my dreams.

Thank you, Mum, for being my rock, my confidante and my best friend. Your love and support have been the foundation upon which I have built my aspirations. I dedicate this thesis to you with all my heart, knowing that your love and blessings will forever guide me on this journey called life.

With deepest love and gratitude

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ACRONYMS AND ABBREVIATIONS

AEZ	Agro-Ecological Zones
Gis	Geographical Information System
BOD	Biological Oxygen Demand
CSO	Central Statistics office
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DO	Dissolved Oxygen
DRASTIC	D- depth, R- recharge rate, A- aquifer, S- soil, T-topography, I- impact C- aquifer’s hydraulic conductivity
EC	Electro Conductivity
GIZ	Deutsche Gesellschaft fur International Zusammenarbeit
GPS	Ground Control Points
HOP	Hazard of the Place
HCA	Hierarchical Cluster Analysis
IPCC	Intergovernmental Panel on Climate Change
IMWQ	Integrated Multi-Parameter Water Quality Index
IWRM	Integrated Water Resource Management
LULC	Land Use/ Land Cover
MLC	Maximum Likelihood Classification
N	Nitrogen
NPCC	National Policy on Climate Change
NPE	National Policy on the Environment

NSTC	National Science and Technology Council
NWASSP	National Water Supply and Sanitation Policy
OLI	Operational Land Imager
P	Phosphorous
PAR	Pressure and Release
PCA	Principal Component Analysis
pH	Potential of Hydrogen
PCSM	Point Count System Model
REDD+	Reduction Emission from Deforestation and Forest Degradation
RHM	Risk Hazard Model
SPPSS	Statistical Package for Social Sciences
SWAT	Soil and Water Assessment Tool
TDS	Total Dissolved Solids
TSS	Total Suspected Solids
USA	United States of America
WARMA	Water Resource Management Authority
WHO	World Health Organization
WRASTIC	W- waste, R- recreation, A- agriculture, S- size, T- transportation, I- Industrials, C- vegetative Cover
WQI	Water Quality Index
WWF	Worldwide Fund
ZRA	Zambezi River Authority

CHAPTER 1: INTRODUCTION

1.1 Background

Water vulnerability to potential contamination is a global concern, as highlighted by Zhao et al. (2020). The Zambezi headwaters are also facing threats, as safeguarding water resources encounters significant challenges (Macdonald, 2007). The management of these headwaters is of paramount importance due to their extensive catchment area and their significant role as a primary water source. Despite their critical significance, headwaters have frequently been overlooked, even though they have a substantial influence on downstream regions and their ecological importance during the transition from hillslopes to channels (Coe, 2007). Effectively managing these headwaters is essential to ensure access to safe water, which is necessary for all forms of life (Set et al., 2018).

Headwaters are frequently exploited for drinking water (Zhao et al., 2020). In Zambia, water contamination adversely affects not only humans but also plants and animals. The degradation of rivers, streams and lake ecosystems due to water contamination has engendered outbreaks of fatal and contagious diseases (Mba, 2019). Although some water pollution can be attributed to natural processes, human activities stand as the predominant cause of water contamination. The discharge of wastewater resulting from agricultural, industrial and domestic practices further exacerbates the vulnerability of these water bodies (Mba, 2019). Additionally, water vulnerability exhibits dynamism and can be influenced by diverse geological materials and glacial deposits (Flaathen, 2009). Research into surface water vulnerability initially emerged from groundwater studies introduced by Albinet in the 1970s, and subsequently expanded to surface water and entire water systems (Set et al., 2018). The International Panel on Climate Change (IPCC) in 1996 linked water vulnerability to climate change further fuelled exploration into the effects of climate change and human activities on water resources (Set et al., 2018). Following the IPCC framework prompted increased research into water resource vulnerability. In Zambia, Mumeka's study in 1986 examined the influence of deforestation and subsistence agriculture on runoff in the Kafue River Headwater, a Tributary of the Zambezi River Basin. The study revealed the significant impact of these activities on runoff and streamflow in the Kafue River headwaters (Mumeka, 1986).

Various methodologies have emerged to assess water vulnerability, for instance, Jabbar (2019) in the assessment and prediction of surface water vulnerability from non-point source pollution in Midwestern watersheds identified six key factors and these include, land use, soil type, average annual precipitation, slope, depth to groundwater and bedrock type to predict and assess surface water vulnerability. Studies such as Maleki et al., (2020) in the Assessment of Water Pollution in the Gorgan Bay Catchment employed the WRASTIC method. The WRASTIC method is a comprehensive approach used to evaluate the vulnerability of water resources to contamination, the acronym is based on seven parameters that affect water quality these include: wastewater; recreational activities; agriculture; watershed size; transportation avenues; industrial activities; and vegetative groundcover to assess vulnerability to surface water contamination. Similarly, a study done by Sikder, (2015) in, Sapporo Japan used the Innovative Integrated Multi-Parameter Water Quality Index (IMWQI) to quantify water vulnerability to pollution, considering dominant parameters like potential hydrogen (pH), electrical conductivity, nitrate, phosphate, escherichia coli and trace elements. Chen et al. (2020) employed Pearson Correlation to study alterations in land use and water quality in Algeria's Mitidja Watershed. However, there appears to be a notable gap in some of these approaches, especially when it comes to handling of environmental influences and the incapacity to calculate vulnerability in the absence of a certain element. Addressing this limitation, the Analytical Hierarchy Process (AHP) offers a valuable advantage. AHP provides a structured and systematic framework for decision-making that allows for the integration of various factors and criteria (Saaty, 1980; Jabbar, 2019). AHP enables the comparison and prioritization of factors based on their relative importance, facilitating the incorporation of both quantitative and qualitative data. In situations where specific factors are missing, AHP allows for the systematic consideration of available factors and their relative weights, ensuring that the assessment remains comprehensive and robust even in the absence of certain elements. Hence this method was used in this study, allowing for factor weighting and rating calculation (Saaty, 1980).

This research concentrated on Ikelenge District, North-Western Province of Zambia and sought to identify potential contaminants and assess vulnerability by utilizing primary and secondary data using Statistical Package for Social Sciences (SPSS version 25) and Geographic Information System (ArcGIS10.7.1). The study results aim to enhance community comprehension of water contamination and guide decision makers on the conservation of the Zambezi River headwaters. This study adopted the Human-Environment vulnerability framework rooted with three principles and these include, exposure, sensitivity and adaptations (Turner et al., 2003). The study's objectives align with the three principles of the human-environment vulnerability framework. Additionally, this study thereby contributes to water resource management knowledge and informs sustainable policy frameworks for water resource management and allocation.

1.2 Problem Statement

The Zambezi headwaters in Ikelenge District, North-Western Province of Zambia, known for its conservation significance, face escalating human activities and environmental changes, leading to the degradation of freshwater ecosystem services and vulnerability of the headwaters (Murisa, 2020). Despite the appearance of intact terrestrial and forest ecosystems, the unsustainable use of forest resources, including land clearing through late burning and tree bark harvesting, threatens water conservation efforts (Kabwe, 2016). Additionally, contamination from agro-chemicals, erosion and the impacts of climate change, such as floods and extended rainy seasons, further contribute to water quality threats (Jabbar, 2019; Macdonald, 2007; Neubert, 2011). Whereas the Zambezi River Basin Authority (ZRA) has policies for water management, water quality has not received adequate attention and an integrated approach to water quality management is lacking (Macdonald, 2007; Nyambe et al, 2018). This study aims to fill this knowledge gap by assessing the water quality of the Zambezi River headwaters, considering all aspects that impact water quality, including physical, chemical and biological parameters. By doing so, the research will contribute essential insights for effective water quality management and conservation of this important natural resource.

1.3 Aim of Study

This study aimed to investigate the vulnerability of the Zambezi headwaters to contaminants in the Ikelenge District, North-Western Province, Zambia.

1.4 Specific Objective

The specific objectives of this study were as follows:

i. To identify the potential contaminants affecting the vulnerability of the Zambezi River headwaters;
ii. To analyze the contamination vulnerability of the Zambezi River headwaters within the North-Western Province of Zambia; and
iii. To investigate the main adaptation measures implemented by the Government, Non-Governmental organizations and the Private Sector to mitigate or prevent vulnerability of the Zambezi River headwaters to contamination.

1.4 Research Questions

To align with the study aims and specific objectives, the following research questions were formulated:

i. What factors make the Zambezi River headwaters vulnerable to contamination? This question aims to identify the main reasons behind the region's vulnerability to contamination;

ii. Which areas of the Zambezi River headwaters are most at risk of contamination? By using spatial analysis and thorough assessment, the study seeks to pinpoint specific locations that are highly prone to contamination enabling targeted conservation efforts; and

iii. What measures are employed by Governmental and Non-Governmental organizations and Private Sector to prevent contamination in the Zambezi River headwaters? This question focuses on evaluating the effectiveness of existing strategies and policies in protecting water quality and ecological health. The goal is to identify successful practices and recommend improvements for sustainable watershed management.

Addressing these research questions, the study's findings contribution by informing policymakers, local communities and relevant stakeholders about the best practices and interventions needed to protect this important ecosystem from potential contaminants and maintain its ecological integrity for future generations.

CHAPTER 2: LITERATURE REVIEW

2.1 General Remarks

The main objective of this chapter is to review previous studies that have investigated the impact of various land uses, including agriculture, urbanization and hydrological factors such as runoff, precipitation and slopes on water quality. Additionally, the chapter discusses different vulnerability methods, plans and actions put in place to ensure water conservation in Zambia, as well as frameworks used in vulnerability studies.

2.2 Global Studies on the Impacts of Agriculture on Water Quality

Agriculture is a major global activity and a significant component of the world economy, but it has increasingly led to water quality degradation due to the release of pollutants (Jabbar, 2019). Pollutants such as phosphorus (P) and nitrogen (N) from animal feeding operations, manure, pesticides, fertilizers and other sources contaminate surface and groundwater during flow and percolation processes (Thalmann, 2021). Numerous studies have explored the relationship between agricultural activities and water quality, focusing on changes in land use and land cover (LULC) and their effects on parameters like turbidity, dissolved oxygen and temperature in rivers and streams. Other studies have investigated the impact of nutrient runoff into surface water (Driscoll et al., 2003), with some employing statistical analysis and modelling approaches to examine the relationships between watershed characteristics. For instance, Wilkison and Armstrong (2015) studied the impact of commercial fertilizers in the Lower Grand River and found high levels of agricultural chemicals like phosphorus (P) and nitrate (N) in water quality.

2.3 Global Studies on the Impact of Urbanization and Deforestation on Water Quality

Urbanization and deforestation have negative consequences on water quality (Wang et al., 2020). As urban areas expand, forest cover and grassland decrease, leading to reduced precipitation, increased surface runoff and influence the river flow patterns. These changes can cause riverbank erosion and increase sediment loads after heavy rainfall. Domestic sewage, industrial wastewater, surface runoff and municipal pipeline water discharged into rivers after rain contribute to nitrogen and phosphorus contamination, adversely affecting water quality and aquatic biodiversity (Bowden, 2015). Studies in different regions have shown correlations between urbanization and water quality parameters like biological oxygen demand (BOD), carbon oxygen demand (COD), conductivity factor (CF), turbidity (TU) and total suspended solids (TSS) (Estrada-Rivera et al., 2022; Chen et al., 2022). Intensity of urbanization, expressed as the ratio between urban land area and the total basin area, influences water quality (Wang et al., 2020).

2.4 Global Studies on the Impact of Hydrological Factors on Water Quality

Hydrological factors, such as precipitation, runoff and surface slopes, significantly affect water quality (Jabbar, 2019). Studies have demonstrated a strong relationship between water quality parameters and precipitation (Rostami, 2018). Pollution often occurs during leaching processes and the discharge of effluents (Revitt & Ellis, 2016). Streams and rivers in developing countries are heavily contaminated by effluent discharges resulting from various hydrological factors (Ionesiy, 2006). Surface slopes increase flow rates, causing soil erosion, sedimentation and transport pollutants like nutrients, pathogens and pesticides into nearby rivers (Croke, 2007). Landscape changes have been found to affect water quality, with correlations observed between water quality parameters like temperature, dissolved oxygen, nitrates, phosphates and copper (Zhao et al., 2020). This study builds upon previous research using validated methods like the weight and rating method.

2.5 Impact of Land use and Hydrological Factors on Water Quality in Zambia

In Zambia, water contamination has been affecting humans, plants, animals and the aquatic life (Mba, 2019). The ecosystem of rivers, streams and water sources is deteriorating due to water contamination from various sources. Human activities are the primary cause of the contamination, although certain natural processes may also contribute. For instance, a study by Nguvulu (2021) in the Upper Chongwe River Catchment of Zambia investigated the response of surface water quality to land use and land cover changes resulting from urbanization. Water samples were collected, remote sensing and ArcGIS were used to detect land use and land cover changes. The study revealed significant positive correlations between built-up and agriculture land with some water parameters, whereas forest cover and grassland showed significant negative correlations with most of the water quality parameters. However, the study only focused on land use and land cover changes as factors influencing water quality, neglecting other important aspects like precipitation and topography.

Another study by Mumeka (1986) explored the impact of deforestation and subsistence agriculture on the runoff of the Kafue River headwaters, a tributary to the Zambezi River Basin. The findings showed that deforestation and subsistence agriculture contributed to increased runoff and streamflow in the Kafue River headwaters, leading to changes in the flood hydrograph due to alterations in land use. However, the study did not consider water quality aspects, which this research seeks to investigate in relation to runoff from precipitation and land use. In a study by Winton et al. (2020) on anthropogenic influences on Zambian water quality, focusing on hydropower and land-use change in Zambezi River and Kafue headwaters, it was found that certain tributaries of both Zambezi River and Kafue River with significant anthropogenic land cover exhibited signs of pollution, such as higher concentrations of nutrients and dissolved ions. The study highlighted specific human activities as hotspots of degradation, indicating that certain areas within the watershed experience higher levels of pollution due to human influences.

Overall, these studies demonstrate the importance of understanding and addressing water quality issues in Zambia. This research aims to build upon and complement these previous studies by considering multiple factors like precipitation, land use, surface slope and depth to groundwater.

2.6 Assessment of Watershed Vulnerability

Quantifying the vulnerability to potential contaminants is crucial for identifying which rivers or streams are at higher risk of contamination (Jabbar, 2019). The most influential factors impacting water quality are changes in land use, topography, precipitation, hydrology and other landscape variables (Neupane, 2015). To assess watershed vulnerability effectively, hydrologists and environmental scientists are increasingly turning to convenient statistical techniques and risk indicators. Utilizing an appropriate model for watershed assessment is essential to evaluate continuous spatial and temporal variations in watershed information (Jabbar, 2019).

Over the years, various watershed assessment methods have been developed to evaluate the cumulative impacts of human activities and hydrological factors on watershed health and aquatic systems. One such method is the WRASTIC model, is based on seven parameters includes, wastewater, recreational activities, agriculture, watershed size, transportation avenues, industrial activities and vegetative groundcover to assess vulnerability to surface water contamination (Maleki et al., 2020). However, this method is limited to urban areas and cannot be adopted in rural or protected areas. Other studies have employed the Soil and Water Assessment Tool (SWAT) to assess potential land use changes and climate variability effects on hydrological processes in Big Sioux River (BSR) watershed in the United States of America (Neupane, 2015). This study builds on previous research by considering additional factors such as, land use, surface slope, precipitation and depth to groundwater.

Researchers have used weighted overlay, ArcGIS software's and Analytical Hierarchy Process (AHP) methods to assess watershed vulnerability to contamination (Jabbar, 2019). AHP provides a structured and systematic framework for decision-making that allows for the integration of various factors and criteria (Saaty, 1980). Specifically, AHP enables the comparison and prioritization of factors based on their relative importance, facilitating the incorporation of both quantitative and qualitative data. In the context of watershed vulnerability assessments, AHP is particularly useful. In situations where specific factors are missing, AHP allows for the systematic consideration of available factors and their relative weights, ensuring that the assessment remains comprehensive and robust even in the absence of certain elements. Hence, this method was used in this vulnerability study, allowing for factor weighting and rating calculation (Saaty, 1980). For instance, a study by Jabbar (2019) used the AHP method for vulnerability assessment by considering factors such as land use, soil type, average annual precipitation, slope, depth to groundwater, and bedrock type. This demonstrates the practical application of AHP in ensuring comprehensive and robust vulnerability assessments. Similarly, Innovative integrated multi-parameter water quality index (IMWQI) have been used to quantify water pollution, considering dominant parameters like potential hydrogen (pH), electrical conductivity (EC), nitrate, phosphate, escherichia coli and trace elements (Sikder, 2015). However, these indices may lack integrity and have limitations concerning their specific purposes, such as addressing community participation and the environmental impacts. Hence, this study used the questionnaire survey to fill this knowledge gap. Other studies in Indonesia Gajahwong watershed utilized mathematical models, the point count System model (PCSM) to assess contamination vulnerability (Widyastuti, 2006). Principal component analysis (PCA) has been employed to interpret water quality variations in surface ponds used for domestic purposes (Soneye, 2013). Additionally, the DRASTIC method, mainly applicable to groundwater studies, has been used to assess aquifer vulnerability (Barbulescu, 2020). The acronym DRASTIC stands for seven key factors that influence groundwater vulnerability which includes, depth to water, recharge (net), aquifer media, topography, impact of the vadose zone and conductivity (hydraulic) of the aquifer (Barbulescu, 2020). However, for this research, the focus lies on surface water vulnerability in relation to land use change and hydrological factors.

2.7 Measures Implemented at Global and Local level to Ensure Water Conservation

Globally, comprehensive measures are in place to counter water scarcity and pollution, through international collaboration, policy frameworks, technology and community involvement

(United Nations, 2010). The United Nations' Sustainable Development Goals (SDGs) serve as a foundation for water conservation and ecosystem protection (United Nations, 2010). International agreements like the Ramsar Convention and the United Nation Convention foster cross-border cooperation for sustainable water management (Ramsar Convention, 2008). Water efficiency initiatives cut across agriculture, industry and urban areas, advocating water-saving techniques and policies (FAO, 2018). Addressing water pollution, international efforts such as the Marine Pollution Convention (MPC) and the Global Programme of Action (GPA) minimize contamination from both land-based and marine sources (United Nations, 2022). Integrated Water Resource Management (IWRM) coordinates social, economic and environmental sustainability of water use (GWP, 2019). Community-led water action projects engage communities in water conservation at regional, national and local levels. Technological advancements, including efficient irrigation systems and real-time monitoring, support global water conservation efforts. Additionally, Smith and Johnson (2009) recommend establishing buffer distances of 50 meters for rivers to effectively protect headwaters. This distance has been shown to mitigate runoff and enhance water quality by providing a vegetative barrier that filters pollutants.

These collective actions globally safeguard and sustainably manage water resources, addressing pressing challenges for future generations. In Zambia, water conservation forms a crucial aspect of sustainable environmental management (GRZ, 2008). The Government policies aim to combat water pollution, deforestation and climate change. The Ministry of Water Development and Sanitation prioritizes budget increases for the Water Resources Management Authority (WARMA), allowing water monitoring, licensing enforcement and groundwater protection (GRZ, 2005). The Ministry of Lands' investment plan combats deforestation through the REDD+ strategy, adopting a landscape approach for balanced development (GRZ, 2017). Despite these efforts, community sensitization in water pollution reduction remains lacking. Policies may overlook local engagement, leaving communities unaware on the importance of water conservation. There is therefore a strong gap in rural communication, bridging this gap, the study seeks community engagement through interviews to raise conservation awareness.

2.8 Vulnerability Framework and Models

Due to different definitions and views on vulnerability have led to the development of a variety of theoretical frameworks and conceptual models. Some of the major frameworks and models are discussed below.

2.8.1 The Risk-Hazard (RH) Model

This model considers the hazard and its impact as a function of exposure to the hazard (Ii et al., 2003). This framework portrays vulnerability as not only registered by the exposure to stresses but also resides in the sensitivity and resilience of the system experiencing stress (Turner et al., 2003). The risk hazard model has mainly been used in studies that examine the effects of food insecurity and natural hazards on the natural environment (Eakin and Luers, 2006). This framework also has been used by different sectors such as engineers and economists to assess risks to certain valued elements, known as exposure units. The major disadvantage of this model is that it does not show how the underlying conditions of the system under study, rather the impacts of the threat as well as the role institutions and social structure play in shaping different exposure and consequences (Ii et al., 2003) in addition, it is always difficult to apply this model to people whose exposure depends mainly on their behaviours (Eakin and Luers, 2006). Figure 2.1 provides an overview of the data flow involved in the risk hazard model, the flow starts from (a) up to (e).

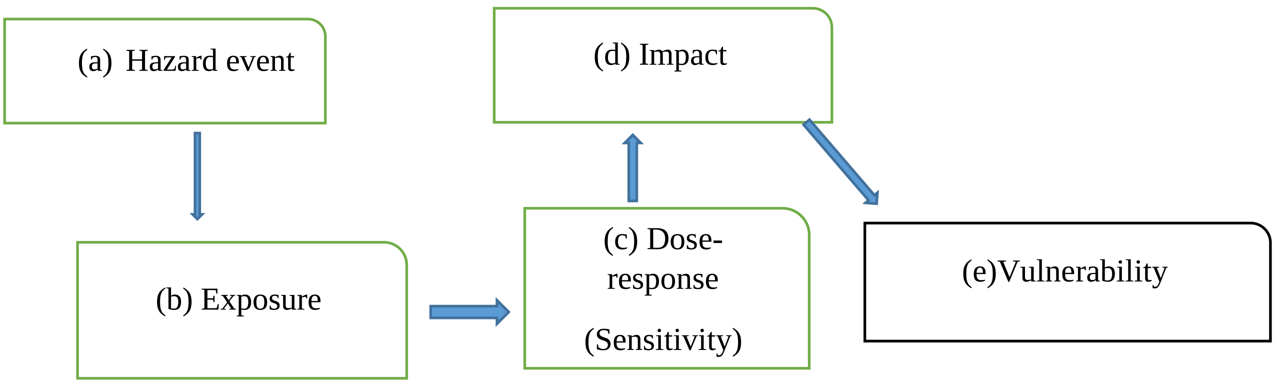

Figure 2.1: The risk hazard model adapted from (Turner et al., (2003) for vulnerability assessment.

2.8.2 The Pressure and Release (PAR) Model

This model was proposed by Blaikie (Cannon and Wisner, 2018) and developed further by Wisner (2022). Pressure and release model views vulnerability as the interaction between physical exposure to natural hazards and different processes that create vulnerability in different levels within a given society. This model presumes that vulnerability is between two major processes, pressure and release. The pressure aspect focuses on the root causes of vulnerability (Cardona et al., 2013; Tapsell et al., 2010) and the release aspect focuses on relieving the pressure to reduce vulnerability. The major drawback of this model is that it does not address the coupled human-environment systems when considering the overall vulnerability of the biophysical system and it focuses too much on the pressures with little emphasis on the releases that could increase resiliencies and overall coping capacity (Joakim et al., 2015).

2.8.3 The Hazard of Place Model (HOP)

This model was introduced by Carolina et al., (2015). The hazard of place model is composed of the biophysical and social components into a place-specific assessment of vulnerability (Cannon and Wisner, 2018). The biophysical view of this model deals with vulnerability related to the environment and its processes that generate hazard conditions and suggest that vulnerability is a pre-existing condition. From the social point of view, the patterns of vulnerability under this model are influenced by political powers, social relations and economic development, inclusive of indicators such as age, race, gender and income (Joakim, 2008).

2.8.4 The Double Structure Framework

This framework of vulnerability views vulnerability at both internal and external side (Gathongo, 2019). The external side of vulnerability involves exposures to environmental stress and mostly influenced by political economic approaches, human ecology perspectives and the entitlement theory. Most of these factors are largely beyond the control of a particular community (Gathongo, 2019). The internal side, also known as coping, has been described as the capacity of a system to cope with, anticipate, resist and recover from the impact of a disaster (Birkmann and Wisner, 2006). The internal is influenced by the crisis and conflict theory, in this case, groups of individuals who control key assets cope more effectively with disasters, making them less vulnerable (Paul, 2014). Therefore, the internal side focuses on the inner working of a community and their ability to respond to stress associated with the external side of vulnerability (Gathongo, 2019).

2.8.5 The Coupled Human- Environment Framework

The vulnerability framework developed by Turner et al., (2003), treats systems as coupled human environment systems, in this framework human and environmental systems interact and influence each other’s vulnerability with regards to exposure, sensitivity and resilience. Exposure consists of the different components of the human-environment system such as individuals, households, ecosystems, flora, fauna and the characteristics of the stress, inclusive of the magnitude, frequency, duration and area extent of a natural hazard, the higher the exposure the more vulnerable the community or system is and the lower the exposure the less exposure to vulnerability (Turner et al., 2003). Whereas developing the framework, Turner et al., (2003) noted that any vulnerability analysis, especially for studies aimed at advancing sustainability, should include the following elements: the exposure of the system beyond the presence of a perturbation and stress, the sensitivity of the coupled system to the exposures and the system's resilience or adaptions. Considering all the models above, the study adopted the coupled human- environment framework because it aliens with the study objectives. By adopting this framework, the study can better understand the complex relationship between humans and the environmental system and how they influence each other.

CHAPTER 3: DESCRIPTION OF THE STUDY AREA

3.1 Study Location

This study was conducted at the Zambezi River headwaters (Figure 3.1) in Ikelenge District, North-Western Province, Zambia. The Zambezi River is the fourth-longest river system in Africa, flowing into the Indian Ocean (Balek, 1977). The district covers an area of 2,284 km², including the Kalene hills and the Zambezi River Basin Source. It shares borders with Mwinilunga, Mufumbwe and Kabompo to the South, Angola to the North and the Democratic Republic of Congo to the Northeast. The district lies within latitude 10º50'S to 13º10'S and longitude 23ºE to 24º40'E (Kabwe, 2016). According to the 2019 Central Statistics (CSO, 2019), the district has a population of 32,919 people and an annual population growth rate of 2.5%.

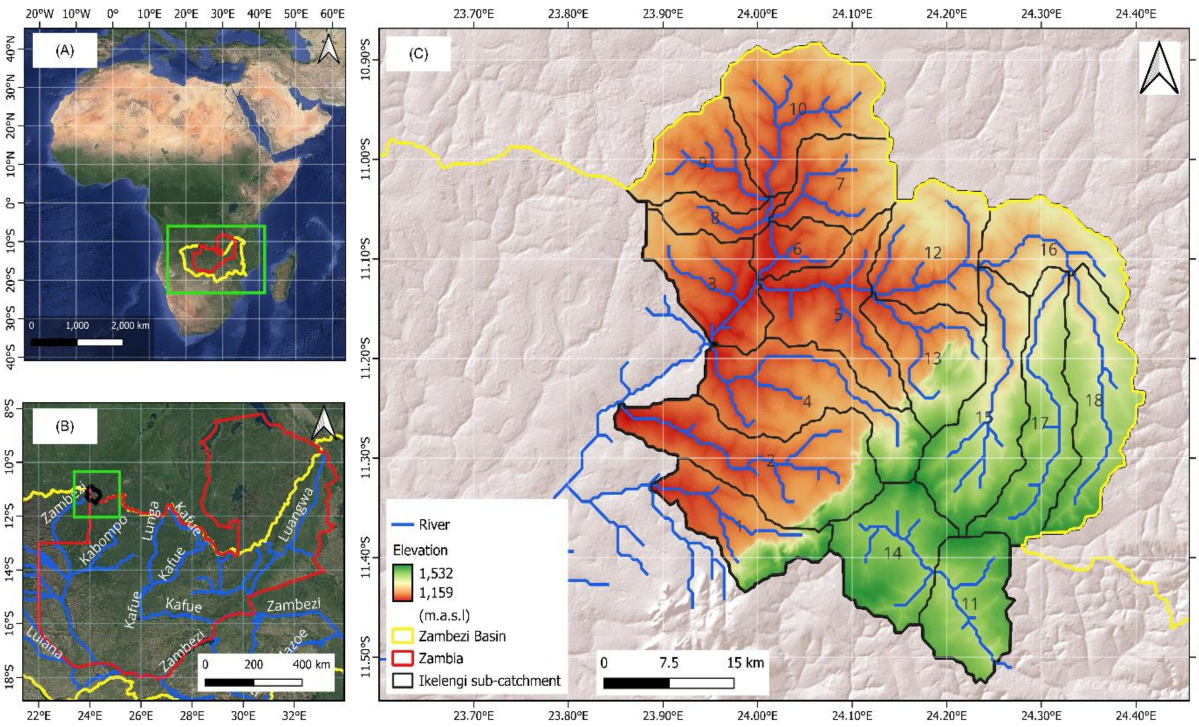

Figure 3.1: Map showing (a) location of the Zambezi Basin and Zambia in Africa, (b) location of Ikelenge Sub-basin in Zambezi Basin and (c) the Ikelenge sub-basin, North-Western Province, Zambia.

3.2 Physical Characteristics of the Study Area

The physical characteristics of the study area are described in terms of topography, hydrology, geology, climate (including rainfall, precipitation, humidity and evaporation), demography, soils, land cover, land use, language and economic activities.

3.2.1 Topography

The topography of Ikelenge District is diverse, reaching its highest point at approximately 1524 meters above sea level, making it the highest point in the North-Western Province, Zambia (Murisa, 2020). In the southern parts of the district, the altitude is about 458 meters above sea level. Moving northward, a watershed separates the Zambezi River and the Congo River, featuring various escarpments where the watershed descends into deep valleys. The watershed itself is characterized by flat plains. The West Lunga and Kabompo River in the southern part of the district exhibit steep escarpments and deep valleys, showcasing distinctive River Gorge vegetation (Murisa, 2020). These rivers in the district have minor rapids, rendering them unsuitable for navigation (Murisa, 2020). Overall, the topography of Ikelenge District encompasses high peaks, flat plains, escarpments and valleys, creating a diverse geographical landscape.

3.2.2 Hydrology

The Zambezi River is about 2,575 km in length from the headwaters to the coastal delta and has a catchment area of 1.32 million km^2, which includes portions of eight countries (Murisa, 2020). This makes it the largest river in Southern Africa, with a cumulative mean annual flow of the main stream and tributaries of approximately 97 m^3/s (Moore, 2007). The hydrology of the Zambezi Catchment is determined by the interplay of various factors. The annual variation in summer rainfall is due to the Intertropical Convergence Zone between the North-East Monsoon and the South-East Trades for the Middle and Lower Zambezi and the Congo Air Boundary between the South-West Monsoon and the South-East Trades for the Upper Zambezi River. The further south the two boundaries move, the greater the total delivery of rainfall (Andy, 2007).

The hydrology of the Zambezi River Basin is further influenced by water exploitation by different users. The catchment as a whole is relatively undeveloped so that off-take by irrigation, industrial and domestic users. However, usage by these sectors is more than offset by the increased runoff due to changes in land use, particularly since the middle of the last century (George, 2020).

3.2.3 Geology of the Study Area

The geology of Ikelenge District is predominantly characterized by hard, impermeable crystalline basement metamorphic and igneous rocks, along with indurated Palaeozoic sediments, which are widespread in the area (Macdonald, 2007). Within the Zambezi River

Basin, the Kalahari and Kendelunga rock units are prominent, covering extensive areas (Thieme, 1981) (Figure 3.2).

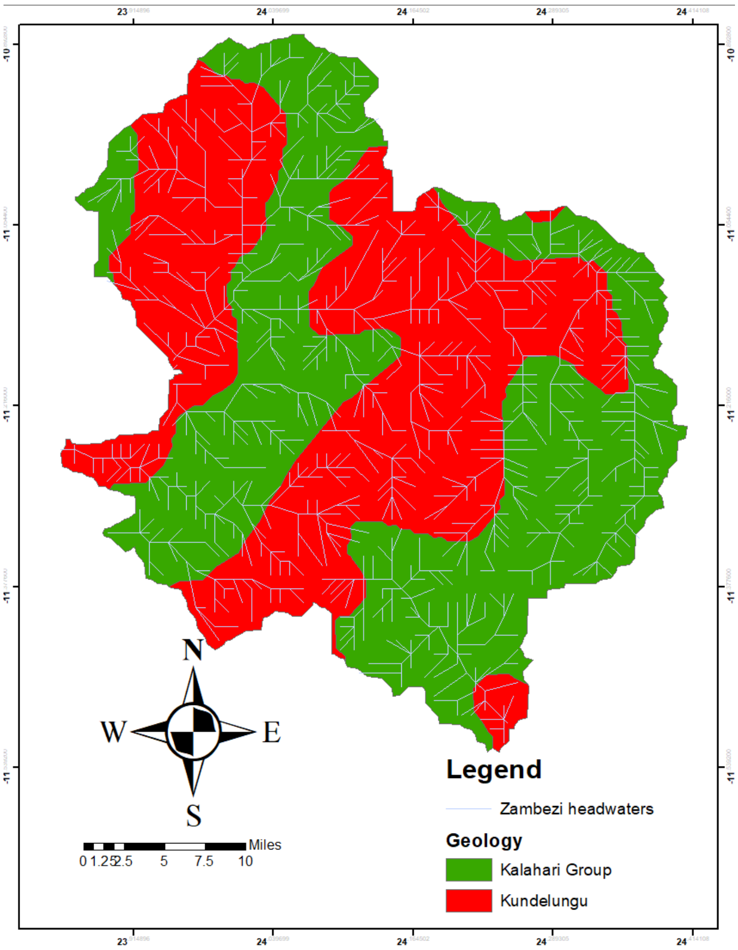

Figure 3.2: Map showing the geology of the Zambezi headwaters in Ikelenge District, North-Western Province, Zambia (adapted from Thieme, 1981).

The Kendelunga Group primarily consists of sedimentary rocks such as sandstones, siltstones, mudstones and minor conglomerates, reflecting diverse depositional environments over time (Thieme, 1981). In contrast, the Katanga Group in the region comprises sedimentary rocks, including shales, sandstones and conglomerates (Macdonald, 2007). This formation is notable for hosting most of Zambia's copper and cobalt deposits, concentrated around the periphery of the Palaeozoic sedimentary area (Macdonald, 2007).

Understanding the geological characteristics of the Ikelenge District is crucial for assessing the water quality and vulnerability of the Zambezi River headwaters, as the composition and distribution of these rock units significantly influence groundwater flow and surface water interactions.

3.2.4 Climate

The district experiences a relatively moderate climate influenced by humid air masses from the Congo Basin, which bring rain from October to April. The period from June to August is dry, with almost no rain. September and October are warm months, whereas the coolest months are from May to July (Civil et al., 2003).

(a) Rainfall Patterns

Ikelenge District historically experiences rainfall from October through April, with the number of rainy days being higher between November and March (Civil et al., 2003). The average annual rainfall in Ikelenge District is 1,500 mm. On average, there are 119 rainy days, typically from October to April, making Ikelenge one of the wettest districts in Zambia. Such amounts of rain have both negative and positive implications for the district. The abundance of water provides sufficient resources for streams and rivers (Civil et al., 2003). The historical rainfall trends of Ikelenge District in North-Western Zambia from 1981 to 2021 are illustrated in Figure 3.3 (Spark, 2021).

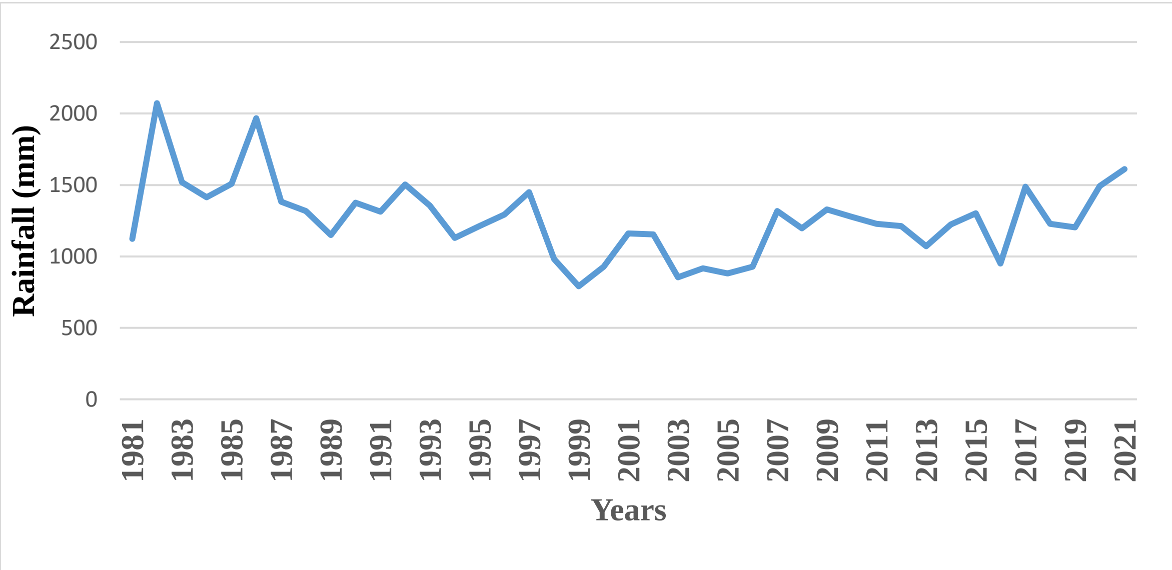

Figure 3.3: Historical rainfall trends of Ikelenge District, North-Western Province, Zambia (Spark, 2021).

The district falls in the Agro-Ecological Zone III (AEZ III) and receives an annual average precipitation of 1 000-1 600 mm (Lehner, 2020).

(b) Temperature

Ikelenge District of North-Western Province, Zambia is subjected to sub-tropical climate. The average temperature ranges from 10 to 20 degrees Celsius in winter whereas the maximum temperature goes up to 35 degrees Celsius (Chongo, 2022). These fluctuations are influenced by factors such as latitude, elevation, seasonal changes, local weather patterns and the region's topography (Lehner, 2020, figure 3.4).

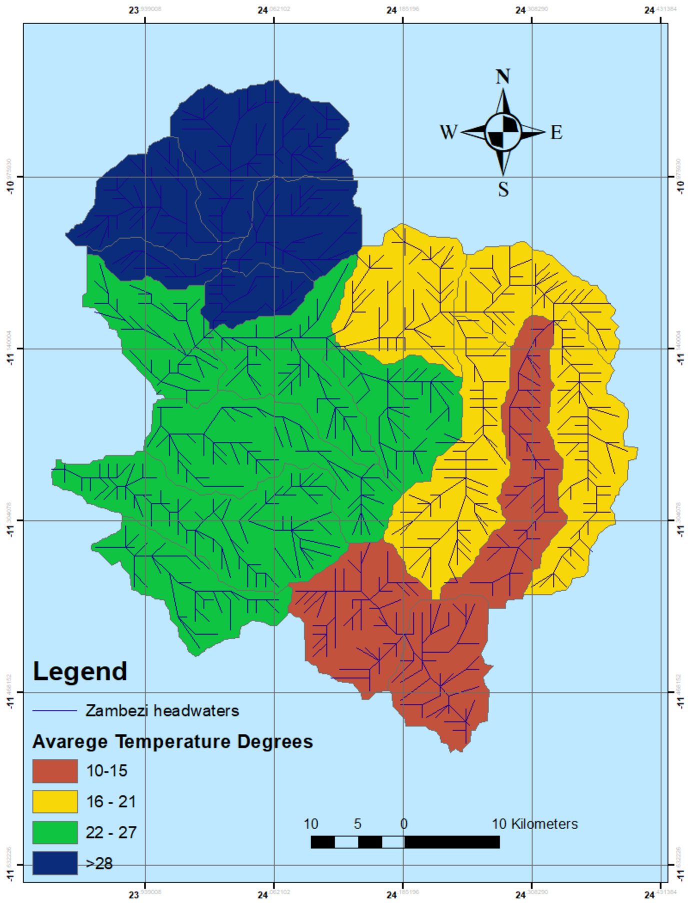

Figure 3.4: Map showing annual average temperature of the Zambezi headwaters in Ikelenge District, North-Western, Zambia (adapted from Lehner, 2020).

(c) Humidity and Evaporation

The mean relative humidity between December and March is 75% ranging from 40 to 70% from September to January respectively. The mean evaporation ranges from 120mm in February to 217mm in October. The average growing season for crops is about 90-160 days (Chongo, 2022).

3.3 Demography

The district office of the Central Statistics Office (CSO) estimated the population of the district to be 32,919 (CSO, 2019). The males comprise (47%) of the population and females comprise the remaining 53%. The population is concentrated between the age of 15 years and 49 years which constitute 43 per cent of the population. The district has a population density of 6 people per square kilometer. The current growth rate is 2.5 % per year. The main population centers are the district centers, around the chief's capitals, along the main roads and areas with the potential for production. Specific areas of high population are those along Mwinilunga Road and Jimbe Road (Bank, 2010).

3.4 The Soils of Ikelenge District North- Western Province, Zambia

The soils of Ikelenge District, North-Western Province of Zambia are described as being sand type of soil (Bank, 2010). The soils found in the valley are characterized as the Kalahari soils (Cambic Arenosols and Xanthic ferrolsols) and these soils are underlined by rocks of the Karoo Supergroup (Figure 3.5).

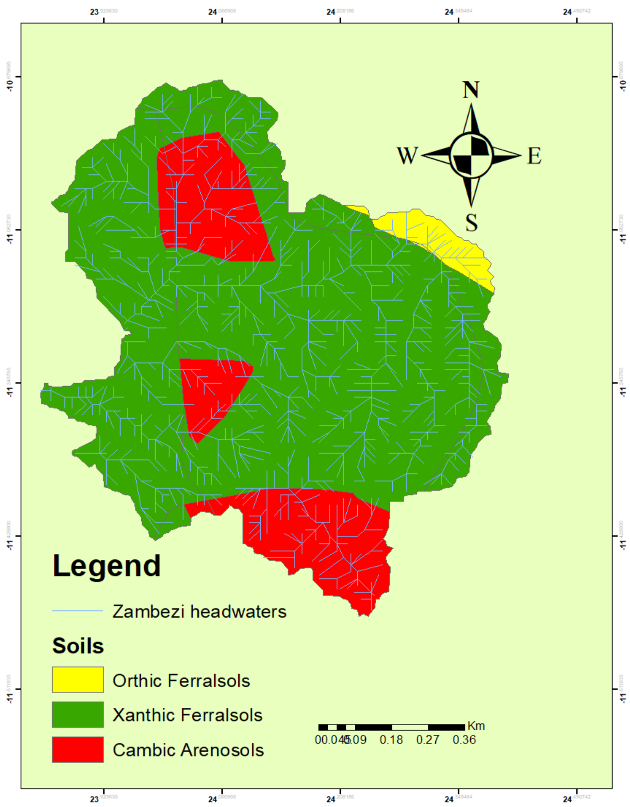

Figure 3.5: Figure 3.5: Soils of Ikelenge District, North-Western Province, Zambia. Source: Adapted from FAO (2018) shapefiles.

The sands are a Pleistocene Deposit, the erosion product of the weak upper Karoo sandstones. They vary in colour from pallid to orange, are moderately acidic and contain 3 to 12% silt plus clay. The sands are not very fertile, the nitrogen content is particularly low where the humus has been disturbed by cultivation. The Kalahari sands supports growth of vegetation which is of great value to local people both domestic and commercial uses (Bank, 2010).

3.5 Land Cover and Land Use of Ikelenge District, North-Western Province, Zambia.

The vegetation of Ikelenge District, North-Western Province of Zambia is predominantly grassland with breaks of semi-evergreen forest, evergreen forest, deciduous forest and shrub land. Other land cover types include mosaic cropland, water bodies and regularly flooded vegetation which covers the area (Day, 2014). The evergreen and semi-evergreen forest is composed of swamp and riparian woodlands whereas the deciduous forest is of Kalahari and woodlands. The major land use in this area includes agriculture, cattle grazing, timber production, small-scale miners and settlements (Day, 2014).

3.6 Languages and Economic Activities

The majority of the population in the district are Lunda's, one of the defining cultural features of the Lunda people is Mukanda Ceremony which is a boys' initiation ceremony (Day, 2014). The major settlement areas are along the main roads in Ikelenge District and substance agriculture is the major livelihood activity done in the district. Agriculture production is mostly on a small-scale with cassava being the major crop grown mainly for local consumption. Other crops grown on a small-scale is maize and beans. Beekeeping and honey production using traditional bark hives are other economic activities practised by the locals. Pineapples are also grown on a large scale by the majority of smallholder farmers (Civil et al., 2003). About 95% of the population is employed in the informal agricultural sector, whereas only 5% are engaged in formal employment (Civil et al., 2003).

CHAPTER 4: METHODOLOGY

4.1 General Remarks

This chapter outlines the study conceptual framework, primary and secondary data sources, sampling procedures and data analysis.

4.2 Study Conceptual Framework

This study utilize vulnerability framework concept developed by Turner et al., (2003). The framework treats systems as coupled human-environmental systems. In this system human and environmental subsystems interact and influence each other's vulnerability with regards to exposure, sensitivity and resilience. Figure 4.1 provides an overview of the data flow involved in the conceptual framework of this study; the flow starts from (a) up to (h).

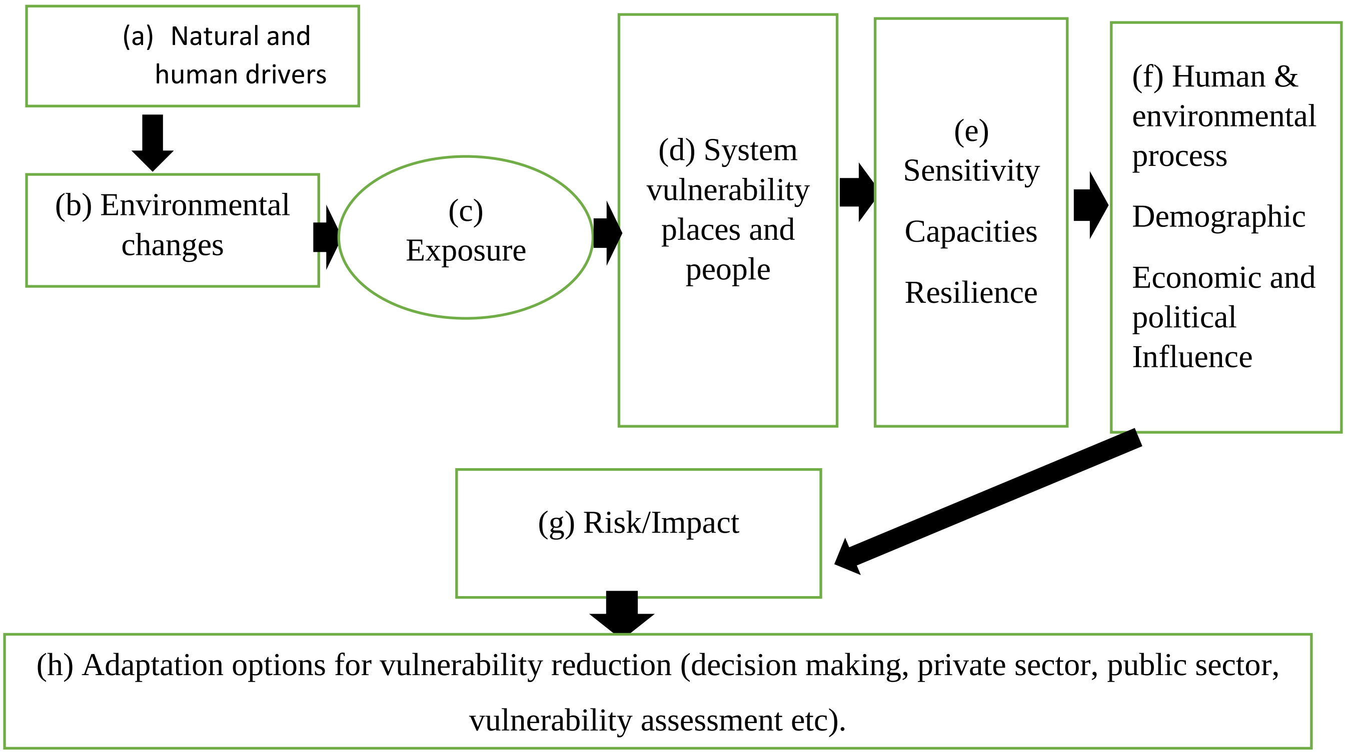

Figure 4.1: The coupled human- environment framework adapted from Turner et al.,(2003) was used in this study.

4.3 Sources of Data

Secondary Data Collection: A thorough review of existing literature was conducted to gather secondary data on factors influencing surface water vulnerability. This involved sourcing various published and unpublished documents, including research papers, reports, academic publications, from libraries and online databases. The collected secondary data provided valuable information on potential factors affecting surface water contamination risks, the relationship between different variables and water quality, vulnerability analysis methods and successful measures to mitigate potential contaminants.

The primary data: This data was collected through various methodologies, including the utilization of questionnaires, interview schedules, field observations and collection of surface water samples during both the dry and wet seasons. These methods aimed to identify potential contaminants affecting the vulnerability of the Zambezi headwaters by assessing local knowledge of conservation, understand the impact of nearby land use activities and identify stakeholders involved in conservation efforts.

The data collection process took place in several communities and villages within the study area, including Sokasoka Village, Kelonde Village, Yambezhi Village, Kankawami Village, Zambezi Main Source, Kagwandi Tributary, Matochi Tributary, Kanyizhiwu Tributary, Kasonka Tributary, Ilemena Tributary, Sakeji Tributary, Lwiinga Tributary, Chinyazhi Tributary and Jimbe Tributary. These locations were carefully selected to represent diverse areas within the Zambezi headwaters region, ensuring a comprehensive understanding of the water vulnerability across different settings.

Spatial Data: To comprehensively analyse surface water vulnerability, spatial datasets was utilized. Landsat 8 satellite images from 10 June 2021 to 10 December 2021 (http://ClimateEngine.org) were utilized to examine land cover and land use changes, which play a significant role in water quality. Additionally, shapefiles containing crucial environmental variables, such as surface slope, average annual precipitation and depth to groundwater along with its associated drainage network data were obtained from Hydro ATLAS Zambia (Lehner, 2020). The integration of spatial datasets allowed us to gain valuable insights into the spatial distribution of vulnerability factors.

4.3.1 Questionnaire

The questionnaire method is a crucial tool that allows researchers to gather valuable insights from specific groups, individuals, or entire populations (Young, 2015). It serves as an effective means of collecting diverse information from a large number of respondents. In this study, a well-structured questionnaire was utilized to gather data from the community of Ikelenge District in the North-Western Province of Zambia (Appendix 1).

The information collected through the questionnaire covered various aspects, including livelihood activities, land use practices, the community's involvement in water conservation, their perceptions of rainfall and temperature changes and their observations regarding how these changes impact water quality. Questionnaires were also conducted with Government officers from key line ministries involved in natural resources management, particularly water conservation and these ministries included: The Ministry of Water, Development and Sanitation; Ministry of Tourism; Ministry of Green Economy; Ministry of Lands and Natural Resources; Ministry of Agriculture; and the Ministry of Health. Private sector representatives, Non-Governmental Organizations and traditional leaders, through their representatives, were also interviewed included: The World-Wide Fund (WWF); The Deutsche Gesellschaft fur International Zusammenarbeit (GIZ); World Vison Zambia; Stanbic Bank; and Kansanshi Mine. The questionnaires covered topics such as stakeholders' objectives, their role in the conservation of the Zambezi headwaters, the effectiveness of current policies on water and land conservation, common land use types in the study area, ongoing research on water conservation, limitations in water conservation, community awareness on water conservation in the Zambezi headwaters and plans to mitigate vulnerability to potential contaminants (Appendix 2).

4.3.2 Field Observation

First and foremost, a field survey was conducted to have a visual understanding of the study area and ground control points (GPS) were captured. Field observation method was conducted by the way of capturing photos using a digital camera, field notes of observed land use activities and geographic features. Using this method photos of different land use and land cover, were captured on the camera and also the current condition of the Zambezi headwaters was observed (Figure 4.2).

Figure 4.2: Site (a) visual observation of the water at Chinyazhi Tributary in Ikelenge District. Site (b) visual observation of agriculture land at Lwiinga Tributary in Ikelenge District. Site (c) visual observation of forest at Zambezi Source, Ikelenge District. Site (d) visual observation of settlements at Sakeji Tributary, Ikelenge District. Site (e) transport system used for field observation and data collection in Ikelenge District. Site (f) visual observation of wells near the Zambezi Source in Ikelenge District, North-Western Province, Zambia.

4.3.3 Measuring and Collecting Surface Water Samples

During the field reconnaissance survey, the Zambezi Source and its nine tributaries, namely Kangwadi, Matochi, Kanyizhiwu, Kasonka, Ilemena, Sakeji, Lwiinga, Chinyazhi and Jimbe which are connected to the Zambezi River Basin, were sampled during both the dry and wet seasons. In the dry season 21 water samples were collected from key sites including the Zambezi Source, Kangwadi, Matochi, Kanyizhiwu, Kansoko, Ilemena and Sakeji. Expanding the investigation to the wet season 71 samples were collected and key areas include, the Zambezi Source, Kangwadi, Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji, Lwiinga, Chinyazhi and Jimbe. Samples were collected from their source to the confluence with the Zambezi River. The increase in sample size in the wet season was motivated by the recognition of unsampled tributaries with high anthropogenic activities and drinking water usage, posing health risks. Various physicochemical parameters, including temperature, potential hydrogen (pH), total dissolved solids (TDS), dissolved oxygen (DO) and electrical conductivity (EC), were measured on site using the Yellow Springs Instrument multimeter (YSI). Additionally, parameters related to chemical composition, microbial content and trace elements were collected for further laboratory analysis. These comprehensive data collection efforts aimed to gain an understanding of the water quality in the Zambezi headwaters and provide essential information for the assessment of their ecological health and vulnerability to contamination.

4.3.4 Sampling Method

This study used a simple random sampling method to avoid errors and to ensure the sample size is representative of the population and that each respondent had an equal probability of being selected proportionally (Singh, 2003). The Raosoft random sample calculator (www.raosoft.com) was used to determine the sample size of the selected household of Ikelenge District, North-Western, Province of Zambia. The margin error was 10% at a confidence level of 99% and 50% respondents' distribution. The district population is 32, 919 (CSO, 2019); from the district population using the software, the sample size was 166. The sample size of 166 respondents was very reasonable in this study, whose results could be referred to the entire population of the Ikelenge District (Table 1).

Table 1: The calculated proportional sample size of 166 people using the Raosoft random sample calculator in Ikelenge District, North-Western Province, Zambia.

Study Area	District Population	Calculated Proportional Sample
Ikelenge District, North-Western	32, 919	166

4.3.5 Selection of Water Quality Parameters and Sampling Method Used

The selection of water quality parameters for this study was based on recommendations from the literature review, focusing on key indicators of stream contamination (Sikder, 2015). The review highlighted a few crucial parameters that significantly impact surface water quality and have important implications for both human health and the aquatic environment (Sikder, 2015). The following water quality parameters were sampled between 2022 and 2023: potential hydrogen (pH); electrical conductivity (EC; turbidity; temperature; total dissolved solids

(TDS); dissolved oxygen (DO); biochemical oxygen demand (BOD); nitrates; total phosphate; sulphate; total coliforms; fecal coliforms; lead; manganese; and iron. These parameters are widely recognized for their importance in influencing human health and aquatic ecology (Sikder, 2015; Chaturvedi and Bassin, 2010). The frequency of sampling was determined using the transect method (Thomas et al., 2009), which involved dividing the stream into sections with a meter to ensure that the samples collected were representative of the overall stream condition.

4.4 Data Analysis

Data analysis of this study involved the use of ArcGIS 10.7.1, the weighing and rating method for vulnerability analysis and the Statistical Package for Social Sciences (SPSS version 25) for quantitative data, the principal component analysis and the water quality index.

4.4.1 Quantitative Data Analysis

Data from 166 participants were collected through questionnaires and interviews and analysed using SPSS version 25, a statistical software widely used for data analysis in social sciences (Frey, 2017). The data entry process was performed in the data view tab, where different codes were applied to represent the data accurately. After performing the analysis, graphs and tables were generated to visually present the desired descriptive statistics.

4.4.2 Selecting and Pre-Processing the Land Use Imagery

In this study, Landsat data from June 1, 2021 to 10 December 2021, was acquired through the Climate Engine platform (http://ClimateEngine.org). Climate Engine utilizes Google Earth Engine's cloud-computing platform to overcome computational barriers and enables real-time processing, visualization, download, sharing of climate and remote sensing datasets (Justin, 2017). The Landsat imagery was imported into ArcGIS 10.7.1 and the specific region of interest, the Zambezi headwaters catchment was clipped from the imagery. The clipped imageries then underwent a supervised classification process using Landsat 8 OLI multispectral bands 3, 4, 5 and 7. The Maximum Likelihood Classifier (MLC) was used as the decision rule, which calculates a Bayesian probability function for each pixel and assigns it to the most probable class (Reyes, 2021). The land use classification in this study was based on knowledge obtained from field observations of the Zambezi headwaters. It consisted of five classes: built-up areas; agricultural land; forest land; grassland; and water bodies. Class signatures were generated for each class and the images were classified with appropriate colours and names for easy interpretation. Iterative comparisons with Google Earth images were performed to ensure accuracy in selecting the final classified image for generating statistics. Figure 4.3 provides an overview of the data flow involved in creating the land use map for this study; the flow starts from (a) up to (h).

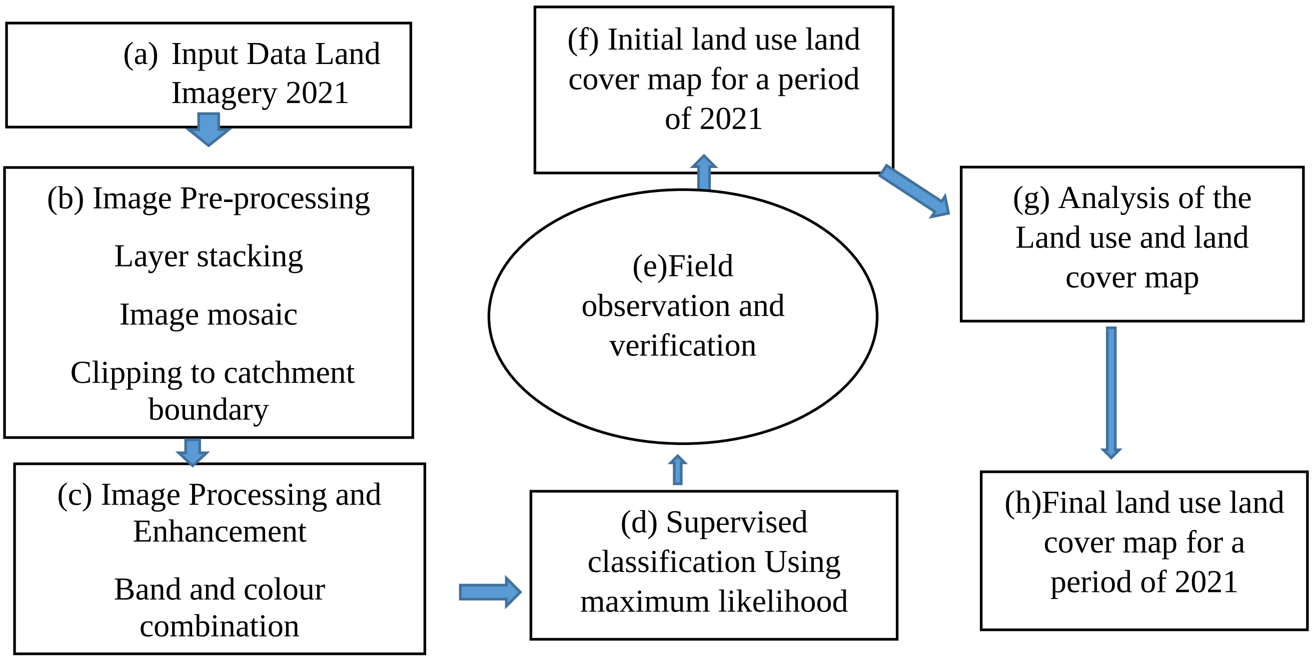

Figure 4.3: Flowchart for land use and land cover map analysis of the Zambezi headwaters Ikelenge District, North-Western Province, Zambia.

The land use image classification accuracy was assessed using the overall accuracy, producer's accuracy and user's accuracy were determined in addition to the Kappa Coefficient (K). The Kappa Coefficient is widely used because it compensates for change agreement (Li, 2010). The Kappa Coefficient lies typically on a scale between 0 (no reduction in error) and 1 (complete reduction of error). The latter indicates complete agreement and is often multiplied by 100 to give a percentage measure of classification accuracy. In practice, the agreement is taken to be strong when K is greater than 0.80 (80%), moderate when values fall between 0.40 (40%) and 0.80 (80%) and poor when values are less than 0.40 (40%) (Li, 2010).

4.4.3 Slope, Precipitation and Depth to Groundwater Data Processing

Slope, precipitation and depth to groundwater data were processed using data provided and maintained by HydroATLAS-Zambia (Lehner, 2020). HydroATLAS Zambia offers a comprehensive compendium of hydro-environmental attributes for all catchments and rivers in Zambia, organized into seven categories, including hydrology, physiography, climate, soils, geology, land cover and land use, anthropogenic influences and Zambia-specific ecological information (Lehner, 2020). Version 1.0 of HydroATLAS-Zambia provides data for 51 variables in shapefiles, which were obtained from https://www.hydrosheds.org/hydroatlas-zambia and processed in ArcGIS 10.7.1. The shapefiles of Zambezi headwaters were added and clipped with the HydroATLAS Zambia data. After clipping, data analysis was conducted and the results were displayed in the form of maps for slope, precipitation, depth to groundwater with each variable categorized different classes.

4.4.4. Analytical Hierarchy Process (AHP) Evaluation Model

This study employed the Analytical Hierarchy Process (AHP) to compute weights for the factors of contamination. AHP, is a measurement theory of derives ratio scales from paired comparisons of both discrete and continuous variables (Saaty, 1980). These comparisons encompass real measurements signifying relative preference strength. AHP minimizes variable conflicts like interdependence, relative weights of each evaluated component were determined through AHP and pairwise comparison matrix techniques. The Comparative Scale (Saaty, 1980), a standard tool, gauges distinct parameter comparisons. Using integers from 1 to 9, it quantifies relative factor importance, with 1 signifying equal importance and 9 indicating extreme importance (Table 2).

Table 2: Judgments Scale and Definitions for the Pairwise Comparison of the AHP adapted from (Saaty, 1980).

Qualitative Definition	Explanation	Intensity of Importance
Equal importance	two activities contribute equally to the objective	1
Weak		2
Moderate importance	Experience and judgement slightly favour one activity over other	3
Moderate plus		4
Strong importance	Experience and judgement strongly favored one activity over other	5
Strong plus		6
Very strong importance	One activity is favored strongly over the other and dominate in practice	7
Very very strong		8
Extreme importance	The evidence favoring one activity over another is of the highest order	9

In this study, seven key stakeholders through their representatives from both Government, Private Sector and Non-Governmental Organization involved in water and environmental management were consulted and these includes: The Ministry of Water Development and Sanitation; Ministry of Tourism; Ministry of Green Economy; Ministry of Land and Natural Resources; Ministry of Agriculture; The World-Wide Fund (WWF); and The World Vison Zambia. These stakeholders were responsible to assign weights and rates based on their expertise to significant variables, including: Land use and land Cover (LULC); precipitation; slope; and groundwater depth along with drainage. The study revealed that LULC held the highest significance, followed by precipitation and slope. Conversely, groundwater depth exerted the least influence, as outlined in stakeholder's assessments pairwise comparison matrix (Table 3).

Table 3: A pairwise comparison matrix developed for assessing the relative importance of the criteria for watershed vulnerability assessment used in Ikelenge District, North-Western, Zambia.

Factor	**Land use and Land cover**	**Slope**	**Precipitation**	**Depth to Groundwater and Drainage**	**Criteria Weights**
Land use and Land cover	1	5	4	7	0.6038
Slope	0.2	1	0.5	3	0.1365
Precipitation	0.25	2	1	3	0.1957
Depth to Groundwater and drainage	0.14	0.3	0.3	1	0.0646
Total sum	1.59	8.33	5.83	14	
Lambda max (λmax) = 4.1007					
Consistency index = 0.003358					
Consistency ratio = 0.037311					

The Analytical Hierarchical Process (AHP) was employed, using numeric indicators 'm' and 'n,'. The entries within the matrix, denoted as 'aij,' encapsulated performance values linked to the 'ith' and 'jth' components (Jabbar, 2019; Saaty, 1980). The values above the diagonal in the upper matrix facilitated comparisons among factors, whereas the lower matrix values were their reciprocals. The matrix 'A,' formed through pairwise comparisons, symbolized the significance of selections (Equation 1).

$$A = \begin{bmatrix} 1 & a_{12} & \ldots\ldots & a_{in} \\ 1/a_{12} & 1 & a_{23} & a_{2n} \\ 1/a_{in} & 1/a_{2n} & \ldots & 1 \end{bmatrix} \quad \text{Equation 1}$$

where, a_J; I, j=1, 2, ……, n is the element of row i and column j of the matrix and equal to the number of alternatives. The eigenvectors were calculated for each row using geometric principles in Equation 2 (Saaty, 1980).

$$Eg = n\sqrt{a_{11}\ x\ a_{12}\ \ x\ \ a_{13} \ldots\ a_n} \quad \text{Equation 2}$$

where, Eg = eigenvector for the row i; n = number of elements in row i

The priority vector (Pr_i) was determined by normalizing the eigenvalues to 1 using the Equation 3 (Saaty, 1980).

$$Pr_i = Eg_i \sum_{k=0}^{n} Egk \quad \text{Equation 3}$$

The value of lambda max (λ max) was computed by summing the products of each element in the priority vector and the corresponding column sum from the reciprocal matrix, as demonstrated in equation 4(Saaty, 1980).

$$\lambda_{max} = \sum_{j=1}^{n} (W_j \ x \sum_{i=1}^{n} a_{ij}) \quad \text{Equation 4}$$

Where, a_{ij} = the sum of criteria in each column in the matrix; Wi = the value of weight for each criterion corresponding to the priority vector in the matrix of decision, where the values i = 1, 2, … m, and j = 1, 2, … n. The Consistency Ratio (CR), evaluating weight consistency and pairwise differences, was computed. CR below 0.1 is acceptable; otherwise, subjective assessments are reviewed and weights recalculated (Saaty and Vargas, 2001). To calculate the consistency ratio (CR), the following Equation 5 was utilized.

$$CR = \frac{CI}{RI} \quad \text{Equation 5}$$

In this case, CI refers to the consistency index, which is calculated as shown in equation 6.

$$CI = \frac{\lambda max - n}{n-1} \quad \text{Equation 6}$$

where λmax is the result of multiplying the sum of each column in the comparison matrix by the corresponding relative weights and n represents the dimension of the matrix. RI stands for the random index, a measure of the consistency of the pairwise comparison matrix, obtained from a randomly generated set. This index is determined as the average of the random consistency indexes, which were computed by Saaty (1980) based on a collection of 500 randomly generated matrices. To calculate the watershed vulnerability of the study area, the weighted overlay analysis was applied based on the following equation 7 (Jabbar, 2019).

$$WS = \sum_{j=1}^{n} W_j \times C_{ij} \quad \text{Equation 7}$$

In this context, WS represents the susceptibility of the watershed for a specific area denoted by i. Wj stands for the weight indicating the relative significance of a criterion. Cij corresponds to the grading value assigned to area i based on criterion j. Additionally, n signifies the total count of criteria being considered (Jabbar, 2019).

4.5 Factors Used for Vulnerability Assessment

This study assessed the vulnerability of Zambezi headwaters to contamination using four main factors: land use; average annual precipitation; slope; and depth to groundwater (Jabbar, 2019: (Neupane, 2015). These factors were chosen based on their significant impact on surface water quality and essential water characteristics are described here:

Land Use/Land Cover: Activities like agriculture and human settlements can lead to surface water contamination from point and nonpoint sources, including nutrients, organic matter and bacteria (Thalmann, 2021). Land use in this study was divided into five classes with agriculture having the highest impact (rated 10) and water with lowest impact (rated 1) (Appendix 3);

Precipitation: The study recognized a direct link between increasing pollution levels in surface water and precipitation (Rostami, 2018). Heavy rainfall can reduce water quality through surface runoff of contaminants. Precipitation was classified into five classes, with higher ratings indicating higher susceptibility to contamination (Appendix 4);

Land Surface Slope: Steep slopes can negatively impact surface water quality by causing soil erosion and transporting contaminants like nutrients, pathogens and pesticides into nearby rivers (Croke, 2007). The study proposed six slope classes, with gentle slopes having the lowest impact (rated 1) and steep slopes having the highest impact (rated 10) (Appendix 5); and

Depth to Groundwater: The study recognized the relationship between surface water and groundwater (Jabbar, 2019; Xi Liu, 2020; Banda et al, 2023). Shallow groundwater can significantly influence water quality, with factors like geological characteristics playing a role. Depth to groundwater in this study was categorized into five classes, with shallow groundwater receiving a higher rating (rated 10) and deep groundwater a lower rating (rated 1) (Appendix 6).

Through the evaluation of these four factors, along with their respective ratings and weights (Table 4) (Appendix 7), the study gained valuable insights into the potential vulnerability of the Zambezi headwaters to surface water contamination. These insights were derived from expert knowledge and the assigned ratings, determined based on the perceived impact of each factor (Saaty, 1980).

Table 4: The relative weights and rating scores of the factors used for vulnerability assessment of the Zambezi headwaters in Ikelenge District, North-Western Zambia.

FACTOR	Weights	Sub-Criteria	Rating	Normalized Rating
Lulc	0.604	Cropland	10	0.521
		Built-up	7	0.218
		Grassland	5	0.128
		Forest	4	0.067
		Water	1	0.065
Average Annual Precipitation (mm)	0.196	>1600	10	0.534
		1401-1600	8	0.207
		1201-1400	6	0.095
		1001-1200	4	0.074
		800-1000	1	0.056
Slope (Degree)	0.137	>60	10	0.348
		31-60	8	0.314
		16-30	6	0.119
		11-15	4	0.039
		4-10	2	0.104
		0-3	1	0.076
Depth to Groundwater and drainage (m)	0.065	<1.58	10	0.539
		1.59-1.77	8	0.203
		1.78-2.06	6	0.113
		2.07-2.26	4	0.092
		>2.27	1	0.052

4.6 Surface Water Quality Assessment Across Dry and Wet Seasons in the Zambezi Headwaters, Ikelenge District, North-Western, Zambia (2022-2023)

This study presents a comprehensive evaluation of water quality parameters during both dry and wet seasons of 2022-2023. Some water quality parameters were acquired in situ and these include: temperature; potential hydrogen (pH); electro conductivity (EC); dissolved oxygen (DO); total dissolved solids (TDS); and were measured with a YSI multimeter. Samples acquired from the field for trace elements such as iron, manganese and lead were taken to the University of Zambia, School of Mines, Geo-Chemical Laboratory and for microbiota (total and feacal coliforms) and physio-chemical parameters (phosphate, nitrate, sulfate, total hardness, biological oxygen demand and turbidity) were taken to the University of Zambia Environmental Engineering Laboratory. Surface water collecting procedures were well followed, including equipment calibration, all sampling equipment was sterilized and rinsed with distilled water (Wilde, 1998). Phosphate and nitrate samples were collected in sterilized polypropylene bottles, whereas sample bottles for trace elements were preserved within 2 ml of nitric acid. All samples were preserved on ice during transportation and refrigerated at 4°C until procession. Laboratory procedures were based on manufacturers recommendations and they were analyzed using the spectrophotometer.

4.7 Water Statistical Data Analysis

This study utilized multivariate statistical techniques, first the raw data was standardized by subtracting the mean of the data set from each variable and dividing by the standard deviation to produce a normal distribution (Watkar, 2015). Using SPSS version 25, The Principal Component Analysis (PCA) is then used to evaluate selected parameters through a correlation matrix. The PCA is specifically used to extract the factors with correlated values while at the same time giving spatial and temporal changes in the water quality (Soneye, 2013). The PCA is expressed mathematically as (Equation 8).

$$Z_{ij=} a_{ij}x_{ij} + a_{i2}x_{2j} + a_{i3}x_{3j+ \ldots +} a_{im}x_{mj} \qquad \text{Equation 8}$$

where, z = component score, a = component loading, x = measured value of variable, i= component number, j = sample number, and n = the total number of variables. Factor analyses were used to determine the pollution factors affecting the water quality among the sampling sites where factor loading value > 0.75 is described as “strong” loading, 0.75 - 0.50 is moderate and 0.50 - 030 is described as weak (Alexandre, 2020).

4.8 Water Quality Index

This study utilized the National Sanitation Foundation's Water Quality Index (NSF -WQI) proposed by Horton Brown et al. (Shokuhi, 2012; Parastar et al., 2014) which is widely recognized and extensively used globally. The NSF-WQI assesses water quality for various purposes, including irrigation, water supply and navigation, across different water bodies such as lakes, reservoirs and rivers. The index incorporates nine parameters namely, temperature, pH, turbidity, phosphate, nitrate, total solids, dissolved oxygen (DO), biochemical oxygen demand (BOD) and fecal coliforms, each with assigned weights determined through a statistical survey conducted by 142 experts using the DELPHI technique (Programming Language) (Parastar et al., 2014). The mathematical expression for the NSF-WQI is provided (Equation 10).

$$\text{WQI}= \sum_{i=1}^{n}(wi\ xQi) \qquad \text{Equation 8}$$

Where n represents the total number of parameters, wi denotes weights assigned to each parameter, and qi signifies the corresponding water quality rating (Chidiac et al., 2023). The weights were obtained through a statistical survey by 142 experts using the DELPHI technique Qi represents the sub-index value for each parameter, ranging from 0 to 100, indicating the desired level or objective function (Chidiac et al., 2023).

4.9 Validation and Sensitivity Analysis of the Vulnerability Index

In this study, the sensitivity analysis of the vulnerability calculation method involved comparing the vulnerability rating to various water quality parameters and the water quality index method. Additionally, two-sided t-tests of significance were conducted at the 0.05 level. This analysis was conducted using the Pearson Regression Coefficient with a marked significant of ($p \leq 0.05$), whereas coefficients with values above 0.5 were considered a strong positive correlation and negative correlation was considered as a weak negative correlation (Bishara and Hittner, 2012).

CHAPTER 5: RESULTS AND DISCUSSION

5.1 General Remarks

The main aim of this study as indicated earlier was firstly, to investigate the vulnerability of the Zambezi headwaters to potential contaminants. The first objective centred on identifying the potential contaminants, whereas the second objective involved analysing contamination vulnerability through methods including weighing and rating system, GIS and sensitivity analysis. The third objective was to assess primary measures introduced by Governmental and Non-Governmental Organisations to minimize or eradicate vulnerability to contaminants in the Zambezi headwaters.

5.2 Seasonal Water Quality Analysis of the Zambezi headwaters, Ikelenge District North-Western Province, Zambia.

In this section, the water quality of the Zambezi headwaters in Ikelenge District, North-Western Province of Zambia is described for both the dry and wet seasons (Tables 5 and 6). The Zambezi Source is denoted as ZS, whereas the tributaries are represented as follows: T1 for Kangwadi; T2 for Matochi; T3 for Kanyizhiwu; T4 for Kansoko; T5 for Ilemena; T6 for Sakeji; T7 for Lwiinga; T8 for Chinyazhi; and T9 for Jimbe.

Table 5: Water samples analysis for dry season on physio-chemical, biological and heavy metals parameters for the Zambezi headwaters in Ikelenge District, North Western Province Zambia.

Parameters	ZS	T1	T2	T3	T4	T5	T6
Temperature (°C)	21.4	19.7	21.6	21.4	22.2	20.4	24.4
Dissolved oxygen (mg/l)	3.2	3.7	3.4	3.5	3.2	3.6	3.2
pH	5.4	5.8	5.9	6.1	6.1	6.0	6.5
Electrical conductivity (µS/cm)	3.3	2.1	6.4	5.0	7.8	2.4	7.1
Total dissolved solids (mg/l)	11	4	5	4.3	3.3	3.5	7.3
Turbidity (NTU)	34.1	40.9	3.1	22.7	3.9	6.9	6.7
Total hardness	14.7	15.3	21.3	18.7	10.7	4.0	4.7
Biological oxygen demand (mg/l)	0.8	0.9	1.0	0.32	1.0	0.5	1.4

Feacal coliforms (No/100ml)	5	0	0	125	170	38	25
Total coliforms	3	0	0	82	125	15	10
Potassium (mg/l)	0.05	0.08	0.10	0.16	0.14	0.13	0.12
Phosphates (mg/l)	0.50	0.37	<0.001	<0.001	<0.001	<0.001	<0.001
Iron (mg/l)	0.62	0.82	0.68	0.31	0.33	0.35	0.35
Manganese, Lead and Nitrates (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 6: Water samples analysis for wet season on physico-chemical, biological and heavy metals parameters for the Zambezi headwaters in Ikelenge District, North-Western Province Zambia.

Parameters	**ZS**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**
Temperature (°C)	19.8	17.1	20.9	20.2	20.3	20.5	21.0	21.7	22.8	24.3
Dissolved oxygen (mg/l)	4.8	5.2	6.8	5.6	6.7	4.4	5.8	6.9	6.1	6.2
pH	5.2	3.9	4.1	4.0	3.8	4.1	4.9	6.0	4.7	4.4
Electrical conductivity (µS/cm)	9.4	8.7	7.2	7.9	22.4	10.4	8.0	20.0	9.3	8.3
Total dissolved solids (mg/l)	5.0	4.7	3.4	3.7	10.5	4.8	4.0	10.0	5.3	4.4
Turbidity (NTU)	3.7	3.3	3.4	3.5	0.3	0.4	4.0	4.1	4.3	3.8
Biological oxygen demand (mg/l)	1.0	0.9	1.0	1.3	1.0	0.7	1.3	1.0	0.8	0.8
Feacal coliforms (cfu)/100 ml	2	5	15	196	71	139	66	56	119	24
Total Coliforms (cfu)/100 ml	5	9	8	340	57	117	44	36	81	76
Potassium (mg/l)	0.01	0.19	0.17	0.20	0.20	0.24	0.32	0.48	0.3	0.20
Nitrates and Phosphates (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Iron (mg/l)	0.12	0.05	0.13	0.35	0.27	0.18	0.24	0.39	0.38	0.52
Manganese and Lead (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

The water quality of the Zambezi headwaters in Ikelenge District, North-Western Province of Zambia, during both the dry and wet seasons, as presented (Tables 5 and 6 above), are further discussed as follows.

pH and Temperature: In the dry season, pH levels ranged from 5.4-6.5, with most tributaries falling below the World Health Organization (WHO) standards limit of 6.5-7.0, whereas temperatures ranged from 19.7-24.4 degrees Celsius, aligning with WHO standards. In the wet season, pH values ranged from 3.8-6.0, again below the WHO limit, with temperatures spanning 17.1- 24.3 degrees Celsius, conforming to the standards (WHO, 2011). In both seasons, the pH levels in the water were below the recommended WHO standards. These results indicate that the pH is highly acidic.

The lower pH values during the wet season suggest a potential increase in acidity compared to the dry season due to factors such as the area's geology and increased precipitation, which can introduce acidic substances into the water, for example, regions with certain rock types, such as shale or those containing sulphide minerals, can release acidic compounds when exposed to water, particularly during increased rainfall. Additionally, the weathering of these rocks can produce sulfuric acid, contributing to lower pH levels in the water. Increased precipitation can also enhance the leaching of organic acids from soil and decaying vegetation into the water, further lowering the pH. In a similar study, Nienie et al. (2017) in exploring the seasonal variability of water quality, analysing physicochemical indexes and traceable metals in a suburban area in Kikwit, Democratic Republic of the Congo, revealed that pH values during the wet season were acidic and below the WHO (2011) standards, whereas during the dry season, the pH values fell within the WHO (2011) accepted limit. The low pH in the wet season could be a result of the geology of the sampling sites and rainfall likely influenced the acidity of the pH through dilution.

Turbidity and Hardness: Turbidity during the dry season varied from 3.1-40.9 NTU, exceeding limits at specific sites. Total hardness ranged from 4.0-15.3, adhering to (WHO, 2011) standards. In the wet season, turbidity ranged from 0.3- 4.1 NTU, well within the acceptable limit of 10 NTU (WHO, 2011). Total hardness remained undetectable in the wet season. The study results suggest that, as turbidity values remained within acceptable thresholds during the wet season, it indicates good water quality in the study area. Additionally, total hardness was undetectable during the dry season, signifying a lower concentration of minerals in the water.

Conductivity, TDS and DO: Conductivity and TDS during the dry season ranged from 2.1-7.8 µS/cm and 3.3-11.0, respectively, in accordance with WHO guideline. Dissolved oxygen (DO) levels during the dry season ranged from 3.2-3.7 mg/l. In the wet season, conductivity ranged from 7.2-20.0 and TDS ranged from 3.4 -10.5, both within (WHO, 2011) limits. DO levels in the wet season ranged from 4.4 -6.9 mg/l. DO was lowest in the dry season (3.2 mg/l) observed at Zambezi Source, Kansoko and Sakeji tributaries. This is attributed to animal manure, which is used as fertiliser in the gardens nearby and also water stagnation as observed at Zambezi Source. On the other hand, DO was highest in the wet season (6.9 mg/l) at Lwiinga Tributary indicating absence of animal manure that deplete DO. A similar finding by Jabbar (2019) in assessing and predicting surface water vulnerability from non-point source pollution in Midwestern watersheds, USA, revealed that dissolved oxygen (DO) was significantly higher during the spring, possibly due to increased water in the streams associated with higher discharge.

BOD, Total and Feacal Coliforms: BOD during the dry season ranged from 0.5-1.0 mg/l, indicating moderate organic pollution. Feacal and total coliforms in both seasons remained within limits, except for Kanyizhiwu which exceeded the WHO limit of 200 cfu/200 mm in the wet seasons. In the wet season, BOD ranged from 0.8-1.3 mg/l, slightly below standards (WHO, 2011). Across both seasons, feacal coliform levels ranged from 0 to 170, with Zambezi Source, Kangwadi, Matochi and Ilemena consistently below the recommended limit of 50 cfu/100 mm. The observed high concentrations of these coliforms indicators were not surprising, as most of these areas were associated with increased anthropogenic activities. For instance, Kanyizhiwu, Kansoko, Ilemena and Chinyazhi tributaries, had the presence of human activities such as livestock rearing, sawmill and open defecation. These were identified as being sources of water contamination.

Nitrates (NO_3), Phosphates (PO_4^3) and Potassium: In both seasons, NO_3 values remained consistently below 0.001, indicating low concentrations at all sampling points. During the dry seasons, Zambezi Source and Kangwadi Tributary showed phosphate levels of 0.57 and 0.37, respectively, whereas other tributaries in both seasons had no detectable phosphates. Dry season potassium levels ranged from 0.05-0.12 mg/l and in the wet season, potassium levels ranged from 0.01-0.48 mg/l, with elevated levels at Lwiinga Tributary (T7) and Chinyazhi Tributary (T8) due to agricultural practices and settlements. Phosphates at Zambezi Source and Kangwadi were attributed to the decay of organic matter, such as dead plants, observed during data collection.

Trace Element Analysis: Manganese (Mn), lead (Pb) and iron (Fe) concentrations were assessed in both seasons. Throughout both seasons, concentrations of manganese and lead remained consistently below the detection limit of 0.001 mg/L, indicating generally low levels of these metals. However, iron concentrations showed variation. In the dry season, iron levels ranged from 0.31 to 0.85 mg/L, with Kangwadi displaying the highest concentration. In the wet season, iron concentrations ranged from 0.05 to 0.52 mg/L, with Jimbe Tributary having the highest concentration within the WHO (2011) limits. This indicates that water quality remains within its natural state, a finding similar to that of Nyambe et al. (2018) in their study on the determinants of spatio-temporal variability of water quality in the Barotse Floodplain of the Zambezi River, Western Zambia. Their results showed that concentrations of heavy metals were negligible (< 0.002 mg/l) and within the World Health Organization (WHO, 2011) standards. This suggests that water quality within the floodplain is still in its natural state concerning mining contamination.

These findings highlight the dynamic nature of water quality within the Zambezi headwaters across distinct seasons. The study results underscore the interplay between natural processes and human activities. These insights are invaluable for informed conservation efforts and the preservation of water.

5.2.1 Principal Component Analysis of the Zambezi Headwater in Ikelenge District, North-Western Province, Zambia

The result of principal components analysis (Table 7) indicates that of the 11 components (iron, pH, turbidity, potassium, temperature, dissolved oxygen, electrical conductivity, total dissolved solids, feacal coliforms, total coliforms and biological oxygen demand), only 4 had extracted eigenvalues over 1. This is based on Chatfield and Collin (1980) assumption which stated that components with an eigenvalue of less than 1 should be eliminated. The 4 extracted components underwent varimax rotation to facilitate interpretation and understand their significance in assessing the water quality of the selected tributaries of Zambezi River. The rotation revealed that the cumulative variance of the 4 components accounts for 74.42% of the total variance of the observed variables, demonstrating that these components effectively capture the variance in the data. Table 7 presents the calculated components loadings, eigenvalues, total variance and cumulative variance, whereas (Figure 5.8) displays the scree plot of the eigenvalues of the observed components.

Table 7: The rotated components loadings, eigenvalues, total variance, and cumulative variance of the principal component analysis in Ikelenge District, North-Western Province, Zambia.

Variable	**Component**			
	1	2	3	4
Iron	0.782			-0.235
pH	0.764	0.187		
Turbidity	0.761	-0.364		
Potassium	0.649	0.415		
Temperature	0.572	-0.179	-0.141	-0.564
Dissolved oxygen	0.469	0.125	-0.164	0.170
Electrical conductivity		0.967		
Total dissolved solids	0.104	0.959		
Feacal coliforms			0.979	
Total coliforms	-0.142		0.973	
Biological oxygen demand	0.175	-0.190		0.838
Eigenvalue	3.03	2.23	1.82	1.11
Variability %	27.52	20.26	16.55	10.09
Cumulative %	27.52	47.77	64.33	74.42

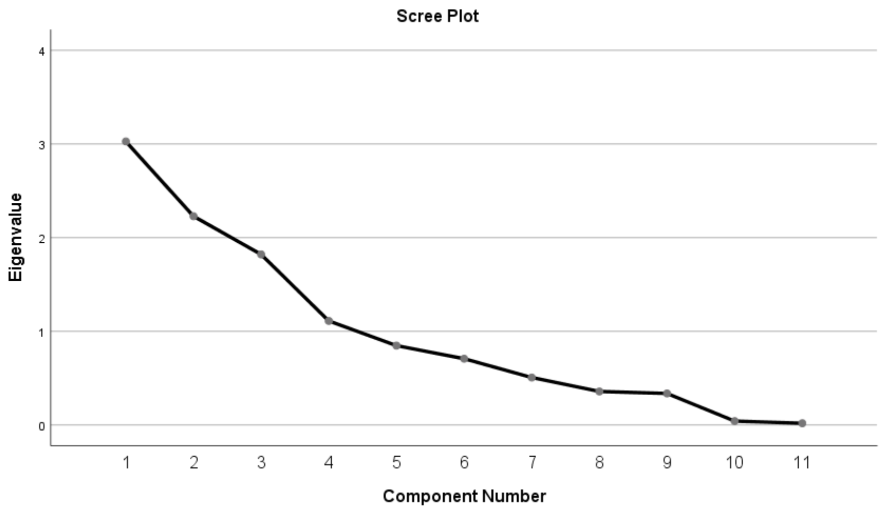

Figure 5.1: Scree Plot of the principal component analysis of the Zambezi headwaters in Ikelenge District, North-Western, Zambia.

The results of (Table 7) shows, Factor 1 accounts for 27.52% of the total variance in the water quality parameters. It exhibits strong factor loadings for iron, pH, turbidity and potassium. Additionally, it shows moderate loadings for temperature, dissolved oxygen (DO), total dissolved solids (TDS), total coliforms and biological oxygen demand (BOD). The high factor loading for iron, pH and turbidity suggests a close relationship between these parameters, indicating that they often increase or decrease together. This could be attributed to natural variations in water quality resulting from geological influences, environmental factors, or anthropogenic sources that simultaneously impact these parameters. Similar findings were reported by Nguvulu (2021) in assessing surface water quality response to land use/land cover change in an urbanizing catchment of Upper Chongwe River Catchment, Zambia. His study revealed that sediment runoff from loose soils on agricultural lands, geological and environmental activities strongly influence the variation of the quality of surface water which is similar to the study findings. Factor 2 accounts for 20.26% of the total variance in the water quality parameters and is primarily influenced by electrical conductivity (EC) and total dissolved solids (TDS). It also exhibits loadings for pH, turbidity, potassium, temperature, dissolved oxygen (DO) and biological oxygen demand (BOD). The dominant influence of EC and TDS suggests that this factor may represent the presence of dissolved minerals and salts in the water. Such characteristics can serve as indicators of geological or anthropogenic influences on the water quality. Factor 3 accounts for 16.55% of the total variance in the water quality parameters and exhibits strong loadings for fecal and total coliforms. Additionally, it shows loadings for temperature and dissolved oxygen (DO). This factor is characterized by the presence of fecal and total coliforms, along with some association with temperature and DO. The high loadings of fecal and total coliforms suggest that this factor may be related to microbial contamination, potentially originating from human or animal sources. Similar findings were reported by Soneye (2013) in the interpretation of surface water quality using principal components analysis in Lagos, Nigeria. His study indicated that microbial pollution from domestic and agricultural waste, as well as the geological composition of the area, strongly influenced the surface water quality. Factor 4 accounts for 10.09% of the total variance in water quality parameters. It is strongly influenced by biological oxygen demand (BOD), indicating a link to organic pollutants in the water, likely from human or agricultural sources. Similar results were reported Soneye (2013) in the interpretation of surface water quality using principal components analysis in Lagos, Nigeria, which showed that the presence of BOD in water quality is an indication of high level of organic pollution, caused usually by poorly treated waste water from humans and industrials. The factor also shows moderate negative loadings for iron and temperature, suggesting that as organic pollution increases, iron and temperature tend to decrease. This could be due to complex interactions between organic pollutants, iron precipitation and microbial processes. Additionally, there is a weak positive association with dissolved oxygen (DO), indicating that organic pollutants may lead to reduced DO levels in water bodies.

The four factors extracted by Principal Component Analysis (PCA) play a crucial role in understanding the patterns and potential sources of variation in the water quality parameters.

5.2.2 Water Quality Index

As indicated earlier, in this study spanning 2022-2023, the innovative Water Quality Index (NSF-WQI) developed by the National Sanitation Foundation in collaboration with Horton Brown's team (Parastar et al., 2014) was used. The range of the water quality index corresponding to specific quality levels (Table 8).

Table 8: The NSF-WQI grading and rating used for the Zambezi headwaters, in Ikelenge District, North-Western Province Zambia.

Water Quality Rating	Water Quality Status
91-100	Excellent quality
71-90	Good Quality
51-70	Moderate quality
26-50	Poor quality
0-25	Very poor quality

Through the utilization of the NSF-WQI, as indicated earlier the index used the incorporates nine parameters namely: temperature; Ph; turbidity; phosphate; nitrate; total solids dissolved oxygen (DO); biochemical oxygen demand (BOD); and fecal coliforms (Parastar et al., 2014). The index final output is obtained on a NSF-WQI Rating curves that range from 0-100 (Appendix 9). This index effectively categorizes the Zambezi headwaters, water quality into five tiers: excellent; good; moderate; poor; and very poor. The findings of the water quality index of the Zambezi headwaters are shown in Figure 5.2.

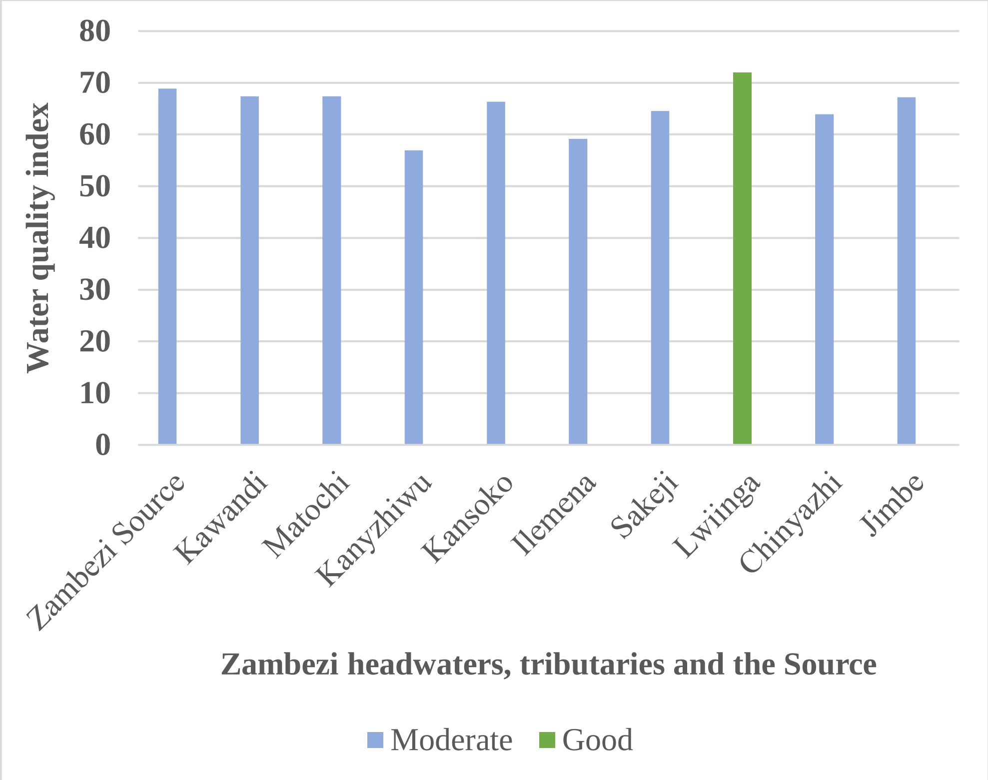

Figure 5.2: Water quality Index of the Zambezi headwaters, Ikelenge District, North-Western Province, Zambia.

The water quality index (WQI) in Figure 5.2 reveals that the Zambezi Source, Kangwadi Tributary, Matochi Tributary, Kanyizhiwu Tributary, Kansoko Tributary, Ilemena Tributary, Sakeji Tributary, Chinyazhi Tributary and Jimbe Tributary all had water quality indices ranging from 51 to 70, indicating moderate water quality. However, Lwiinga Tributary stands out with a WQI of 72, suggesting good water quality (Parastar et al., 2014) (Appendix 9). Despite the Lwiinga Tributary being mapped as highly exposed to contamination vulnerability (Figure 5.9), it consistently maintains good water quality. This intriguing situation indicates the resilience of groundwater depth, along with its effective drainage network and high precipitation in the area, especially in the face of intense agricultural and settlement activities. The depth to groundwater, along with its drainage network and high precipitation at the Lwiinga Tributary, was categorized as high (Lehner, 2020). This explains the water buffering and neutralization process contributing to the good water quality status of Lwiinga Tributary. In addition, the interplay of these findings highlights the WQI as a crucial instrument, shedding light on water quality dynamics. This knowledge is essential for making informed decisions in safeguarding and enhancing water resources.

5.3 Land Use Land Cover Classification and Accuracy Assessment of the Zambezi Headwater, Ikelenge District, North-Western, Zambia.

The land use and land cover (LULC) map of the Zambezi headwaters (Figure 5.3), of the year 2021 shows the Chinyazhi Tributary, covering a total area of 129.7 km² with a predominant 46% of agricultural activities, emerges as a crucial focal point. The intensive agricultural practices within its boundaries could potentially result in increased nutrient runoff, including fertilizers and pesticides, into water bodies. This inflow of pollutants has the potential to affect water quality, potentially leading to issues like eutrophication and algal blooms, thus demanding careful management strategies (Wilson and Weng, 2010).

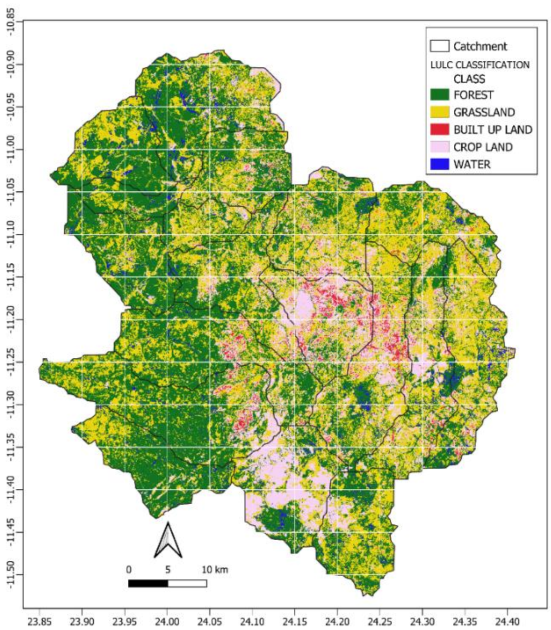

Figure 5.3: LULC Map of the Zambezi headwaters in Ikelenge District, North-Western Province, Zambia.

Similarly, the prevalence of built-up areas, in Chinyazhi and Matochi tributaries, raises concerns about increased pollution of surface water. This phenomenon can result in increased storm water runoff, carrying contaminants such as oil, heavy metals and sediments into nearby water bodies (Jabbar, 2019). On the other hand, the 82.9 and 72.4% of forest cover of the total area of the Zambezi Source and Kangwadi Tributary respectively contributes significantly to water quality preservation. Forests act as natural buffers, filtering pollutants, stabilizing soil and regulating water flow (Gong, 2021). The forest cover observed in these areas could potentially enhance water quality by minimizing sedimentation and mitigating the influx of pollutants into the aquatic ecosystem. Ilemena and Sakeji tributaries were highly dominated with grassland coving 46.9% and 44.7% of their total areas respectively. Grassland may contribute to nutrient retention, sediment trapping as well as carry the risk of contributing to excess nutrients from livestock activities (Jabbar, 2019). Areas of high grassland in this study area were observed as areas of animal rearing, such as the Nchila Wildlife, along the Sakeji Tributary and animals such as goats and pigs were observed feeding on grass at Ilemena Tributary. Effective environmental management practices are important to ensure that these areas do not become sources of water quality deterioration. The varying percentages of water bodies in different tributaries highlight their vulnerability to land use changes. High proportions in water bodies of 6.0% of the total area of both Kanyizhiwu and Matochi Tributary need vigilant monitoring to prevent contamination from nearby land uses and safeguard aquatic ecosystem health. The image accuracy classification was assessed by determining the overall accuracy, producer's accuracy and user's accuracy (Li, 2010). (Table 9).

Table 9: Image classification accuracy using producer's, user's, overall and kappa coefficient of Ikelenge District, North-Western Province, Zambia.

Class	**Producer Accuracy**	**User Accuracy**
Grassland	0.96%	0.98%
Forest	0.98%	0.97%
Agriculture	0.99%	0.96%
Water	0.86%	0.92%
Built-up	100%	0.78%
Overall accuracy= 0.97%		
Kappa= 0.95%		

The objective of accuracy assessment as indicated earlier is to quantitatively evaluate how well pixels were accurately assigned to their respective land cover categories. The focus during pixel selection for accuracy assessment was primarily on areas easily identifiable in both Landsat high-resolution imagery and on Google Earth and Google Maps (Li, 2010). The results showed various categories, shown by producer and user accuracy measures. For instance, grassland had 96% producer and 98% user accuracy. Forest achieved 98% producer and 97% user accuracy. Agriculture had 99% producer accuracy and 96% user accuracy. Water achieved 86% producer and 92% user accuracy. Built-up areas showed perfect 100% producer accuracy but 78% user accuracy. Key metrics included a Kappa Coefficient of 96%, highlighting agreement between predicted and actual classes. Overall accuracy of 97% demonstrated model capacity and method effectiveness, affirmed by high accuracy values of Kappa Coefficient. These findings enhance accurate land cover classification comprehension (Li, 2010). The LULC distribution of the Zambezi headwaters, are well summarized (Table 10)

Table 10: Summarizes percentages of land use/land cover distribution in Ikelenge District, North-Western Province, Zambia.

Name of the River / Tributary	**Cropland %**	**Built-up %**	**Grassland %**	**Forest %**	**Water %**
Zambezi Source	0.63	0.00	11.9	82.9	4.5
Kangwadi	1.2	0.00	23.0	72.4	3.1
Matochi	14.6	7.1	31.9	40.5	6.0
Kanyizhiwu	14.0	3.0	43.0	34.0	6.0
Kansoko	22.1	5.8	30.2	40.9	1.0
Ilemena	11.2	2.5	46.9	33.9	5.6
Sakeji	24.6	2.4	44.7	25.0	2.6
Lwiinga	26.0	5.0	43.0	24.0	2.0
Chinyazhi	46.0	9.0	29.0	15.0	0.01
Jimbe	7.6	0.4	34.3	55.3	2.4

To explore land uses, a questionnaire-based interview conducted with 166 participants of Ikelenge District, North-Western Province, Zambia indicated the various activities done in the area (Figure 5.4).

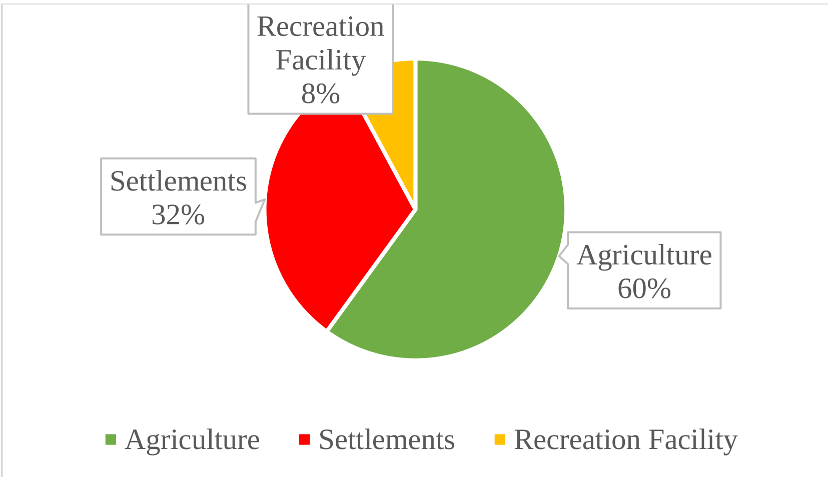

Figure 5.4: Community perception on Land use in Ikelenge District, North-Western Province, Zambia.

The data from Figure 5.4 indicates that agriculture is the dominant land use at the Zambezi headwaters with 60% of respondents engaged in it. Settlements are the second most common land use at 32%. The presence of agriculture and settlements emphasizes the close interaction between human activities and the environment, requiring careful planning to balance conservation efforts and development (Mallin et al., 2008). Additionally, 8% of respondents use the land for recreation, offering potential for eco-tourism and supporting conservation initiatives. Overall, attention to these land uses is essential for preserving natural resources and promoting sustainable development.

5.4 The Average Annual Precipitation

Precipitation and rising pollution levels in surface water are commonly assumed to be directly related. For example, surface runoff of pollutants increases with rapid precipitation and can degrade river and stream water quality (Mallin et al., 2000). The high correlation between precipitation and watershed health is due to the impact of rainfall magnitude and intensity on sediment and nutrient loading (Jabbar, 2019). The rainfall year period of this study is from 2000-2023 years and precipitation data ranges from 800-1600 mm (Figure 5.5) (Lehner, 2020).

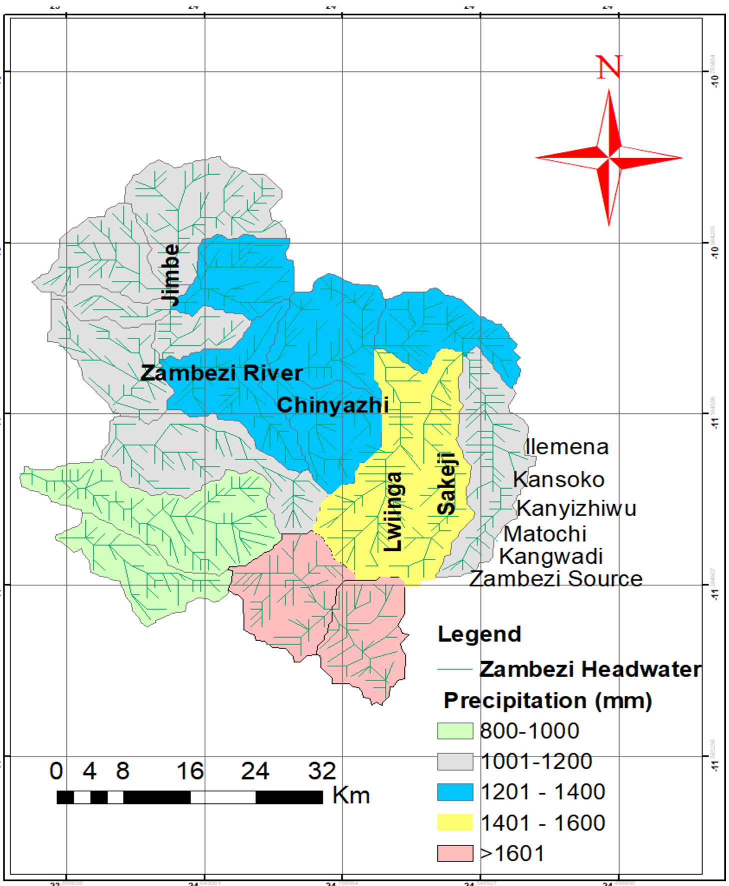

Figure 5.5: Annual Average Precipitation at Zambezi headwaters in Ikelenge District, North-Western Province, Zambia (Lehner, 2020).

The distribution of rainfall in Ikelenge District, North- Western, Zambia from figure 5.5 above it shows that Lwiinga and Sakeji tributaries receiving the highest rainfall, ranging from 1401 - 1600 mm per year. The Zambezi Source and the remaining sampled tributaries of the study area received 1000-1400 mm/year of rainfall (Lehner, 2020). Areas with high precipitation like Sakeji and Lwiinga had high rating of ten (10). The high rating of precipitation of these areas is associated with rainfall magnitude and intensity due to their impact on sediment and nutrient loading (Jabbar, 2019).

To gain a deeper understanding of the impact of precipitation in the study area, a questionnaire-based interview was administered to 166 community members. The primary questions asked were aimed at assessing the community's perception of rainfall in relation to water quality and crop productivity (Figure 5.6).

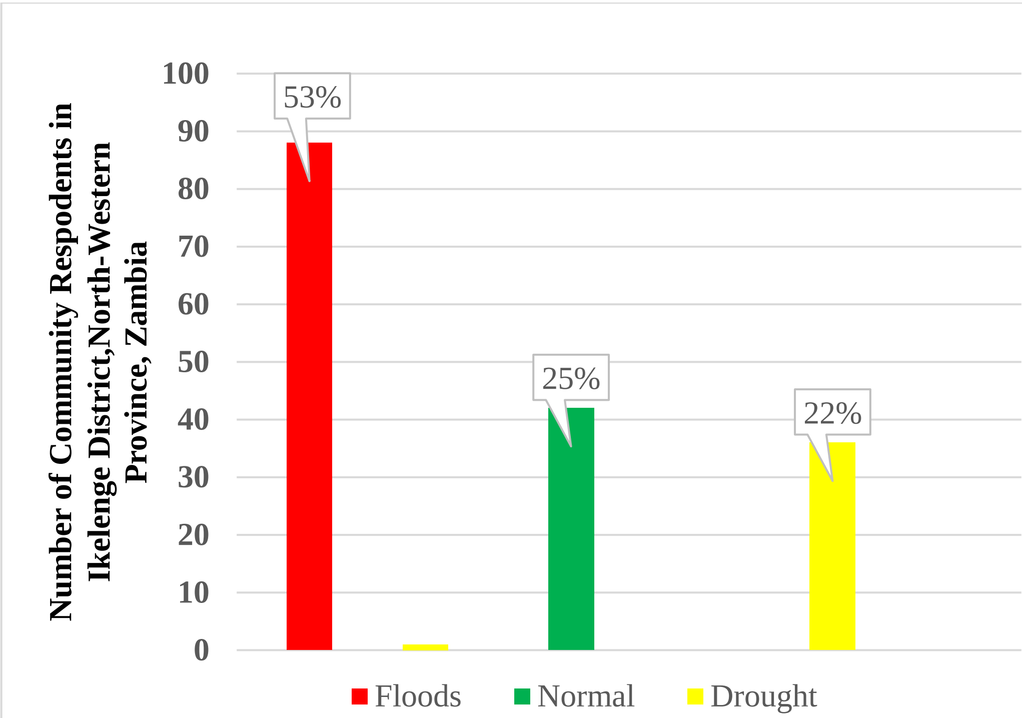

Figure 5.6: Community Perception on Precipitation at Zambezi headwaters in Ikelenge District, North- Western Province of Zambia.

Based on community perception, it is clear that 88 respondents (53%) reported observing changes in precipitation, characterized by floods and high-water turbidity. Similar results were found by Nyambe et al. (2018) in their study on the determinants of spatio-temporal variability of water quality in the Barotse Floodplain, western Zambia. The study results revealed high turbidity in the Zambezi River, attributed to the substantial amount of sediment recruited as water from various tributary streams converges upstream from these rivers. Meanwhile, 42 (25%) of respondents did not notice any precipitation changes, while the remaining 36 (22%) of respondents observed a decrease in precipitation, leading to drying rivers, streams and crop failure due to insufficient water. Among the tributaries from field observation, Sakeji, Lwiinga and Chinyazhi had high turbidity. High turbidity was observed in certain tributaries in the analyzed water samples, ranging from 4.0 to 4.3. Although these values fell within the accepted limit according to the World Health Organization (WHO, 2011), they were high compared to other tributaries, indicating water contamination. This can be attributed to the high precipitation in the area, as illustrated on the precipitation map in Figure 5.5 above and it is also supported by community perception.

5.5 Land-Surface Slope of Ikelenge District, North-Western Province, Zambia.

Land-surface slope determines the amount of precipitation that becomes overland flow and contributes to surface water or pond storage. Surface water is more vulnerable to contamination in areas with steeper surface slopes. When all other factors are the same, precipitation infiltrates into the subsurface in areas characterized by low slopes, whereas in areas with high slopes, precipitation predominantly runs off the land surface (Jabbar, 2019). Land-surface slope in this study ranged from 0-60 degrees (Figure 5.7).

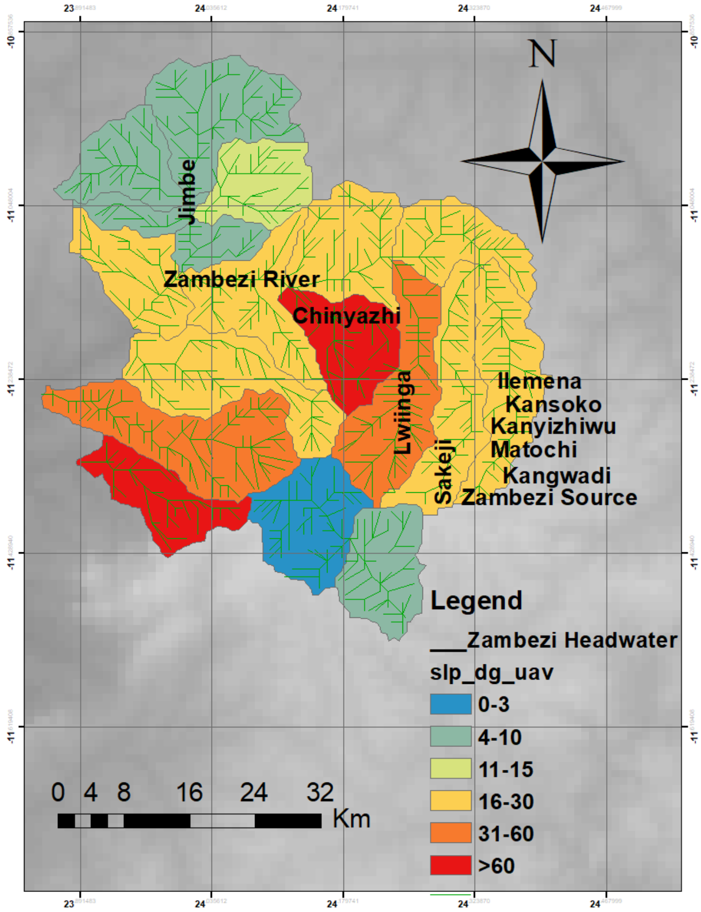

Figure 5.7: Slope analysis of the Zambezi headwaters in Ikelenge District, North-Western Province, Zambia.

The results of figure 5.7 shows that Jimbe had a lower slope in the range of 4-10 degrees, whereas the Zambezi Source, Kangwadi, Matochi, Kanyizhiwu, Kansoko, Ilemena and Sakeji exhibited a slope in the range of 16-30 degrees. Lwiinga had a steep slope of 31-60 degrees, whereas Chinyazhi had an even steeper slope of more than 60 degrees. As a result, potassium levels at both Chinyazhi and Lwiinga tributaries were high in the wet season ranging with values of 0.34mg/l and 0.48mg/l respectively. These results indicate runoff and soil erosion as causes of water contamination. A similar finding by Tedesco et al. (2005), in their assessment of water quality at Eagle Creek, revealed that the steepest slopes in the study area, located near riverbanks, exhibited high surface runoff rates and soil erosion.

5.6 Depth to Groundwater

Different catchment mechanisms connect surface water with groundwater (Banda et al, 2023). Groundwater-surface water interactions are likely influenced by an interplay of factors, such as water levels in the groundwater and surface level and hydrogeological conditions (Banda et al, 2023). Geological variables profoundly influence groundwater quality, primarily through the chemical processes of water-rock interaction. During rainfall events, the water table rises to the surface and groundwater leaks into the river, leading to the mixing of surface water and groundwater (Jabbar, 2019). In this study, as indicated previously the depth to groundwater was categorized into five classes, with shallow groundwater receiving a high rating (10) and deep groundwater receiving a low rating (1) (Figure 5.8).

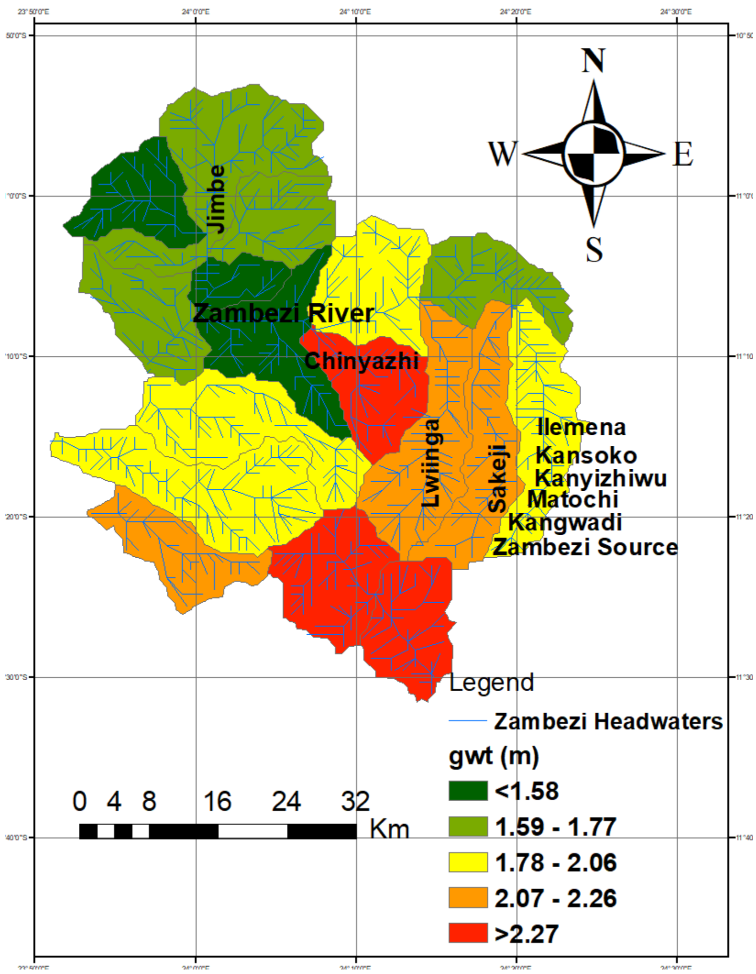

Figure 5.8: Depth to groundwater of the Zambezi headwaters in Ikelenge District, North Western Province of Zambia.

The results from Figure 5.8 underscores a critical insight, low-depth groundwater in the Zambezi headwaters, particularly areas like Jimbe, ranging from 1.59 m to 1.77 m, poses a higher risk of surface water vulnerability. Shallow groundwater levels are at high chance of contamination from land use activities and geological factors (Liu, 2020). In this study Jimbe Tributary with shallow depth had the presence of total coliforms, potassium and high iron concentrations. Although within (WHO, 2011) standards, the study attributes these parameters to human activities like agriculture and settlements, despite a limited footprint of such activities in the area. Similar findings were reported by Liu (2020) in assessing the impact of land use on shallow groundwater quality characteristics associated with human health risks in a typical agricultural area in Central China. The study establishes a correlation between shallow groundwater pollution and land use patterns, particularly nitrogen and phosphorus contamination positively correlated with cultivated land. In contrast, sites with deeper depths to groundwater, like Zambezi Source, Kangwadi, Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji and Lwiinga, exhibit values in the range of 1.78 m to 2.27 m and Chinyazhi tributaries (deepest at 2.27 m). Despite higher concentrations of potassium in areas of greater depth, such as Chinyazhi and Lwiinga tributaries, the study attributes this to extensive agriculture practices and human settlements in these regions, evident on the land use/land cover map.

5.7 Vulnerability Mapping and Calculation

As indicated earlier, in order to assess the vulnerability of the Zambezi headwaters to contamination, a vulnerability index was calculated by incorporating the four identified factors: land use/land cover; precipitation; surface slope; and depth to groundwater. The rating factor multiplied by a weight factor, result in a single vulnerability index value. The calculated vulnerability index (VI) for the Zambezi Source and the nine tributaries are as follows: The Zambezi Source and Kangwadi Tributary had VI of 17.8; Matochi; Kanyizhiwu; Kansoko; and Ilemena Tributary had VI of 28.4; Sakeji Tributary had VI of 29.5; Lwiinga had VI of 31.3; Chinyazhi Tributary had a VI of 30.8; and Jimbe Tributary had a VI of 29.3 (Figure 5.9a and b) (Appendix 8). From the spatial plotting of the vulnerability index in Figure 5.9a, it is observed that the Zambezi River actually flows through areas with a high vulnerability index, suggesting contamination in those areas.

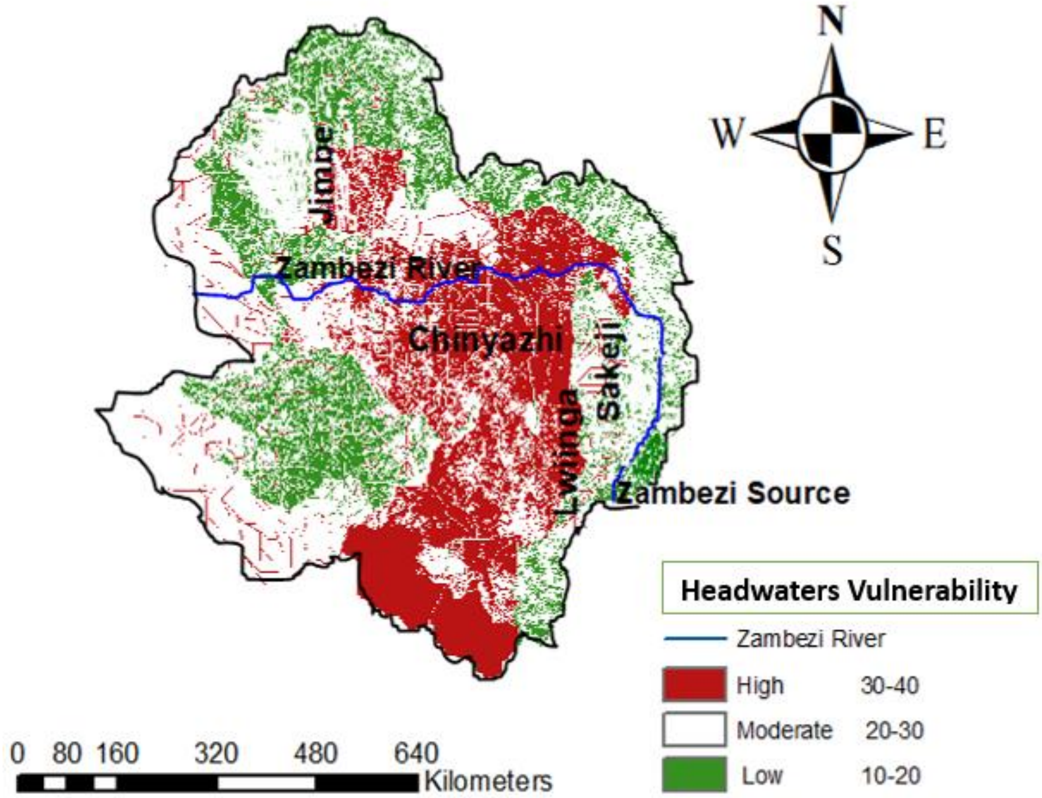

Figure 5.9a: Vulnerability Mapping of Zambezi headwaters in Ikelenge District, North-Western Province of Zambia.

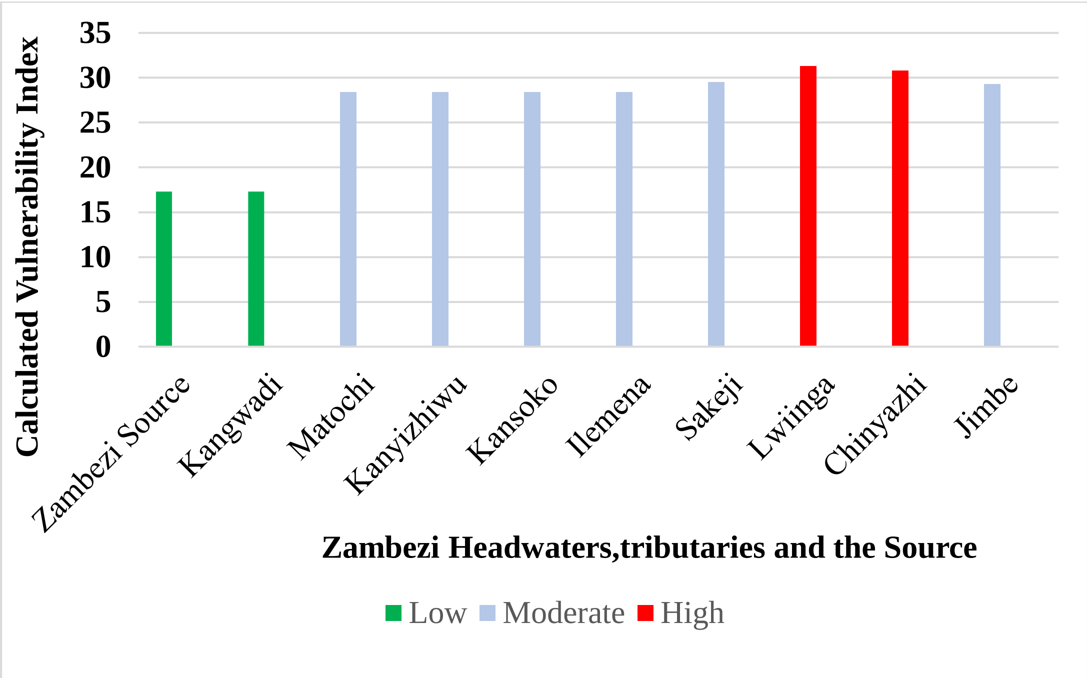

Figure 5.9b: Vulnerability Mapping of Zambezi headwaters in Ikelenge District, North-Western Province of Zambia.

The vulnerability index in this study ranges from 10-40, whereas values of 10-20 indicate low vulnerability to contamination, values of 20-30 indicate moderate vulnerability and values of 30-40 indicate high vulnerability to contamination. The vulnerability of the Zambezi headwaters to contamination is visually represented in Figure 5.9, offering a comprehensive understanding on the varying degrees of vulnerability exposure across the tributaries. The figure serves as a critical asset in gauging and addressing environmental vulnerabilities within the region. Among these tributaries, Lwiinga and Chinyazhi tributaries, emerges as the most vulnerable, exhibiting a vulnerability index ranging between 30-40. This heightened vulnerability underscores the urgent necessity for monitoring and the implementation of safeguarding measures within these areas. Other tributaries namely, Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji and Jimbe displayed a moderately vulnerable profile, characterized by vulnerability index ranging between 20-30. This indicate that these areas have moderate vulnerability not as high as Lwiinga and Chinyazhi tributaries. These tributaries demand focused attention and management strategies to ensure the preservation of their water quality and from the vulnerability calculations area such as Sakeji and Jimbe tributaries their vulnerability is close to high this indicate urgent implementation measures that will ensure environmental sustainability, such as land use control where agriculture activities should be done away from these tributaries as it was observed to be the case in these tributaries. On a more positive note, the Zambezi Source and the Kangwadi Tributary, exhibit a low vulnerability index, ranging between 10-20. This encouraging finding suggests that these regions are less exposed to contamination, signifying a relatively healthier state of water quality within their domains. A similar study was conducted by Widyastuti (2006) to assess contamination vulnerability in the Yogyakarta watershed in Indonesia for water quality monitoring. The study involved three key parameters: land use; precipitation; and surface slope. The outcomes of the study pinpointed areas characterized by high vulnerability, guiding resource allocation. Additionally, the vulnerability index serves as a valuable tool to prioritize areas for conservation and early warning. It underscores the importance of proactive measures to protect the highly vulnerable tributaries, whereas also recognizing areas with low vulnerability as potential candidates for sustainable development and conservation initiatives.

5.8 Relationship Between Vulnerability Index and Water Quality Parameters in Ikelenge District, North-Western Province, Zambia.

The relationship between the vulnerability index and water quality is fundamental in environmental conservation (Jabbar, 2019). To understand this relationship, as indicated earlier the study used the Pearson Correlation method to determine the correlation for both the dry and wet seasons of water quality parameters. During the dry season, the vulnerability index showcased a significant positive correlation with attributes such as electrical conductivity (EC), temperature and pH, with correlation coefficients of $R^2 = 0.93$, $p \leq 0.05$, $R^2 = 0.72$, $p \leq 0.05$ and $R^2 = 0.70$, $p \leq 0.05$ respectively. This shows that as vulnerability increases, these attributes tend to increase as well, hinting at potential shifts in water quality. Other parameters like turbidity and total dissolved solids (TDS) had a negative correlation with correlation coefficients of -0.87 and -0.27, respectively. This suggests a possible reduction in sediment and dissolved solids in the water. In the wet season, a positive significant correlation existed between the vulnerability index and dissolved oxygen (DO), iron, temperature and potassium, resulting in a correlation coefficient of $R^2 = 0.57$, $p \leq 0.05$, $R^2 = 0.70$, $p \leq 0.05$, $R^2 = 0.72$, $p \leq 0.05$ and $R^2 = 0.63$, $p \leq 0.05$ respectively. This potentially reflects high nutrient levels, high levels of iron content, oxygen availability and higher water temperature. Nevertheless, some relationships emerged as more delicate. For instance, the positive correlation between the vulnerability index and EC, TDS, BOD and pH stood as less positive with correlations of 0.24, 0.22, 0.05 and 0.13 whereas the correlation with turbidity had a significant negative correlation of $R^2 = -0.03$, $p \leq 0.05$. This implies a negative connection between vulnerability and turbidity. For fecal and total coliforms, there was a significant negative correlation coefficient of $R^2 = -0.02$ and $R^2 = -0.03$ respectively. This clearly shows that areas with high exposure to vulnerability might exhibit low levels of microbial contamination. A similar study by Nguvulu (2021), assessing surface water quality response to land use/land cover change in an urbanizing catchment of Upper Chongwe River Catchment, Zambia, revealed a positive correlation between built-up/bare land and total dissolved solids (TDS), conductivity, chlorine and turbidity. These correlations are most likely attributed to sediment runoff from construction sites, weathering of rocks and erosion from bare areas. The yielded correlation coefficients in this study demonstrate how the vulnerability is connected to water quality parameters. These findings are important for protecting water from human impacts.

5.9 Enhancing Water Conservation in Ikelenge District, North-Western Zambia Collaborative Initiatives by Government, Private Sector and Non-Governmental Organizations.

The third objective of this study focused on investigating the primary actions taken by the Government, Non-Governmental Organizations and the Private Sector to reduce or eliminate the vulnerability of the Zambezi headwaters to contamination as indicated earlier, when vulnerability arises, various approaches are employed to mitigate the risks. These alternatives include: enhancing adaptive capacities; reducing system exposure to harm or stress; and decreasing system sensitivity to stress or harm (Turner et al., 2003).

The Zambian Government's efforts to protect the Zambezi headwaters encompass a range of research and extension activities (GoZ, 2008). Through the questionnaire interviews the Zambian Government, in Ikelenge District through different line ministries such as, the Ministry of Water Development and Sanitation, Ministry of Tourism and Arts, Ministry of Green Economy and Ministry of Lands and Natural Resources have focused on research activities mainly understanding aquatic biodiversity, culture studies, projects related to ecosystems services, environmental protection and sustainability. Additionally, the Government of Zambia aims to update the water policy to include the protection for the Zambezi Source, which is essential to ensure adequate conservation measures are in place. Collaboration with educational and research institutions allows the dissemination of knowledge and information, leading to better decision-making in resource management (Sievers, 2006). Future studies, by the Government of Zambia through the earlier mentioned line ministries include, hydrological assessments and water conservation. These efforts, planned to further enhance water resource sustainability of the Zambezi headwaters.

The agriculture extension activities highlight the Government of Zambia’s commitment to promote conservation farming and supporting livelihood activities within the community (Ferris et al., 2014). During the interviews with the Ministry of Tourism and Arts, under the Department of National Heritage Conservation Commission, revealed that different measures to empower local communities include encouraging the maintenance of water points and water sources, as well as promoting the adoption of agro-forestry practices and honey production through the use of modern beehives (Figure 5.10).

Figure 5.10: Beehives Instilled at Zambezi Source Ikelenge District, North-Western Province Zambia.

The Government of Zambia also emphasizes investment in renewable energy resources, advocating for environmental conservation and fostering community-based participation in the management of forests, water and protected areas (GoZ, 2008). Efforts to improve sanitation, particularly through the use of well-contrasted toilets in the district, play a significant role in preventing water contamination. Moreover, the promotion of local arts and indigenous knowledge helps foster environmental care among the local people.

Non-Governmental Organizations and the Private Sector such as the World-Wide Fund (WWF), the Deutsche Gesellschaft fur International Zusammenarbeit (GIZ), World Vision Zambia, Stanbic Bank and Kansanshi Mine, these organizations are actively involved in water conservation initiatives of the Zambezi headwaters in Ikelenge District, North-Western Province, Zambia. Their collaboration with the Zambian Government demonstrates their commitment to maintaining the sustainability of the Zambezi headwaters. These stakeholders have undertaken research and implemented plans to ensure water conservation at the Zambezi Headwaters. In addition to advocating for environmental policies, they actively engage local communities and traditional leadership, empowering youths and women to lead climate change response efforts and promoting nature-based solutions like tree planting, an activity that is done at Zambezi Source to restore the degraded areas (Figure 5.11).

Figure 5.11: Her Royal Highness, Chieftainess Ikelenge leading the tree planting process at the Zambezi Source, Ikelenge District, North-Western Province, Zambia.

Preventive measures, such as avoiding ploughing along river banks and controlling animal movements, are also emphasized to preserve water quality at Zambezi headwaters. The initiation of the Zambezi Source Ecosystem Restoration Project by the Government of the Republic of Zambia, in cooperation with various stakeholders, represents a significant step towards protecting the Zambezi headwaters. By restoring the ecosystem to its natural state and supporting alternative livelihoods, this project enhances natural resource management and contributes to the long-term conservation of the vulnerable Zambezi Headwater.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study identified low pH, low dissolved oxygen and high levels of fecal and total coliforms as the major contaminants in the Zambezi headwaters. These issues arise from factors such as land use, precipitation, surface slope and depth to groundwater. The second objective of this study was to analyze the contamination vulnerability of the Zambezi River headwaters in Ikelenge District, North-Western Province of Zambia. The vulnerability index ranged from 10-40, revealing that two tributaries, Lwiinga and Chinyazhi, were highly vulnerable, with vulnerability indices ranging from 30 to 40. One of the major contributing factors to the vulnerability of these two tributaries is the extensive coverage of agricultural land, accounting for nearly 26% and 46% of their respective total areas. On the other hand, the vulnerability indices for the Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji, and Jimbe tributaries were classified as moderate, falling within the range of 20-30. The vulnerability of the Zambezi Source and the Kangwadi Tributary was categorized as low, with vulnerability indices ranging from 10-20. These regions of low vulnerability exhibit high forest cover, specifically 82.9% for the Zambezi Source and 72.4% for Kangwadi.

A sensitivity and validation analysis of vulnerability was conducted through regression correlation. The findings revealed a significant positive correlation between the vulnerability index and water parameters during the dry season, particularly with electrical conductivity (r^2=0.93, $p \leq 0.05$), pH (r^2=0.70, $p \leq 0.05$) and temperature (r^2=0.72, $p \leq 0.05$). The values of turbidity (r^2= -0.87, $p \leq 0.05$) and total dissolved solids (r^2= -0.27, $p \leq 0.05$) demonstrated a significant negative correlation with vulnerability. During the wet season, the results demonstrated a significant positive correlation between water quality and vulnerability, particularly regarding dissolved oxygen (r^2=0.57, $p \leq 0.05$), iron (r^2=0.70, $p \leq 0.05$), potassium (r^2=0.63, $p \leq 0.05$), electrical conductivity (r^2=0.24, $p \leq 0.05$), total dissolved solids (r^2=0.22, $p \leq 0.05$), biological oxygen demand (r^2=0.05, $p \leq 0.05$) and pH (r^2=0.13, $p \leq 0.05$). The values of turbidity, total and fecal coliforms exhibited a significant negative relationship with vulnerability. For fecal and total coliforms, there was a significant negative correlation coefficient of r^2 = -0.02, $p \leq 0.05$, and r^2 = -0.03, $p \leq 0.05$, respectively. The positive correlation proved the sensitivity and validation analysis. The Principal Component Analysis loadings indicate that geological influence, mineral salts, organic pollution and agricultural waste significantly influence the water quality of the Zambezi headwaters. The water quality index revealed that the Zambezi Source, Kangwadi, Matochi, Kanyizhiwu, Kansoko, Ilemena, Sakeji, Chinyazhi and Jimbe tributaries had an index of 51-70, indicating moderate water quality, whereas Lwiinga Tributary had a water quality index of 71-90, indicating good water quality. The study results highlight the significant vulnerability of certain tributaries within the Zambezi headwaters due to agricultural practices and other land uses. This indicates a pressing need for targeted interventions to reduce contamination and improve water quality. The correlation between water parameters and vulnerability indices underscores the importance of continuous monitoring and assessment to mitigate potential risks. The findings emphasize the critical role of sustainable land use practices and effective watershed management in preserving water quality and reducing vulnerability. Finally, the study revealed measures implemented by the Zambian Government, Non-Governmental Organizations and the Private Sector to reduce headwaters vulnerability. Plans, such as promoting agroforestry, conducting research and engaging the community in policy advocacy, play a significant role in protecting the Zambezi headwaters. Projects like the Zambezi Source Ecosystem Restoration represent a significant step towards safeguarding the Zambezi headwaters. Restoring the ecosystem to its natural state and supporting alternative livelihoods enhance natural resource management and contribute to the long-term conservation of the vulnerable Zambezi headwater. These efforts underscore the importance of integrated approaches involving multiple stakeholders to ensure the sustainability of critical water resources.

6.2 Recommendations

Based on the findings of this study, the following recommendations are made for the water resources managers in Government, Private Sector, Non-Governmental Organization and academic and research institutions:

i. The Government of Zambia to implement restoration projects to rehabilitate degraded areas such as Lwiinga and Chinyazhi tributaries that are marked as highly vulnerable areas. These projects and actions should include, reforestation efforts, erosion control measures and the establishment of buffer zones to protect water bodies from sediment and pollutants;
ii. The Government of Zambia through the Ministry of Water Development and Sanitation and WARMA to implement effective water pollution monitoring and prevention programmes. This will help maintain the water quality of the Zambezi headwaters and protect it from potential contaminants;

iii. The Government of Zambia through the Ministry of Agriculture to promote the development of small-scale beneficiary-managed irrigation schemes, emphasizing efficient water management practices to ensure water availability whereas preserving environmental integrity;

iv. The Government of Zambia in all line ministries, the Non-Governmental organizations and the Private Sector to train and re-orient extension officers to actively engage and involve local communities in natural resource management. Empowering communities with knowledge and skills will foster their active participation in safeguarding the Zambezi headwaters;

v. The academic and research institutions, such as the University of Zambia, should consider conducting comprehensive research on groundwater, surface water, climate change, biodiversity and buffer zones in the region to raise public awareness about the interrelationships of these factors and their impact on the environment;

vi. The Government of Zambia, Non-Governmental Organizations and the Private Sector to consider providing alternative income-generating activities for local communities to reduce their dependence on forest products. The promotion of commercial use of non-timber forest products can alleviate pressure on the forests, ensuring their conservation for water resource sustainability; and

vii. Strong collaboration and partnerships among Government agencies, Non-Governmental Organizations, Private Sector and local communities to build a strong Integrated Water Resource Management that will ensure the sustainability of the Zambezi headwaters.

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APPENDIX 1: Questionnaire for the community on vulnerability of Zambezi Basin headwaters: a case study of Ikelenge District, North-Western Province, Zambia.

The University of Zambia, School of Mines

Thank you for choosing to participate in this academic study. My name is Stephen Mbewe, and my student number is 22000338. I am a student at the University of Zambia, pursuing a Master of Science degree in Integrated Water Resource Management. This study is undertaken in partial fulfilment of the University of Zambia's requirements for a master's degree program. The study is being conducted at the Zambezi source in Ikelenge District, North-Western Province, Zambia. The aim of the study is to investigate the vulnerability of the Zambezi Headwater to potential pollutants. This research project is guided by the following objectives:

i. To identify the potential contaminants of the Zambezi headwaters' vulnerability.
ii. To analyze the contamination vulnerability of the Zambezi headwaters using the weighing and rating method, GIS, and sensitivity analysis.
iii. To investigate the main measures implemented by the government and non-governmental organizations to mitigate or prevent the vulnerability of the Zambezi headwaters to potential contaminants.

Therefore, I kindly request that you take the time to respond to the various questions in the questionnaire, as applicable. The questions will cover topics related to water resource management and other related areas. Given the complexity of the study area and the realities in Zambia, I am relying largely on purposive sampling, which is based on the researcher's judgment of who might have reliable data on the topic. Your participation in this study is entirely voluntary. Any information collected in this study will be used for academic purposes and will be anonymized accordingly.

Yes ☐ No ☐

Sign: …………………………. Date: ……………………………

End! Thank you for your time and participation.

PART 1: DEMOGRAPHIC AND SOCIAL ECONOMIC CHARACTERISTICS OF RESPONDENTS			
Respondent's code	Age: ……years	Gender: Male ☐ Female: ☐	
Marital status: ☐ Single ☐ Married ☐ Divorce ☐ Widowed:		Catchment:	
Occupation:		Longitude: Elevation:	Latitude:

PART 2: LIVELIHOOD QUESTIONS

i. What crops are grown here? …………………………………………………………………………………………. ..
……...

ii. Crops grown here depends on? (a) fertilisers (b) manure (c) non (d) both a and b

iii. What are the major livelihood activities in this region?..
………

iv. Do you see any effect of land use on water quality? (a) yes (b) no

v. What effect did you observe (a) water clean (b) water dirty (c) non

vi. What are the common land cover type in this region?
……………………………………………...
…….

vii. Do you see any effect of land cover on water quality? (a) yes (b) no

viii. What effect did you observe on land cover type (a) water increase (b) water reduction (c) non

PART 3: SOURCE OF WATER AND CONSERVATION

ix. What do you understand by the term water conservation?..
....

x. What is the source of drinking water in this region? (a) streams (b) tapes (c) wells (d) streams and wells

xi. What is the source of farming water in this region? (a) irrigation (b) rainfall (c) both a and b

xii. Do you know any information of water conservation? (a) yes (b) no

xiii. Where do you get the information on water conservation? (a) government (b) private sector (c) both a and b (c) non

xiv. Indicate institutions that are present in the area that are key in water resource management?

- ☐ Forestry department
- ☐ Traditional leadership
- ☐ WARMA
- ☐ National Heritage Conservation Commission
- ☐ Private sector ☐ Others, please specify…………………

xv. How do you hear information on water conservation? (a) radio (b) community meetings (c) megaphones (d) non

xvi. What role do you play to ensure water conservation in this region?...
....

xvii. Are you willing to join the groups advocating for water conservation? (a) yes (b) no

xviii. What is the major limitation of water conservation in this region?...
....

PART 4: SANITATION AND DISEASES

xix. Do you have any records of water borne diseases in this region? (a) yes (b) no

xx. If yes what are the common water borne diseases in this region and how do you treat it?
....

xxi. What type of toilet system do you have in this region? (a) no proper toilets (b) proper toilets

xxii. What type of water purification do you apply in this region? (a) boiling (b) chlorination (c) solar disinfection (d) non

PART 5: RAINFALL AND TEMPERATURE

xxiii. What rainfall changes have you been observing for the past years? (a) floods (b) droughts (c) non

xxiv. How does this rainfall affect the water quality in this region? (a) clean (b) dirty (c) non

xxv. When did you observe these changes in rainfall?...

xxvi. What changes have you been observing for the past years in temperature? (a) Increase (b) reduction (c) normal

xxvii. How does this temperature affect the water quality? (a) reduce water (b) increase water(c) non

xxviii. When did you observe these changes in temperature? ....

PART 6: ENDING

xxix. Do you have any other information that you can add or ask to what we have already discussed?
……………………………………………………………………………………………………..

End! Thank you for your time and participation.

APPENDIX 2: Questionnaire for key stakeholders on vulnerability of Zambezi Basin headwaters: a case study of Ikelenge District, North-Western Province, Zambia.

the University of Zambia School of Mines

Thank you for choosing to participate in this academic study. My name is Stephen Mbewe, and my student number is 22000338. I am a student at the University of Zambia, pursuing a Master of Science degree in Integrated Water Resource Management. This study is undertaken in partial fulfilment of the University of Zambia's requirements for a master's degree program. The study is being conducted at the Zambezi source in Ikelenge District, North-Western Province, Zambia. The aim of the study is to investigate the vulnerability of the Zambezi Headwater to potential pollutants. This research project is guided by the following objectives:

1. To identify the potential contaminants of the Zambezi headwaters' vulnerability in Ikelenge District, North-Western Province, Zambia.

2. To analyze the contamination vulnerability of the Zambezi headwaters using the weighing and rating method, GIS, and sensitivity analysis.

3. To investigate the main measures implemented by the Government and Non-governmental organizations to mitigate or prevent the vulnerability of the Zambezi headwaters to potential contaminants.

Therefore, I kindly request that you take the time to respond to the various questions in the questionnaire, as applicable. The questions will cover topics related to water resource management and other related areas. Given the complexity of the study area and the realities in Zambia, I am relying largely on purposive sampling, which is based on the researcher's judgment of who might have reliable data on the topic. Your participation in this study is entirely voluntary. Any information collected in this study will be used for academic purposes and will be anonymized accordingly.

Yes ☐ No ☐

Sign: ………………………… Date: ……………………………

PART 1: DEMOGRAPHIC AND SOCIAL ECONOMIC CHARACTERISTICS OF RESPONDENTS

Name:	Age: ……	Gender: Male ☐ Female: ☐
Marital status: ☐ Single ☐ Married ☐ Divorce ☐ Widowed:		Occupation…………………………… Position…………………………………
Contact# ………………………………… Email…………………................................		Province…………………………………………... District………………………………………………

PART 2: INTRODUCTION

i. What are your main objectives in the country?
....
....

ii. Are your objectives achieved? (a) yes (b) no

iii. Are your objectives in line with environmental sustainability? (a) yes (b) no

PART 3: PROTECTION AND CONSERVATION

i. What is your major role at Zambezi Headwaters?
....
....

ii. How are the Zambezi headwaters protected?
....

iii. What factors limit headwater protection?...

iv. How can these factors be addressed?...

v. How effective is the current policy on water protection and conservation? (a) very effective (b) not effective (c) other ………………………………………………………………………………………

vi. Are there cooperatives in the community working with your sector to ensure water conservation?

vii. Are the community aware on the benefit of water protection and conservation?.......................................

viii. How do the community receive the information on water protection and conservation?.....................................

ix. What actions are done to the people that does not follow conservation principles i.e., deforesters?

……

x. What factors contribute highly to water quality contamination in the Zambezi headwaters?

(a) land use/ land cover (b) slope (c) precipitation (d) depth to ground water

(b) From the scale of 1-9 give each factor a number based on its impact? ………………………………………

xi. On the rate of 1 to 10 give each of these factors a rate?...

xii. Explain how each factor affect water quality?

…….

PART 4: BENEFITS

xiii. What are the major benefits of the Zambezi Headwaters?..

....

....

xiv. What type of ecosystem service are provided by the source?..

………

xv. Are the benefits provided by the Zambezi headwaters recognized worldwide?...

xvi. What are the chances that the Zambezi headwaters will continue to provide these benefits even in future is there anything done to ensure sustainability?...

…………………………………………………………………………………………………..

PART 5: RESEARCH

xvii. Is there any research done in this region?...

xviii. If yes, what type of research was done?...

xix. What are the current or ongoing studies in this area?..

……………………………………………………………………………………………………..

xx. are these studies helpful in water conservation and protection?...

PART 6: STAKEHOLDER ASSESSEMENTS WEIGHTS AND RATIING OF A GIVEN FACTORS IN RELATION TO WATER QUALITY. SEE APPENDIX 3,4,5, 6 and 7.y

PART 7: ENDING

xxi. Do you have any other information that you can add or ask to what we have already discussed? (a) yes (b) no

xxii. If yes pleases do so…………………………………………………………………………………………

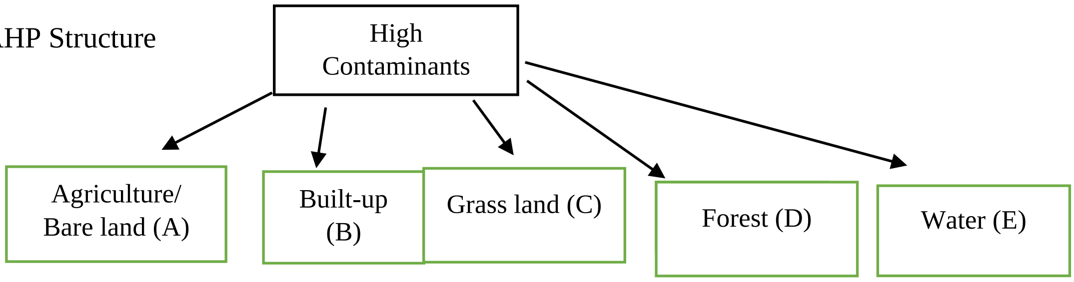
I am asking for any relevant document:

Email: stephenmbewe87@gmail.com

End! Thank you for your time and participation.

APPENDIX 3: Stakeholder Assessment and Analytical Hierarchy Process for Land use/Land cover Calculation in Ikelenge, District, North-Western Province, Zambia.

AHP Structure



Pairwise comparison matrix

FACTORS	A	B	C	D	E
A	1	3	6	7	6
B	0.33	1	3	4	2
C	0.17	0.3	1	4	2
D	0.14	0.3	0.3	1	2
E	0.17	0.5	0.5	0.5	1
eigenvector	1.81	5.1	10.8	16.5	13

Normalised pairwise comparisons weights						
FACTORS	A	B	C	D	E	Criteria weight
A	0.55	0.59	0.56	0.42	0.46	0.52081
B	0.18	0.2	0.28	0.24	0.15	0.2176
C	0.09	0.06	0.09	0.24	0.15	0.12776
D	0.08	0.06	0.29	0.06	0.15	0.06675
E	0.09	0.098	0.05	0.03	0.08	0.06704

<u>Lambdamax calculation</u>

2.47/0.52 = 4.751176053

1.17/0.22 = 5.394425552

0.69/0.13 = 5.394380088

0.38/0.07 = 5.750996255

0.36/0.07 = 5.394286993

lambda max = 5.3

CI=lambda max-n/n-1

CI= 5.3-5/4

CI= 0.075

CR= CI/RI

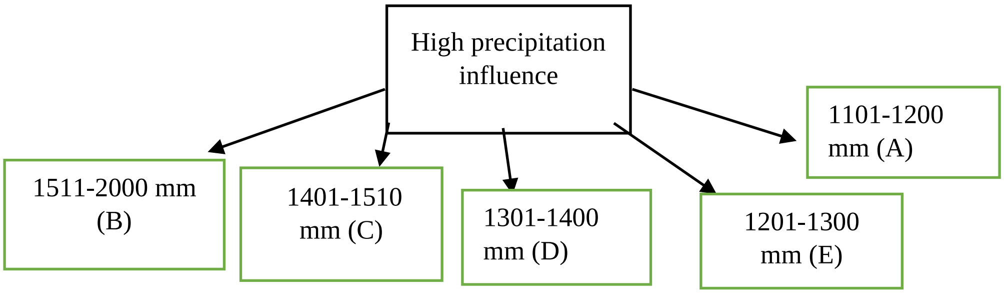
CR=0.067

Weighted values						
FACTORS	**A**	**B**	**C**	**D**	**E**	**VALUE**
A	0.52081	0.6528	0.76656	0.46725	0.06704	2.47446
B	0.171867	0.2176	0.38328	0.267	0.13408	1.173827
C	0.088538	0.071808	0.12776	0.267	0.13408	0.689186
D	0.072913	0.071808	0.038328	0.06675	0.13408	0.383879
E	0.088538	0.1088	0.06388	0.033375	0.06704	0.361633

APPENDIX 4: Stakeholder Assessment and Analytical Hierarchy Process for Precipitation calculation in Ikelenge, District, North-Western Province, Zambia.

1	2	3	4	5	6	7	8	9
Equal Importance	Weak	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong	Very, very strong	Extreme importance

AHP structure



Pairwise comparison matrix

Factors	A	B	C	D	E
A	1	0.167	0.25	0.33	0.5
B	6	1	4	5	6
C	4	0.25	1	2	3
D	3	0.2	0.5	1	1
E	2	0.167	0.33	1	1
eigenvector	16	1.784	6.08	9.33	11.15

<u>Lambdamax calculation</u>

0.26/0.06 = 4.7581

2.6/0.5 = 4.8962

0.97/0.21= 4.6953

0.55/0.09= 5.7677

0.44/0.07= 5.9229

Lambdamax=5.2

CI=lambda max-n/n-1

CI= 5.2-5/4

CI= 0.052

Normalised pairwise comparison weights

Factors	A	B	C	D	E	Weights
A	0.063	0.094	0.041	0.035	0.045	0.0556
B	0.375	0.561	0.658	0.536	0.538	0.5336
C	0.25	0.14	0.164	0.214	0.269	0.2074
D	0.188	0.112	0.082	0.001	0.09	0.0946
E	0.13	0.094	0.054	0.001	0.09	0.0738

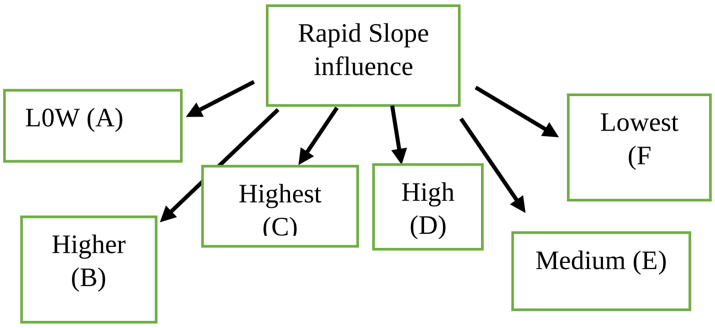
Weighted values

Factor	A	B	C	D	E	Value Weighted
A	0.0556	0.089	0.05185	0.0312	0.0369	0.26455
B	0.3336	0.5336	0.8296	0.473	0.4428	2.6126
C	0.2224	0.1334	0.2074	0.1892	0.2214	0.9738
D	0.1668	0.10672	0.1037	0.0946	0.0738	0.54562
E	0.1112	0.08911	0.0684	0.0946	0.0738	0.43711

APPENDIX 5: Stakeholder Assessment and Analytical Hierarchy Process for Slope calculation in Ikelenge District, North-Western Province, Zambia

1	2	3	4	5	6	7	8	9
Equal Importance	Weak	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong	Very, very strong	Extreme importance

AHP Structure



Pairwise comparison matrix

Slope	A	B	C	D	E	F
A	1	0.25	0.143	0.33	0.25	0.2
B	4	1	2	3	2	7
C	7	0.5	1	5	6	7
D	3	0.33	0.2	1	2	3
E	4	0.5	0.167	0.5	1	2
F	5	0.143	0.143	0.33	0.5	1
eigenvector	24	2.723	3.653	10.16	11.75	20.2

Normalized pair- wise comparison weights

Slope	A	B	C	D	E	F	Weight
A	0.04	0.092	0.039	0.032	0.021	0.0099	0.038983
B	0.16	0.367	0.547	0.295	0.17	0.347	0.314333
C	0.28	0.184	0.274	0.492	0.511	0.347	0.348
D	0.12	0.121	0.055	0.098	0.17	0.149	0.118833
E	0.16	0.184	0.046	0.049	0.085	0.099	0.103833
F	0.24	0.053	0.039	0.032	0.043	0.05	0.076167

<u>Lambdamax calculation</u>

0.2453/0.038983= 6.29

2.263599/0.314333= 7.2

2.52838/0.348= 7.2

0.845279/0.118833= 7.1

0.686798/0.103833= 6.6

0.456927/0.076167= 5.7

=6.7

CI= Lambdamax-6/5

CI= 0.14

CR=CI/CI

CR=0.1

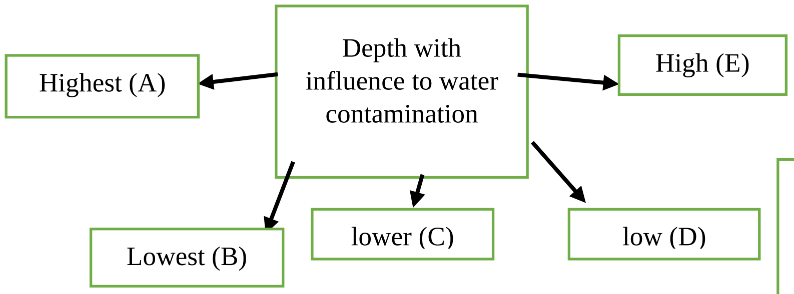
Weighted value

Slope	A	B	C	D	E	F	Value
A	0.038983	0.078583	0.049764	0.039215	0.025956	0.012799	0.2453
B	0.155932	0.314333	0.696	0.356499	0.207666	0.533169	2.263599
C	0.272881	0.157167	0.348	0.594165	0.622998	0.533169	2.52838
D	0.116949	0.10373	0.0696	0.118833	0.207666	0.228501	0.845279
E	0.155932	0.157167	0.058116	0.059417	0.103833	0.152334	0.686798
F	0.194915	0.04495	0.049764	0.039215	0.051917	0.076167	0.456927

APPENDIX 6: Stakeholder Assessment and Analytical Hierarchy Process for Depth to groundwater calculation

1	2	3	4	5	6	7	8	9
Equal Importance	Weak	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong	Very, very strong	Extreme importance

AHP Structure



Lambdamax Calculation

0.263753/0.052053=5.1

2.836888/0.539018=5.3

1.049685/0.203388=5.2

0.571196/0.113287=5.0

0.467206/0.092252=5.0

Lambdamax=5.1

CI= Lambdamax-6/5

CI=5.1

CR=CI/CR

CR=0.024

Pairwise comparison matrix

FACTORS	A	B	C	D	E
A	1	0.142857	0.25	0.3333	0.5
B	7	1	4	5	6
C	4	0.25	1	2	3
D	3	0.2	0.5	1	1
E	2	0.166666	0.33333	1	1
Eigenvector	17	1.759523	6.08333	9.3333	11.5

Normalized pair- wise comparison weights

FACTORS	A	B	C	D	E	WEIGHT
A	0.058824	0.081191	0.041096	0.035679	0.043478	0.052053
B	0.411765	0.568336	0.657535	0.535716	0.521739	0.539018
C	0.235294	0.142108	0.164384	0.214286	0.26087	0.203388
D	0.176471	0.113667	0.082192	0.107147	0.086957	0.113287
E	0.117647	0.094719	0.054789	0.107147	0.086957	0.092252

Weighted value

FACTORS	A	B	C	D	E	VALUE
A	0.052053	0.077002	0.050847	0.037725	0.046126	0.263753
B	0.364371	0.539018	0.813552	0.566435	0.553512	2.836888
C	0.208212	0.134755	0.203388	0.226574	0.276756	1.049685
D	0.156159	0.107804	0.101694	0.113287	0.092252	0.571196
E	0.104106	0.089833	0.067728	0.113287	0.092252	0.467206

APPENDIX 7: Factor Rating of Vulnerability Assessment in Ikelenge District, North-Western Province, Zambia.

Subcategories rating between 1 to 10 where 1 refers to very low impacts on water quality while high scores rate as having a very high impact.

Land use/Land cover rating by stakeholders in Ikelenge District, North-Western Province, Zambia.

Stakeholders	Agriculture	Built-up	Grassland	Forest	Water
Stakeholder 1	10	7	6	4	1
Stakeholder 2	10	9	5	4	1
Stakeholder 3	10	7	5	4	1
Stakeholder 4	10	8	5	4	1
Stakeholder 5	10	7	5	4	1
Stakeholder 6	10	6	6	4	1
Stakeholder 7	10	7	5	4	1
Average	10	7	5	4	1

Precipitation (mm) rating based on literature review and stakeholder's decision in Ikelenge District, North-Western Province, Zambia.

Stakeholders	>1600	1401-1600	1201-1400	1001-1200	800-1000
Stakeholder 1	10	8	6	4	1
Stakeholder 2	10	8	6	4	1
Stakeholder 3	10	8	6	4	1
Stakeholder 4	10	8	6	4	1
Stakeholder 5	10	8	6	4	1
Stakeholder 6	10	8	6	4	1
Stakeholder 7	10	8	6	4	1
Average	10	8	6	4	1

Slope (degrees) rating based on literature review and stakeholder's decision in Ikelenge District, North-Western Province, Zambia.

Stakeholders	**>60**	**31-60**	**16-30**	**11-15**	**4-10**	**0-3**
Stakeholder 1	10	8	6	4	2	1
Stakeholder 2	10	8	6	4	2	1
Stakeholder 3	10	8	6	4	2	1
Stakeholder 4	10	8	6	4	2	1
Stakeholder 5	10	8	6	4	2	1
Stakeholder 6	10	8	6	4	2	1
Stakeholder 7	10	8	6	4	2	1
Average	10	8	6	4	2	1

Depth to groundwater (m) rating based on literature review and stakeholder's decision in Ikelenge District, North-Western Province, Zambia.

Stakeholders	**>2.27**	**2.07-2.26**	**1.78-2.06**	**1.59-1.77**	**<1.58**
Stakeholder 1	10	8	6	4	1
Stakeholder 2	10	7	6	3	1
Stakeholder 3	10	8	5	4	1
Stakeholder 4	10	8	6	4	1
Stakeholder 5	10	9	7	5	1
Stakeholder 6	10	8	6	4	1
Stakeholder 7	10	8	6	4	1
Average	10	8	6	4	1

APPENDIX 8: Vulnerability Calculation of the Zambezi headwaters in Ikelenge District, North-Western Province, Zambia.

$$VI = \sum_{j=1}^{n} W_j \times C_{ij}$$

W_j is the weight of each factor and C_{ij} is the rate of a factor based on its suitability analysis from stakeholder's decision and literature review.

Zambezi Source

VI= (20 X 0.781) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 15.62 + 0.296 + 0.714 + 0.678

VI= 17.3 low

Kangwadi Tributary

VI= (20 X 0.781) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 15.62 + 0.296 + 0.714 + 0.678

VI= 17.3 low

Matochi Tributary

VI= (0.99 X 27) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 26.73 + 0.296 + 0.714 + 0.678

VI= 28.4 moderate

Kanyizhiwu Tributary

VI= (0.99 X 27) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 26.73 + 0.296 + 0.714 + 0.678

VI= 28.4 moderate

Kansoko Tributary

VI= (0.99 X 27) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 26.73 + 0.296 + 0.714 + 0.678

VI= 28.4 moderate

Ilemena Tributary

VI= (0.99 X 27) + (4 X 0.074) + (6 X 0.119) + (6X 0.113)

VI= 26.73 + 0.296 + 0.714 + 0.678

VI= 28.4 moderate

Sakeji Tributary

VI= (0.99 X 27) + (0.207 X 8) + (6 X 0.119) + (4 X 0.092)

VI= 26.73 + 1.656 + 0.714 + 0.368

VI= 29.5 moderate

Lwiinga Tributary

VI= (0.99 X 27) + (0.207 X 8) + (0.314 X 8) + (4 X 0.092)

VI= 26.73 + 1.656 + 2.512 + 0.368

VI= 31.3 high

Chinyazhi Tributary

VI= (0.99 X 27) + (0.095 X 6) + (0.348 X 10) + (0.052 X 1)

VI= 26.73 + 0.57 + 3.48 + 0.052

VI= 30.8 high

Jimbe Tributary

VI= (0.99 X 27) + (4 X 0.074) + (0.104 X 2) + (8X 0.203)

VI= 26.73 + 0.296 + 0.208+ 0.452 + 1.624

VI= 29.3 moderate

APPENDIX 9: National sanitation foundation water quality index (WQI-NSF) Method Applied at Zambezi headwaters in Ikelenge District, North-Western Province, Zambia.

Weighting factor

WQI== $\sum_{i=0}^{n} WIQI$

Zambezi Source

Parameters	Weight	Measured value		Q_I	W_IQ_I
DO (mg/l)	0.17	4.8 mg/l	52.56 % saturation	40	6.8
Feacal coliforms (cfu/100 ml)	0.15	2		92	13.8
pH	0.12	5.2		30	3.6
BOD (mg/l)	0.10	1.0		90	9.0
NITRATES (mg/l)	0.10	0.001		100	10
PHOSPHATE (mg/l)	0.10	0.001		100	10
Temperature (°c)	0.10	19.8		21	2.1
Turbidity (NTU)	0.08	3.7		82.5	6.6
TDS (mg/l)	0.08	5.0		83	6.64
					68.9

Kangwadi Tributary 1

Parameters	Weight	Measured values		Q_I	W_IQ_I
DO (mg/l)	0.17	5.2 mg/l	53.89% saturation	41	6.97
Feacal coliforms (cfu/100 ml)	0.15	5		90	13.5
pH	0.12	3.9		9	1.08
BOD (mg/l)	0.10	0.9		99.9	9.99
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	0.01		100	10
Temperature (°c)	0.10	17.1		26	2.6
Turbidity (NTU)	0.08	3.3		86	6.88
TDS (mg/l)	0.08	4.7		82	6.56
					67.4

Matochi Tributary 2

Parameters	**Weight**	**Measured values**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	6.8 mg/l	76.11 % saturation	74	12.58
Feacal coliforms (cfu/100 ml)	0.15	15		62	9.3
PH	0.12	4.1		11	1.32
BOD (mg/l)	0.10	1.0		90	9.0
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	20.9		19.6	1.96
Turbidity (NTU)	0.08	3.4		85	6.8
TDS (mg/l)	0.08	3.4		80.1	6.41
					67.4

Kanyizhiwu Tributary 3

Parameters	**Weight**	**Measured values**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	5.6 mg/l	61.82% saturation	60	10.2
Feacal coliforms (cfu/100 ml)	0.15	196		30	4.5
pH	0.12	4.0		10	1.2
BOD (mg/l)	0.10	1.3		89	5.9
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	20.2		19.9	1.99
Turbidity (NTU)	0.08	3.5		84	6.72
TDS (mg/l)	0.08	3.7		80.2	6.42
					56.93

Kansoko Tributary 4

Parameters	**Weight**	**Measured values**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	6.7 mg/l	74% saturation	70	11.9
Feacal coliforms (cfu/100 ml)	0.15	71		50	7.5
pH	0.12	3.8		8	0.96
BOD (mg/l)	0.10	1.0		90	9.0
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	20.3		19.8	1.98
Turbidity (NTU)	0.08	0.3		99.5	7.96
TDS (mg/l)	0.08	10.5		88	7.04
					66.34

Ilemena Tributary 5

Parameters	**Weight**	**Measured values**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	4.4 mg/l	48.86% saturation	38	6.46
Feacal coliforms (cfu/100 ml)	0.15	139		33	4.95
pH	0.12	4.1		11	1.32
BOD (mg/l)	0.10	0.7		99.7	9.97
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	20.5		19.7	1.97
Turbidity (NTU)	0.08	0.4		99.4	7.95
TDS (mg/l)	0.08	4.8		82	6.56
					59.18

Sakeji Tributary 6

Parameters	**Weight**	**Measured value**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	5.8 mg/l	65.04% saturation	63	10.71
Feacal coliforms (cfu/100 ml)	0.15	66		52	7.8
pH	0.12	4.9		20	2.4
BOD (mg/l)	0.10	1.3		89	8.9
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	21.0		18	1.8
Turbidity (NTU)	0.08	4.0		81	6.48
TDS (mg/l)	0.08	4.0		81	6.48
					64.57

Lwiinga Tributary 7

Parameters	**Weight**	**Measured values**		**Q_I**	**W_IQ_I**
DO (mg/l)	0.17	6.9 mg/l	78.44 % saturation	80	13.6
Feacal coliforms (cfu/100 ml)	0.15	56		55	8.25
pH	0.12	6.0		50	6.0
BOD (mg/l)	0.10	1.0		90	9.0
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	21.7		17.9	1.79
Turbidity (NTU)	0.08	4.1		80	6.4
TDS (mg/l)	0.08	10		87	6.96
					72

Chinyazhi Tributary 8

Parameters	**Weight**	**Measured values**		Q_I	W_IQ_I
DO (mg/l)	0.17	6.1 mg/l	70.83 % saturation	67	11.39
Feacal coliforms (cfu/100 ml)	0.15	119		38	5.7
pH	0.12	4.7		19	2.28
BOD (mg/l)	0.10	0.8		99.8	9.98
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	<0.01		100	10
Temperature (°c)	0.10	22.8		16	1.6
Turbidity (NTU)	0.08	4.3		79	6.32
TDS (mg/l)	0.08	5.3		83.5	6.68
					63.95

Jimbe Tributary 9

Parameters	**Weight**	**Measured values**		Q_I	W_IQ_I
DO (mg/l)	0.17	6.2 mg/l	74.07% saturation	71	12.07
Feacal coliforms (cfu/100 ml)	0.15	24		60	9.0
pH	0.12	4.4		13	1.56
BOD (mg/l)	0.10	0.8		99.8	9.98
Nitrates (mg/l)	0.10	<0.01		100	10
Phosphate (mg/l)	0.10	0.01		100	10
Temperature (°c)	0.10	24.3		15	1.5
Turbidity (NTU)	0.08	3.8		82	6.56
TDS (mg/l)	0.08	4.4		81.5	6.52
					67.19

NFS-WQI Rating Curves.