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EVALUATING THE IMPACT OF LAND USE ACTIVITIES IN AND AROUND LAKE KARIBA ON THE PRESENCE AND LEVELS OF ANIONS AND CATIONS IN THE WATER BODY

by

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1920318

A dissertation submitted in fulfilment of the requirements for the degree Master of Science in Chemistry to the Faculty of Science at the University of the Witwatersrand

September 2024

DECLARATION

I hereby certify that this dissertation is all my own. It is being submitted to the University of the Witwatersrand, Johannesburg in consideration for the Master of Science degree. It has never been submitted for a degree at another university.



Mokgaetji Andelina Monyai

02 September 2024

ABSTRACT

Huge seas, lakes, and rivers come to mind when we think of surface water. Surface water is vulnerable to water pollution, with consequential repercussions for the well-being of both human and aquatic environments. Furthermore, the diminishing levels of oxygen have a profound effect on the natural ecological equilibrium within river and lake ecosystems. Lake Kariba, situated in the Southern African region, is a vital freshwater ecosystem supporting local communities, wildlife, and regional economies. However, it faces threats from human activities and erratic weather.

This study investigated the influence of land use activities in and around Lake Kariba on water composition and the concentration of anions and cations. The research employed a combination of field surveys and laboratory experiments to identify potential sources of ions. Sixty-nine (69) water samples (53 downstream and 16 upstream) were collected during different seasons in October 2021, July 2022 and April 2023. The Ion Chromatography, Inductively Coupled Plasma equipped with Optical Emission and Mass Spectroscopy detectors were used to concentrations of various anions (F^-, Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}) and cations (Ca, K, Mg, Na, Si, Al, Cr, Fe, Mn, As, Cu, Ni, Ti, and Zn) respectively.

Acidic water was notably observed upstream in two sampling areas, namely the Malasha and Kanzinze rivers. The Malasha River exhibited pH levels ranging from 3.71 to 4.81, while the Kanzinze River showed a pH of 6.01. The electrical conductivity (EC) for Malasha ranged from 1035 to 1484 µS/cm, whereas for Kanzinze, it measured 878.0 µS/cm.

These areas exhibited significantly elevated levels of both anions and cations. In the Kanzinze River, the detected concentrations showed the following descending order: $SO_4^{2-} > Cl^- > NO_3^- > F^- > PO_4^{3-}$ (anions); Ca > Mg > Na > K > Si > Fe > Al > Zn > Cu > Mn > Ni > Cr > Ti > As (cations). Conversely, the Malasha River, exhibited the following order for anions: $SO_4^{2-} > Cl^- > NO_3^- > F^- > PO_4^{3-}$, and for cations: Ca > Fe > Mg > Na > Si > K > Al > Mn > Zn > Cr > Cu > Ni > Ti > As. The significant presence of SO_4^{2-} and NO_3^- indicates that human activities and agricultural practices in certain areas of Lake Kariba's catchment can have a considerable impact on the lake's water quality. Despite this, the corresponding Water Quality Index (WQI) indicated that the water quality from Kanzinze and Malasha rivers was unsuitable for drinking purposes.

The findings revealed variations in ions concentration at different sampling points, with discernible patterns corresponding to specific land use types, such as mining in the upstream that elevated the levels of SO_4^{2-} and some heavy metals and also NO_3^- levels in the downstream due to commercial cage fish farming. Statistical analysis showed significant downstream variations ($p < 0.05$) in water chemistry parameters related to land use, while upstream areas exhibited no significant differences ($p > 0.05$). Water quality index ranged from 13.1 to 230.0, categorizing water quality from "excellent" to "very poor."

The study underscores the complex interplay between land use activities and water chemistry in Lake Kariba, emphasizing downstream impacts. These findings contribute valuable insights for sustainable management and conservation efforts in the region, considering the dynamic nature of the ecosystem and potential threats posed by anthropogenic activities. Continuous monitoring and mitigation strategies are crucial to preserving the ecological balance of Lake Kariba and safeguarding the well-being of its surrounding communities and wildlife.

DEDICATION

My life has always been blessed by and guided by the Almighty God, to whom I devote my dissertation. I appreciate God's constant guidance in my life. I also honour my mother Fanisa Takalani Ledwaba by dedicating this work to her memory.

PRESENTATIONS

Poster Presentation

1. Phaphedi M Poopedi, Yannick Nuapia, Heidi Richards, Mokgaetji Monyai, Imasiku Nyambe, Luke Chimuka, Nikita Tavengwa. Quantification of trace metals using various fish samples by ICP-OES analysis from Siavonga, Lake Kariba, Zambia. AFRICA FOOD SAFETY WORKSHOP (AFSW) 2022, Joining Hands to enable Food Safety in Africa, 27 June – 1 July 2022, Emperor's Palace, Johannesburg (South Africa).

Oral Presentation

1. Mokgaetji Monyai, Luke Chimuka, Hlanganani Tutu, Heidi Richards. Presence and levels of anions and cations in Lake Kariba waters as indicator of the impact of land use activities in and around the Lake. WELCOME Project Stakeholder Workshop 2022, Investigating the current and future status of the Kariba catchment by international collaboration, 23 August 2022, Lake Kariba Inns, Siavonga, Zambia.

2. Mokgaetji Monyai, Luke Chimuka, Hlanganani Tutu, Heidi Richards. Presence and levels of anions and cations in Lake Kariba waters as indicator of the impact of land use activities in and around the Lake. Analitika Conference 2024, 10 – 14 March 2024, Champagne Sports Resort, Central Drakensberg.

3. Mokgaetji Monyai, Bob Mwangala, Luke Chimuka, Heidi Richards, Imasiku Nyambe, Yoshitaka Uchida. Assessing the Lake Kariba Catchment Environment for Sustainable Water, Energy, Livelihoods and eCOsysteM hEalth (WELCOME). AJ-CORE RESEARCHERS' WORKSHOP, 16 – 18 April 2024, Maun Lodge, Maun, Botswana.

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TABLE OF CONTENT

DECLARATION i

ABSTRACT ii

DEDICATION iv

PRESENTATIONS v

POSTER PRESENTATION v

ORAL PRESENTATION v

ACKNOWLEDGEMENT vi

TABLE OF CONTENT vii

LIST OF FIGURES xi

LIST OF TABLES xii

CHAPTER 1: INTRODUCTION 1

1.1. BACKGROUND 1

1.2. PROBLEM STATEMENT AND MOTIVATION OF THE STUDY 4

CHAPTER 2: LITERATURE REVIEW 6

2.1. INTRODUCTION 6

2.2. SOURCES OF ANIONS AND CATIONS IN FRESHWATER WATER ENVIRONMENT 7

2.2.1. Natural sources of chemical constituents 7

2.2.2. Agricultural and anthropogenic sources 9

2.2.3. Farming practices 11

2.2.4. Mining and mineral ore processing 12

2.3. FACTORS AFFECTING THE QUALITY OF FRESHWATER ENVIRONMENT. 15

2.3.1. Hydrogen ion activity (pH) 15

2.3.2. Temperature 15

2.3.3. Electrical conductivity and total dissolved solids 16

2.3.4. Sodium Hazard 17

2.4. OCCURRENCE OF ANIONS AND CATIONS IN FRESHWATER ENVIRONMENT 18
2.4.1. Major anions in water 18
2.4.1.1. Fluoride 18
2.4.1.2. Chloride 18
2.4.1.3. Nitrate 19
2.4.1.4. Phosphate 19
2.4.1.5. Sulphates 19
2.4.1.6. Bicarbonate ions 20
2.4.2. Heavy and critical metals 20
2.5. BIOACCUMULATION OF MAJOR CATIONS AND ANIONS IN THE FRESHWATER ENVIRONMENT 21
2.6. ENVIRONMENTAL AND HEALTH IMPACTS OF CHEMICAL CONSTITUENTS IN FRESHWATER ENVIRONMENT 22
2.6.1. Environmental impacts of anions and cations in freshwater environment 22
2.6.2. Health impacts of anions and cations in freshwater environment 23
2.7. METAL AND ANION ANALYSIS IN WATER SAMPLES 24
2.7.1. Metal analysis 24
2.7.2. Anions analysis 25
2.8. METAL AND ANION ENVIRONMENTAL STANDARDS IN WATER BODIES 25
CHAPTER 3: AIM AND OBJECTIVES 26
3.1. GENERAL OBJECTIVE 26
3.2 . SPECIFIC OBJECTIVES 26
3.3. IMPORTANCE AND LIMITATIONS OF THE STUDY 26
CHAPTER 4: MATERIALS AND METHODS 28
4.1. STUDY AREA AND SAMPLING 28
4.2. SAMPLE COLLECTION PREPARATION 29
4.2.1. First Sampling Points, Lake Kariba downstream in Siavonga 29
4.2.2 Second Sampling Points, Lake Kariba downstream (Siavonga) and upstream 31
4.2.3. Final Sampling Points, Lake Kariba downstream in Siavonga 33
4.3. REAGENTS AND CHEMICALS 36
4.4. INSTRUMENTS AND EQUIPMENT 36
4.5. DETERMINATION OF MAJOR AND TRACE CATIONS IN WATER 36
4.5.1. Preparation using Microwave Digestion 36
4.5.2. Measurements for major cations using the Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP - OES) technique. 38

4.5.3. Measurements for trace cations using the Inductively Coupled Plasma - Optical Mass Spectrometry (ICP - MS) technique. 39
4.6. DETERMINATION OF ANIONS IN WATER 40
4.6.1. Sample preparation 40
4.6.2. Measurements for anions using the Ion Chromatography (IC) technique 41
4.7. QUALITY CONTROL (QC) AND QUALITY ASSURANCE (QA) ON ANALYTICAL METHODS 42
4.7.1. Limit of detection for the method 42
4.7.2. Accuracy 42
4.7.3. Precision 43
4.7.4. Internal standard 43
4.8. ANALYSIS OF STATISTICAL DATA 43
4.8.1. Correlation matrix 43
4.8.2. Water Quality Index (WQI) and Percent Sodium (%Na) 43
4.8.2.1. Water quality Index 44
4.8.2.2. Sodium Percent 44
4.8.3. Principal Component Analysis (PCA) 45
CHAPTER 5: RESULTS AND DISCUSSION 46
5.1. QUALITY CONTROL (QC) AND QUALITY ASSURANCE (QA) 46
5.2. PHYSICAL-CHEMICAL PARAMETERS IN THE WATER 48
5.2.1. Mean and individual physical-chemical parameters in the water of Lake Kariba 48
5.3. ANIONS CONCENTRATIONS IN THE WATER OF LAKE KARIBA 54
5.3.1. Mean and individual concentration of major anions in the water 54
5.4. MAJOR AND TRACE METALS IN THE WATER OF LAKE KARIBA 60
5.4.1. Mean and individual concentration of major elements in the water 60
5.4.2. Mean and individual concentration of trace elements in the water 65
5.5. CORRELATION COEFFICIENT 68
5.5.1. Correlation coefficient between variables in upstream 68
5.5.2. Correlation coefficient between variables in downstream over 3 years 71
5.6. WATER QUALITY INDEX AND SODIUM PERCENT TO ASSESS THE QUALITY OF WATER 74
5.7.PRINCIPAL COMPONENT ANALYSIS (PCA) 76
5.7.1 Correlation plot for upstream between variables (2022) 76
5.7.1.1 Observations in upstream 77
5.7.2 Correlation plot over 3 years (2021-2023) in downstream between variables 78
5.7.2.1 Observations over 3 years in downstream 79
5.8 COMPARISON WITH RESULTS FROM OTHER STUDIES 80
CHAPTER 6: CONCLUSION AND RECOMMENDATIONS 82

6.1. CONCLUSION 82
6.2. RECOMMENDATIONS 83
REFERENCES 84
APPENDIX 96

LIST OF FIGURES

Figure 2.1 Several chemical constituents that can dissolve in freshwater from natural sources 8
Figure 2.2 The diagram depicting various human-made activities polluting both surface and groundwater systems.....10
Figure 2.3. The interactions between the main environmental monitoring systems for water quality 12
Figure 2.4 A graphical representation outlining the steps in a phosphate mine's process 13

Figure 4.1 Study area showing geographical location of Lake Kariba, Siavonga 28
Figure 4.2 Geographical coordinates on Lake Kariba for the first sampling, October 2021..29
Figure 4.3 Geographical coordinates on lake and river for second sampling, July 2022 31
Figure 4.4 Geographical coordinates on the lake for the final sampling, April 2023.....33
Figure 4.5 Illustrates the limited samples collected during (a) October 2021, (b) July 2022, and (c) April 2023.....33
Figure 4.6 Multiwave GO microwave system. 37
Figure 4.7 Inductively coupled plasma - optical emission spectroscopy.....38
Figure 4.8 Inductively coupled plasma-mass spectrometry.....39
Figure 4.9 Eco IC with an 863 Compact Autosampler. 41
Figure 5.1 Water Quality Index, a) upstream water individual sites and b) comparison between downstream and upstream.....74
Figure 5.2 Sodium percent, a) upstream water individual sites and b) comparison between the downstream and upstream.....75
Figure 5.3 Correlation plot for upstream. 76
Figure 5.4 Observation plots for upstream.....77
Figure 5.5 Correlation plot for downstream over three years. 78
Figure 5.6 Observation plots for downstream over three years. 79

LIST OF TABLES

Table 2.1 Desirable values for Zambia Bureau of Standards (ZABS), South African National Standard (SANS) and World Health Organization (WHO) standards on water quality.....25

Table 4.1 Description of the first sampling sites and their GPS coordinates.....30

Table 4.2 Description of the second sampling sites and their GPS coordinates.....32

Table 4.3 Description of the final sampling sites and their GPS coordinates.....35

Table 4.4 Microwave Digestion Program.....37

Table 4.5 Parameter conditions for Microwave Digestion.....37

Table 4.6 Operating parameters for ICP-OES.....39

Table 4.7 Operating parameters for ICP-MS.....40

Table 4.8 Operating parameters for IC.....42

Table 5.1 Linearity, LOD and LOQ for cations and anions.....46

Table 5.2 Percent Recoveries and Relative Standard Deviation (% RSD) for spiked samples.....47

Table 5.3 Individual physical-chemical parameters for upstream during July 2022 (cool-dry) period.....51

Table 5.4 Individual physical chemical parameters for downstream during the period of October 2021, July 2022, and April 2023.....53

Table 5.5 Major anions observed in upstream water samples during July 2022 period.....57

Table 5.6 Major anions observed in downstream during the period of October 2021, July 2022, and April 2023.....59

Table 5.7 Major elements present in upstream water samples during July 2022 period.....62

Table 5.8 Major elements present in upstream water samples during the period of October 2021, July 2022, and April 2023.....64

Table 5.9 Trace metals in upstream water samples during July 2022 period 66

Table 5.10 Trace metal in downstream water samples during the period of October 2021, July 2022, and April 2023 67

Table 5.11 Correlation matrix between variables in upstream.....70

Table 5.12 Correlation matrix between variables in downstream over 3 years 73

Table 5.13 Average chemical composition of water from other studies.....81

LIST OF ABBREVIATIONS

AFSW	Africa Food Safety Workshop
Al	Aluminium
AMD	Acid Mine Drainage
Ar	Argon
As	Arsenic
BAF	Bioaccumulation Factor
Br	Bromide
Ca	Calcium
CaCl	Calcium Chloride
CCV	Continuous Calibration Verification
Cd	Cadmium
Cl^-	Chloride
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
DSL	Downstream of the Lake
°C	Degree Celsius
EC	Electrical Conductivity
F^-	Fluoride
Fe	Iron
GMA	Game Management Area
GPS	Global Positioning System

Hg	Mercury
HNO_3	Nitric Acid
H_2O_2	Hydrogen Peroxide
H_3PO_4	Phosphoric Acid
IC	Ion Chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
JHB	Johannesburg
K	Potassium
KCM	Konkola Copper Mines
kw	Kilowatt
L	Liter
L min^{-1}	Liters per minute
LOD	Limit of Detection
LOQ	Limit of quantification
MES	Multi Elemental Standard
Mg	Magnesium
MgCl	Magnesium Chloride
mg/L	Milligrams per Liter
min.	Minutes
ml	Millilitre
ml/min	Millilitre per minute
mm	Millimetre
mM	Millimolar

Mn	Manganese
mol/L	Moles per liter
mS/cm	Milli Siemens per centimetre
MSM	Metrohm Suppressor Module
N	Nitrogen
Na	Sodium
%Na	Percent Sodium
NaCl	Sodium Chloride
Na_2CO_3	Sodium Carbonate
$NaHCO_3$	Sodium Hydrogen Carbonate
Ni	Nickel
NO_2^-	Nitrite
NO_3^-	Nitrate
NH_4^+	Ammonia
NRF	National Research Foundation
OC	Organic Carbon
P	Phosphorus
Pb	Lead
PCA	Principal Component Analysis
PO_4^{3-}	Phosphate
Pty Ltd	Proprietary Limited
QA	Quality Assurance
QC	Quality Control
R^2	Coefficient of Determination

RPM	Revolutions Per Minute
% RSD	Percent Relative Standard Deviation
SA	South Africa
SBR	Saver Beach Resort
SD	Standard Deviation
Si	Silicon
S/N	Signal to Noise
SO_4^{2-}	Sulphate
STD	Standard
TD2	Tailing Dam number 2
TDS	Total Dissolved Solids
Temp	Temperature
Ti	Titanium
µg/L	Micrograms per Liter
µm	Microns
UN	United Nations
UNZA	University of Zambia
USL	Upstream of the Lake
v/v	Volume per Volume
vs.	Versus
W	Watt
WELCOME	Water, Energy, Livelihoods, and eCOsysteM hEalth
WHO	World Health Organization
WQI	Water Quality Index

ZABS	Zambia Bureau Standards
Zn	Zinc
ZRA	Zambia Revenue Authority

CHAPTER 1: INTRODUCTION

The chapter provides a thorough explanation of the context, the dissertation statement, and the driving force behind the research in a detailed manner.

1.1. Background

Water stands as one of the most vital natural resources at our disposal and humans cannot survive for more than a week without consuming it. In fact, if it weren't for water, there wouldn't be any organic matter because it makes up most of the protoplasm, the basic component of plants and animals (Mishra, 2023). Although the least developed stage of growth, such as seeds and spores, may contain less water than fully established animal life, it still contains some water. Therefore, from a purely physical standpoint, water is necessary for all life. Aside from being essential for biological living, water is also highly significant to business and industry. In many industrial and construction activities, water is used as a production assistance such as food processing, electricity generation, and manufacturing. (Hossain, 2015).

Water resource resilience is the consistent accessibility of water in sufficient quantity and quality to support health, livelihoods, and productivity, while also managing an acceptable level of associated risks. The social welfare and economic activity of a nation can be significantly impacted by the management and use of water. Through direct and indirect contamination that affects the availability of the water resource to other users, economic and social engagements can significantly impact water quality. The aquatic environment is a resource in and of itself, supporting several activities, including tourism and environmental preservation as well as various local means of subsistence. Undoubtedly, a country's ability to expand economically and sustainably depends on its access to water (Muller et al., 2009). Economic, social, human, and natural activities including agriculture, forest fires, industrial emissions, urban runoff, and the release of brine from mining all have an impact on water security (Ali et al., 2011; Marie and Vengosh, 2001).

Seasonal variations, geography, and structural geology can all affect the contour of the water table. The climatic conditions of a region determine seasonal variations. Around that average level, the water table frequently rises and falls. These variations in the water table's level are influenced by several different factors. The usage of groundwater by people and agriculture can cause changes in the water table as well. Aquifers are sought after as a source of water by

growing populations. When people draw water from an aquifer (often through wells), the water table may drop; once it infiltrates into the aquifer, the water-table level will be permanently altered, which may have an impact on the hydrology and soil stability (Mishra, 2023). Contamination of existing freshwater sources presents another challenge that endangers the ecosystem and raises ongoing worries regarding the sustainability of the water resources, even though its scarcity and poor quality continue to be the main barriers to achieving sustainable development in affected countries (Hoekstra et al., 2012).

Even though the UN General Assembly officially recognized access to clean water and sanitation as a fundamental human right in July 2010, the global problem of inadequate access to drinking water, both in terms of quality and quantity, persists as one of the most significant health challenges worldwide. The Zambezi River provides a lifeline for eight riparian nations, providing food, energy, and water to enterprises and populations despite a variety of challenges from extended droughts and destructive floods, development activities including urbanization and mining, and electricity rationing. For instance, the Upper Zambezi Catchment has experienced localized water pollution because of mining activity. Due to its proximity to this significant upstream supply of water for the Lake Kariba Reservoir, the Lake Kariba Catchment is similarly impacted by these vices (Calamita et al., 2019).

South-central Africa consisted of sufficient resources such as minerals, fertile lands, and a favourable climate. Realizing the economic potential of these resources required both expertise and investment in the region (Magadza, 2010). Cheap renewable hydropower is provided by the Zambezi River to give energy for developmental activities for both Zambia and Zimbabwe. However, the river system of the regions of east and southern Africa's semi-arid areas has undergone major threats due to climatic changes and variability along with increased population and urbanization. The increased degradation of the freshwater ecosystem is found in the region that deteriorates the water quality due to increasing pollution (Nel et al., 2011). The deterioration in the freshwater environment affects the delivery of the ecosystem resulting in the often-expensive interventions while involving the loss of tenacity of the ecosystem towards the changing circumstances (Nel et al., 2011). The dam construction in the regions has been considered as another major reason for altering the water quality by shifting the temperature and oxygen content in the outflowing water (Mwedzi et al., 2016; Van Cappellen & Maavara, 2016; Winton et al., 2019).

The construction has affected the aquatic environment from land to oceans due to the accumulation of particles and nutrients in the reservoirs of Lake Kariba. The accumulation of larger quantities of nitrogen (N), organic carbon (OC), and phosphorous (P) in the sediments have shown variabilities in the natural content which affects the environment of Lake Kariba (Kunz et al., 2011). The Zambezi River contributes towards 80% inflow of water in the Lake Kariba. The Kalahari sandy soils from Zambezi River have been known to be nutrient deficient and are responsible for covering most of the upper catchment area of Lake Kariba and the river therefore brings in nutrient poor water causing low productivity in the lake (Haller et al., 2014).

The ecosystem's quality of water is also impacted by anthropogenic activities like infrastructure development, tourism, and fishing in the lake and its tributaries. Overfishing caused by fishing operations results in declining fish stocks and an ecological imbalance. Increased human presence brought on by infrastructure improvements and tourism results in more waste and garbage being generated, which is then dumped into lakes, contaminating, and polluting them (Best, 2019).

Nyamadzawo et al. (2016) carried out further pertinent research that concentrated on the effects of mining activities on cationic and anionic concentrations in Zimbabwe rivers that contribute to the catchment region of Lake Kariba. According to the report, mining operations are to blame for the increasing concentrations of trace metals and their consequent effects on the water quality. Ecosystems and human health are both known to be significantly at danger from heavy metals.

The anthropogenic activities in Lake Kariba have changed the composition of nutrients and resulted in low nutrient contents in the lake. The electrical conductivity and the equilibrium of mineral levels are examples of many natural processes that anions in water are crucial for. Aquatic plants like cyanobacteria develop when nitrate levels in the water rise. Fish deaths and acidic waters can result from the decomposition of dead cyanobacteria, which consumes a large portion of the oxygen in the water. Water flavours can be affected by sulphate and chloride ions from industrial processes, rendering it unappealing for human consumption. Additionally, high concentrations of these ions may promote increased corrosion in canal infrastructure and result in mineral imbalances in aquatic biosystems that can be hazardous (Zak et al., 2021; Duan et al., 2024). The water quality of phosphorus restricting primary production, Lake Kariba has transitioned from nutrient-rich (eutrophic) state to its present nutrient-poor (oligotrophic) one (Ndebele-Murisa, 2011). The process of eutrophication, which involves a rise in both organic

and inorganic nutrients in water and encourages the growth of algae, is brought on by elevated phosphate levels in the water. Fish and other marine life that cannot survive in water with low oxygen levels may perish because of the excessive growth of algae (Ndebele-Murisa, 2011). The increasing concentration of faecal coliform bacteria in the Lake Kariba water have been recorded which represents the movement of lake water towards mesotrophic (Ndebele-Murisa, 2011). However, point pollution sources around the lake have the potential to cause eutrophication and several other aquatic environmental issues in the lake of Kariba.

The best option for meeting the needs for water quality and quantity for both the present and future generations is ensuring the sustainable and effective management of water resources. The nutrient content in the water bodies is analysed by application of the water quality measurement (Coverly et al., 2012). Hence, the nutritional analysis in the water bodies is carried out for determining the level of nutritional content in the surface water. It helps in providing the chemical analysis of the water bodies involving the chemical composition, quality control, and contamination level in the surface water. The determination of NO_3^-, NO_2^-, and PO_4^{3-} are determined for analysing the level of nutrient pollutants within the water bodies. An analysis of inorganic elements' chemical composition, including conductivity, sodium (Na), potassium (K), alkalinity, sulphate (SO_4^{2-}), pH, as well as physical characteristics such as temperature and light distribution, has been conducted to determine nutrient levels (Magadza, 2003).

1.2. Problem Statement and Motivation of the Study

Lake Kariba has several competing users, including tourism with lodges on both the Zambian and Zimbabwean sides, fisheries industries such as kapenta fishing and aquaculture operations like Zamfresh and Yalelo, water use for electricity generation by the Zambezi River Authority, and agricultural and mining activities in and around the lake. The extent to which these activities impact the lake's water quality is not fully studied.

The construction of artificial confinement areas for Lake Kariba's water reservoirs has raised awareness of environmental impacts over the past 10-15 years (Calamita et al., 2019). These developments have posed significant social and ecological challenges, negatively affecting the Lake Kariba catchment area (Tumbare, 2008). While some studies have been conducted in the core Lake Kariba catchment (Kunz et al., 2011), further research is needed to better understand the complex water resource usage within the catchment. It is crucial to systematically appraise

and analyse the water requirements for each usage to ensure sustainable management. Careful consideration is needed for the presence of significant cations and anions in the environment due to their potential effects on human health (Wang et al., 2019). This understanding will enable the implementation of measures to mitigate pollution and protect the lake's water quality.

The study involved systematic monitoring and data collection, measuring various physicochemical factors such as electrical conductivity, pH levels, and ion concentrations. Advanced analytical instruments like ion chromatography (IC), inductively coupled plasma-optical emission spectroscopy (ICP-OES), and inductively coupled plasma-mass spectrometry (ICP-MS) were used to precisely determine the concentrations and sources of cations and anions in the water. The chemical data obtained was utilized for surface water quality modelling to predict pollutant levels and their distribution within the lake's water bodies.

CHAPTER 2: LITERATURE REVIEW

This chapter highlights the description of sources of anions and cations in water, environmental factors affecting the quality of water, occurrence, environmental and health effects of anions and cations that are of concern.

2.1. Introduction

According to Tumbare (2008), Lake Kariba stands as the world's biggest artificial lake and reservoir in terms of its volume. It is located 1,300 kilometers (810 miles) upstream of the Indian Ocean at the Zambia–Zimbabwe border. The Kariba Gorge on the Zambezi River was flooded because of the Kariba Dam, which was built at the northern end of Lake Kariba between 1958 and 1963. The towns of Sinazongwe and Mlibizi, along with Binga Village in Zimbabwe, as well as Siavonga and Sinazongwe in Zambia, have experienced growth due to the migration of residents from areas where water levels were rising. Kariba town in Zimbabwe was built specifically for those who were working on the lake's dam. Lake Kariba is 40 kilometers in width and about 223 kilometers in length. Its surface area is 5,580 square kilometers, and its storage capacity is 185 cubic kilometers. With a mean depth of 29 meters, the lake has a maximum depth of 97 meters. It is the biggest artificial reservoir in the world in terms of its volume, being four times bigger in size compared to Gorges Dam (https://en.wikipedia.org/wiki/Lake_Kariba). The decaying plants have increased the concentration of nutrients pollutants in the lake (Balon and Coche, 2012). The bottom layer of the lake was very thick composed of decayed plants and soil. Different fish species introduced from Lake Tanganyika to Lake Kariba including the sardine-like kapenta have become the cornerstone for commercial fishery. Other fauna including Hippos and Nile crocodiles are additional creatures to Lake Kariba.

The primary invasive weeds in Lake Kariba are Kariba weed (Salvinia Molesta) and water hyacinth (Eichornia Crassipes). The Lake Kariba hydropower sector has operating challenges due to invasive weeds introduced to hydropower works. The Kariba weed was widespread in Lake Kariba prior to its eutrophication. As part of a biological weed management strategy, the South American grasshopper Paulina and the sardine species known as Kapenta (*Liomnothrissa miodon*) from Lake Tanganyika were brought in 1969. While the Kapenta helped lower the nutrients in the lake, the grasshopper assisted in reducing Kariba weed development. The weed eventually disappeared when the lake's biological equilibrium was reached, and today it is only

sometimes seen there. On the other side, the water hyacinth developed into a significant annoyance starting in August 1994, when Lake Kariba's persistent below-average water intakes caused the lake levels to remain below normal. By heavily aerially spraying water hyacinth with the phenoxy herbicide 2,4-D at a rate of 6 l/hectare in August 1998, Zambia Revenue Authority (ZRA) and its collaborating partners implemented a campaign to reduce and control the spread of the plant. According to Ndhlovu et al. (2017), to check for any harmful effects, samples of the water and fish should be collected before, during, and after the spraying operation. None were required, and the spraying procedure was well documented. Spraying 2,4-D on the water hyacinth was highly effective, and within a week, the treated plant had died and become submerged. 1,671 hectares of water hyacinth were taken out. The residual water hyacinth-infested areas that couldn't be sprayed were then subjected to a biological management campaign using weevils (Neochetina spp.), including at household water intake systems. Thanks to this technique, the development and multiplication of water hyacinths are presently well under control. ZRA has developed a "Management Toolbox" to be used in Lake Kariba to manage invasive species.

An important environmental concern is the rising ions contamination of freshwater environments from natural resources and industrial effluents. Surface water chemistry has an impact on those who depend on it for their livelihood, agriculture (crop productivity) and human health. Despite the fact that some of these anions are present at lower concentrations, an increase in concentration could have hazardous effects.

2.2. Sources of anions and cations in freshwater water environment

2.2.1. Natural sources of chemical constituents

The dissolved elements found in natural freshwater can be segmented into three groups: major components, minor constituents, and trace constituents. The climate in the recharge areas affects the concentrations of major, minor, and trace components in freshwater, the geology of the freshwater system through which the water is flowing and the chemistry of the unsaturated zone. Figure 2.1 shows, freshwater contains many dissolved chemical components. Major ions are the six components (cations: Na^{+}, Ca^{2+}, and Mg^{2+}), and (anions: HCO_3^{-}, SO_4^{2-}, and Cl^{-}) that are present in the largest amounts. K^{+}, dissolved organic carbon, Mn^{2+}, Fe^{2+}, Si^{4+}, NO_3^{-}, and F^{-} are some of the minor components that could be present. These small components typically range in concentration from 0.1 to 5 mg/L. Numerous trace elements exist at lower levels, often below the threshold for detection using standard analytical techniques (Poeter et al. 2020).

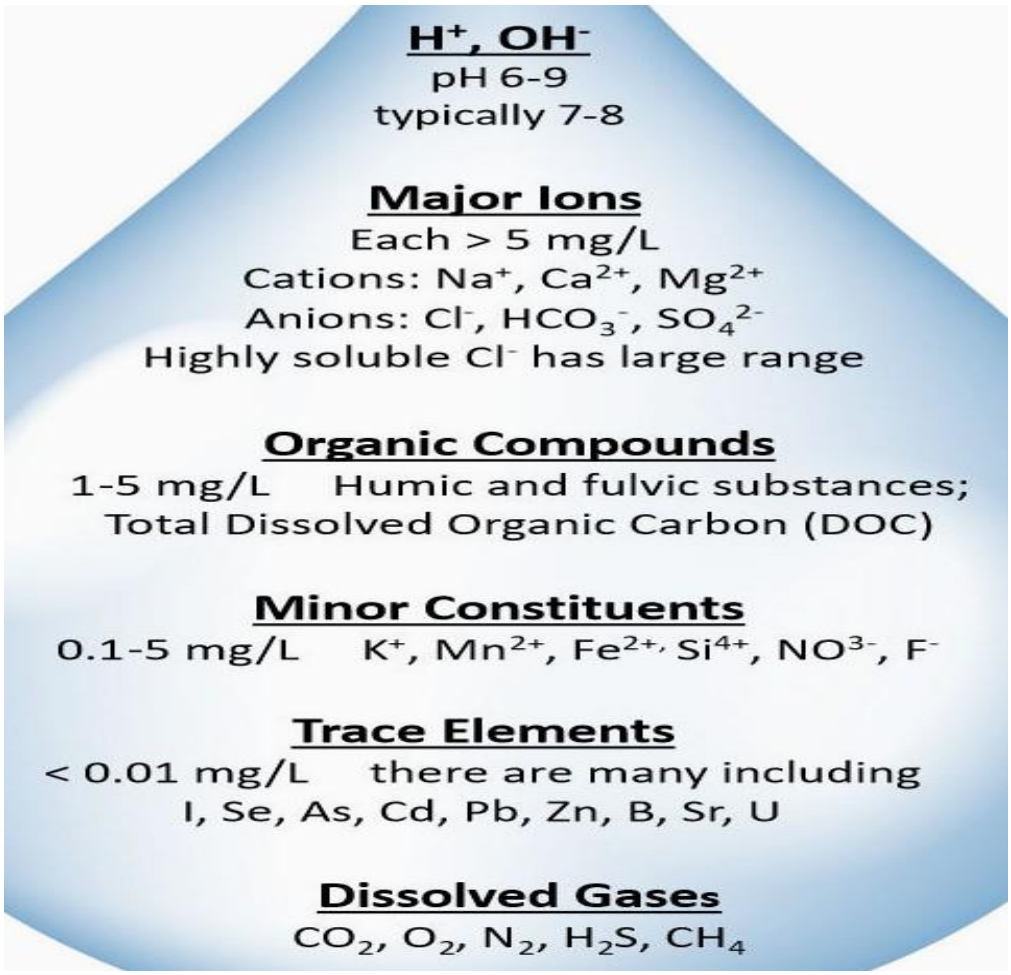


Figure 2.1 Several chemical constituents that can dissolve in freshwater from natural sources (Poeter et al. 2020)

Chemical pollution to the terrestrial systems is mainly from weathering of geological terrains exposed to the surface and results in metal precipitation on the environment (Zheng et al., 2019). Rocks are classified into igneous, sedimentary, and metamorphic rocks depending on how they are formed (Wigger et al., 2018). Igneous rocks are formed when magma cools and solidifies during the eruption of volcano, though sedimentary rocks are formed when sediments accumulate in tectonic and topographically sinks at low temperature (Wigger et al., 2018).

Metamorphic rocks are formed when parent rocks metamorphose under the effect of high pressure and temperature. These rocks are exposed to the surface through weathering and environmental factors including temperature have influence in the physical weathering of surface geological formations (Jones and Deocampo, 2003). These different rock types contain minerals including quartz, feldspars, amphibole, and many others, as well salts that may be

harmful to the environment. The geochemistry of rocks contains both crucial metals (Fe, Ca, K, Na and Mg) and anions (Cl^-, SO_4^{2-}, PO_4^{3-}) (Zhang et al., 2017). The environmental concern is when these rocks are weathered, and chemical constituents leach into surface water when they dissolve.

2.2.2. Agricultural and anthropogenic sources

Surface water may be polluted by accumulation of anions and cations from agricultural activities, atmospheric deposition, domestic waste, contaminated materials, and discharge from wastewater treatment plant output (Appunni et al., 2016; Anush et al., 2020). Water is a polar solvent, and it can easily transport particulate matter, and this may lead to water pollution when natural salts present in the soil dissolve (Billah et al., 2022). Environmental chemical pollution of freshwater environment has become a great concern to the public depending on surface water. Although some elements are critical for our daily dietary, absorption at higher concentration may result in adverse health effects (Billah et al., 2023). For plants growth, balance in macronutrients (Ca, Mg, N, P and K) and micronutrients is important. The major concern is that fertilizers, persistent organic pollutants, and manure utilized in agricultural activities affect freshwater environment (Bozorgpour et al., 2016).

Persistent organic pollutants are defined as organic compounds that resist any form of environmental degradation when exposed to photolytic processes, biological and chemical processes (Dotto and McKay, 2020). Some of these agricultural chemicals proved to be quite helpful for disease and pest control as well as in crop production. Environmental pollution caused by agricultural compounds (chemicals) is raising concern globally. This need agent attention as some chemicals including pesticides may bind to soil, through soil degradation and rainfall may end up in freshwater environment (Rad and Anbia, 2021). Pesticides are mostly used to increase crop yield and weed guard in agricultural sites.

The point and non-point sources of nutrient contaminants in a watershed depend on the predominant land uses. The other sources of pollution may be from the following:

- Urban/suburban: excessive lawn fertilizer usage, municipal sewage treatment facilities, rainwater runoff from roadways and parking lots, and motor vehicle emissions.

● Industrial: wastewater outflows from various sectors, air pollution emissions (such those from electric power plants), Figure 2.2 provides a distinct representation of the types of pollution

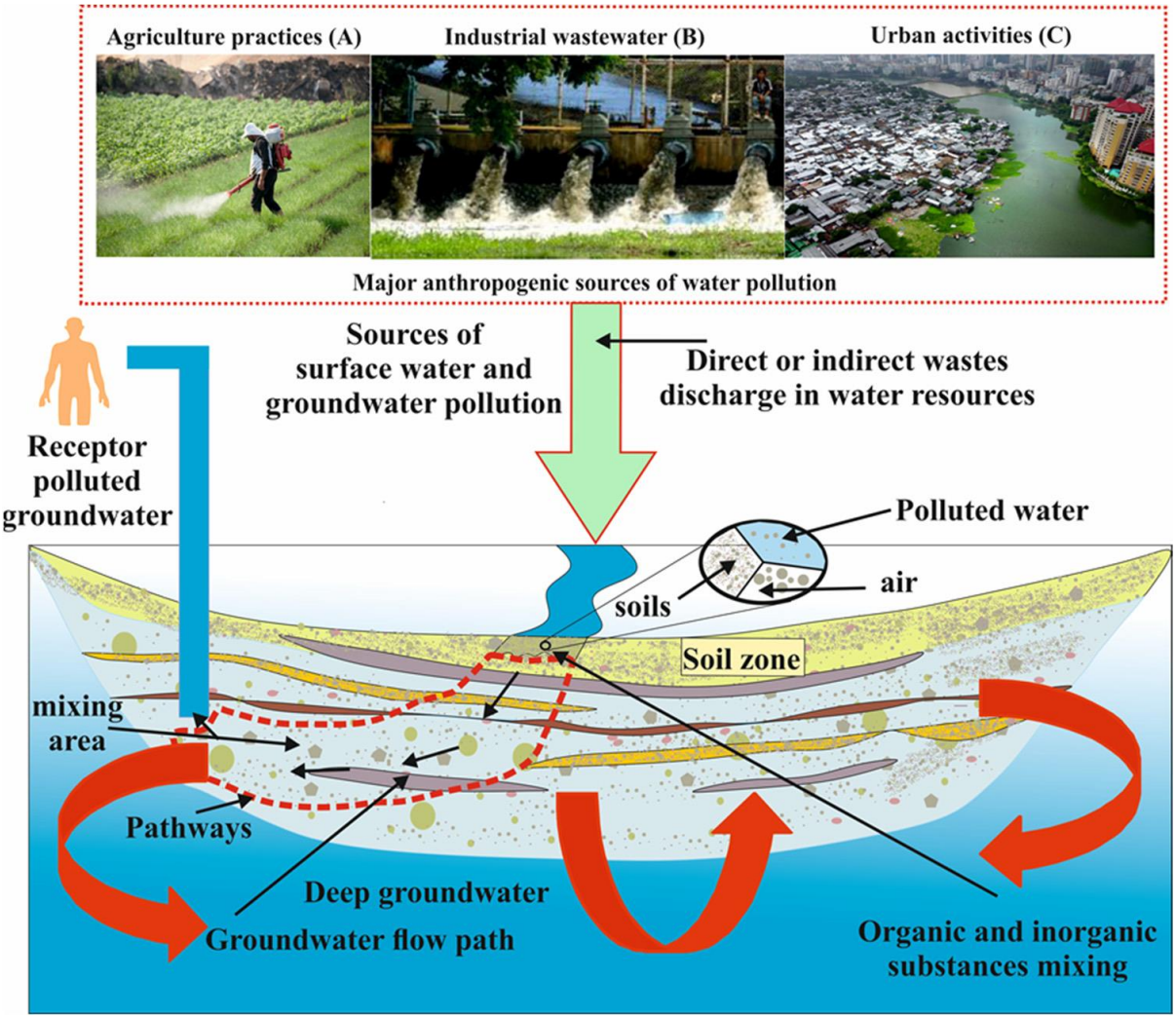


Figure 2.2 The diagram depicting various human-made activities polluting both surface and groundwater systems (Akhtar et al., 2021)

Some pollutants may be carried by wind and water from other areas (non-point source) and nutrient pollution may occur regardless of the local land use. To prevent eutrophication, Winton et al. (2021) shows that it is critical to identify the point and non-point sources that contribute to nutrient loading. Due to some nutrients remaining in the soil, it has been demonstrated that there is a linear link between the amount of phosphorus (P) dissolved in surface water and the quantity that accumulates in the soil. As a result, a large quantity of nutrients loads to soil eventually find their way into the surface and ground water. For instance, NO_3^- and PO_4^{3-} may

be carried through storm drainage, sewage pipes, and as well as surface runoff. Nutrients transported by surface runoff occur mostly on sites associated with agricultural land use. The soil is often fertilized to improve its fertility, and agricultural products are sold on the market. The high load of NO_3^- or PO_4^{3-} results in excess pollution dripping into pastures, groundwater, or surface water systems (Mishra, 2023).

2.2.3. Farming practices

Tillage promotes erosion and sedimentation, and agricultural fields can absorb applied fertilizers and pesticides, claim Simukoko et al. (2022). Human activity always leaves its biogeochemical traces in waterways, which frequently negate whatever advantages that aquatic systems may have for civilization. Such variations in the physico-chemical properties of water caused by human activity are frequently referred to as "water quality" adjustments by the public and professional scientists. However, the term "water quality" lacks a precise scientific meaning. In this study, we refer to the levels of certain physical and/or chemical characteristics that we studied in connection to waters free from human impact as "water quality."

Waters with lower solute concentrations may be regarded as being of "good quality," whereas waters with greater concentrations may be seen as having undergone some type of (typically human) intervention. Freshwater is frequently found to have been significantly polluted by chemical and microbiological pollution in densely inhabited and industrialized parts of the world. In contrast, the Zambezi Basin is mostly unpopulated and has a few river portions that are still in good condition. However, considering how quickly the area is changing, it is unclear how robust the surface waters quality will be to development trends.

Dam building is growing in the area, with 11 to 25 hydroelectric projects now under development or planned to complement the five existing big dams. By 2050, Zambia's population, which makes up 40.7% of the Zambezi Basin, is projected to have tripled. It is now rising at a pace of 2.9% per year. Naturally, the need for food will expand as the population rises, necessitating a rise in agricultural production. According to Mhlanga et al. (2013), Zambia's government has stepped up efforts to boost agricultural exports. Croplands will be expanded to produce higher yields, which will result in an increase in fertilizer use and irrigation water allocation. Would there be significant trophic shifts if the rivers can't handle the increased nutrients that would unavoidably seep from all these new fields? Does the wastewater treatment infrastructure have the capacity to handle the growing urbanization?

Field data covering large geographic regions and concentrating on probable sources of contamination are needed to forecast the likely future of Zambia's surface water quality. Figure 2.2 illustrates the interactions between the main environmental monitoring systems to prevent pollution.

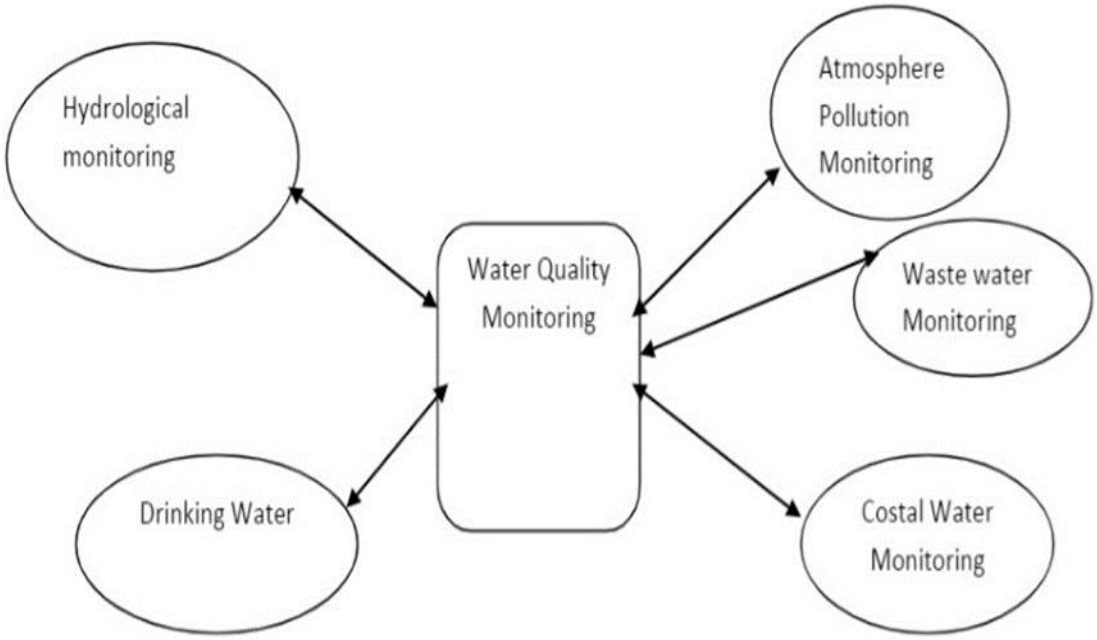


Figure 2.3. The interactions between the main environmental monitoring systems for water quality (Mishra and Dubey, 2015)

2.2.4. Mining and mineral ore processing

Mining methods are implemented to recover economic minerals from ore deposits. After mining, rock fragments are transported to extractive metallurgy laboratories for further processing (ore dressing) to remove commercially precious minerals from their ores. Le et al. (2020) highlighted major steps that could be useful in mineral handling, and this include compression (reduction in particle size), proportioning (isolation of particle sizes by classification or screening), build up (using physical and surface chemical features), and down flow (solid/liquid separation). What drives the above extractive steps is the recovery of quality ore minerals and is less expensive in terms of operation as profit comes first in mining. The calculation of ore reserve is critical as it determines how many years of mine operation, and all

this depends on the ore mineralogy and available analytical methods. Ore deposit is crushed and ground into fine particle size suitable for analysis.

According to Fosso-Kankeu et al. (2015), crushing operations typically use constraint and impact forces, whereas grinding operations are predominantly driven by attrition. Particles are separated by sieves of different sizes based on particle size of interest and this is done through screening. The screening equipment's commonly used includes vibrating screens, flip-flop screens, wedge wire screens, bar screens, grizzlies, multi-deck screens, fine screens, banana screens, wire mesh screens and radial sieves. The screening process may either be stationary or fitted with technology that causes the screen to shake or vibrate, as is frequently the case with very coarse material. Depending on the materials being handled, steps are decided based on the physical and chemical characteristics of the ore mineral and gangue. Example of mining process (Phosphate mine process in central Canada) is illustrated by figure 2.4 (Gold Sim Blog, October 2015).

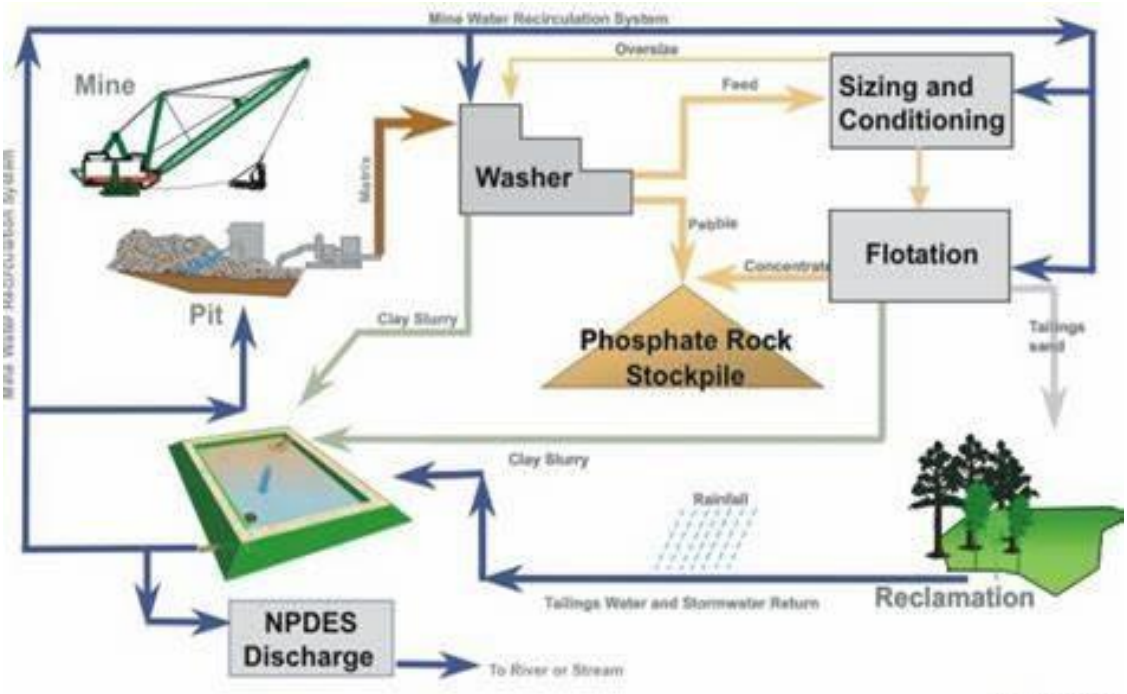


Figure 2.4 A graphical representation outlining the steps in a phosphate mine's process (Gold Sim Blog, October 2015)

According to Mhlanga et al. (2014), environmental issues brought on by mining operations include soil degradation, habitat loss, species extinction, soil pollution, poor air quality, ground vibration due to blasting, groundwater, and surface pollution. Mining negatively impacts

surface and groundwater quality due to poor environmental planning. Tailing dump leach metal and sulphate ions into water systems during rainy seasons. When rainwater reacts with atmospheric oxygen and Fe containing sulphide led to formation of acid mine drainage (AMD). AMD poses a global environmental challenge and has impacts on aquatic ecosystem, surface, and groundwater quality.

The International Atomic Energy Commission authorized uranium mining in Zambia in 2008 and after a short duration, Zambia's government established a new Mining Act permitting mining in protected zones. According to reports, uranium production along the Lake Kariba shoreline started in 2011 (https://doi.org/10.1787/uranium-2011-en). Community leaders raised a concern about the potential consequences of uranium mine waste that may have an effect on environmental and human health during the mine development. According to international law, residents within a 50-mile radius close to mine operation should be relocated to sites that are safe for metal ions exposure.

According to Mukono et al. (2021), the Lower Zambezi Basin is an important catchment. This catchment linked Zambia, Zimbabwe, and Mozambique. Water pollution (metal and anions) from other countries may migrate to other countries was well due to this linked catchment. Mine pollution does not only affect the quality of soil and water but also poses a threat to commercial industries such as commercial fisheries, agriculture, and safari tourism sector. Additionally, Makumbe et al. (2022) claim that foreign investors will receive the vast bulk of the profits from the irresponsible mining business. While the Game Management Area (GMA) and Park copper mines anticipated employing 100 to 200 citizens, the Siavonga uranium mine anticipated employing up to 500 overall, including international workers.

Additionally, it was found that pollution from Konkola Copper Mines (KCM) tailing dam number 2 (TD2) had impacted the Mushishima streams, which flow through the nearby Helen and Shimulala communities in Chingola (also known as TD2). When the stream became contaminated, the locals claimed that KCM had drilled a well for them, but when they took samples, they discovered that the water also contained copper sulfate. They claimed that the water in a tank that the company subsequently delivered also contained contaminants. Since there is no clean water supply in the village, residents must now walk to a little well they dug in the marsh. They are concerned that this might also be polluted.

2.3. Factors affecting the quality of freshwater environment.

The quality of freshwater environment is determined by the physical and chemical properties based on its suitability for use. The presence of main anions and cations dissolved in water describes its properties. Environmental factors including temperature, pH, total dissolved solids, and conductivity may affect chemical constituents in water.

2.3.1. Hydrogen ion activity (pH)

The pH in freshwater environment measures the acidity and alkalinity of water. The water environment with pH value lower than 7 indicates acidic condition, while pH value higher than 7 is alkaline. Human activities such as dumping can alter pH levels, with acid rain, mining run-off, and plants contributing to the lowering of water system pH. Historically, acidification issues were primarily linked to freshwater ecosystems impacted by acid rain (Leduc, 2013). The pH of water decides the speciation of metals by transforming their availability and poisonousness (toxicity) in freshwater environment (Rojas and Horcajada, 2020). The corrosion rate of metal ions in water at pH less than 7 accelerates due to proton dominating compared to hydroxyl ions. Therefore, it is important to monitor the pH of freshwater environment, and this would prevent the dominance of protons to affect the toxicity of elements and chemical reactions which a significant for domestic water treatment, irrigation and for industrial purposes (Priyam et al., 2021). Freshwater pH ranges between 6.5 and 8.5 depending on the environmental conditions. The acidic water environments can destroy flora (aquatic plants) and fauna (animals). The dominance of protons from acid in water influences the solubility of metal ions and as pH increases, the protons is replaced by hydroxyl ions and lead to precipitation of metal ions in form of hydroxides (Pui et al., 2014; Wang et al., 2021). The metal ions speciation is affected by the redox potential, pH, and ionic strength of the aqueous solution (Huang et al., 2021).

2.3.2. Temperature

The influence of temperature on freshwater ecosystems is significant. It affects the water chemistry, biodiversity, stratification, and overall health of freshwater ecosystems (Machado et al., 2016).

Impact on the chemistry of water: Temperature has an impact on the levels of dissolved oxygen, the availability of nutrients, and the pH levels of water (Zhang et al., 2018). Lower oxygen levels are found in warmer freshwater systems because higher temperatures make oxygen less soluble in water (Hall and Limburg, 2019). Furthermore, temperature alters the rates at which nutrients cycle through the soil, which changes how readily available essential elements like nitrogen and phosphorus are.

Impact on biodiversity: Temperature has a significant impact on the distribution, abundance, and behaviour of freshwater species. Fish, insects, and aquatic plant species can have their patterns of distribution altered because of warming waters. Increasing temperatures may have a harmful impact on some species while having a positive impact on others. Such changes in biodiversity have the potential to affect trophic dynamics and disturb the functioning of freshwater ecosystems (Battin et al., 2016).

Stratification: Multiple research projects have thoroughly demonstrated that seasonal thermal stratification substantially alters the diversity and composition of bacterial, fungal, and algal communities (Zhang et al., 2021). Dissolved oxygen (DO) and the temperature (T) gradients along the water column could cause a buildup of contaminants in lower water layers. Once the stratification breaks down and vertical water layers mix, numerous pollutants can move towards the upper water layers, potentially initiating a decline in water quality. This could have direct repercussions on the stability of the ecosystem.

Ecosystem health implications: The general stability and health of freshwater ecosystems can be significantly impacted by temperature fluctuations. Heatwaves and other extreme heat events can increase the mortality rates of aquatic creatures, particularly fish and invertebrates. As a result of temperature-driven changes in water chemistry and biodiversity, the ecosystem's resilience, and capacity to recover from shocks may be compromised (IPCC, 2019).

2.3.3. Electrical conductivity and total dissolved solids

Electrical conductivity (EC) is an important factor when evaluating the quality of water. EC measures the dissolved ions like Cl^-, SO_4^{2-}, NO_3^- (Zhao et al., 2018). The conductivity of water ranging from 150 to 300 mS/cm is considered very salty (Huang et al., 2021). An increase or decrease in conductivity is a sign of pollutants that are impacting the water's quality. Agricultural runoff and sewage leaks create a rise in the EC because they release more ions

like nitrate, phosphate, and chloride, whereas an oil spill decreases it. Both, however, have a detrimental effect on the water quality.

Conductivity is influenced by salinity and temperature, two elements that are crucial to quality of water and preserving aquatic life. Water quality is influenced by changes in conductivity and salinity levels as well as variations in water flow from dams and rivers, tide phases, and evaporation (Atlas Scientific Environmental Robotics, 2021).

Naturally occurring waters comprise dissolved substances is known as total dissolved solids (TDS). The TDS measures the quantity of mineral and salt impurities in water. Due to health considerations, the recommended range for total dissolved solids (TDS) falls below 1,000 mg/L but higher 500 mg/L. Different quality standards categorize these measurements according to salt content or salinity levels. TDS is commonly classified into four types: fresh water, which contains less than 1,000 mg/L; brackish water, ranging from 1,000 to 10,000 mg/L; saline water, with TDS levels between 10,000 and 35,000 mg/L; and hypersaline water, which exceeds 35,000 mg/L in TDS (Rusydi, 2018). TDS ranging from 0 to greater than 200 mg/L may be from industrial wastewater, sewage, natural sources, and agricultural runoff. Freshwater environment with high concentration of total dissolved solids may not be suitable for drinking and irrigation purposes (Biswas et al., 2021). Anywhere in the world where a well is drilled, the shallow groundwater has low TDS which is fresh and is suitable for drinking if human activities haven't had a significant negative impact on it (Poeter et al., 2020).

2.3.4. Sodium Hazard

Continuous irrigation leads to salt accumulation, which promotes the removal of calcium and magnesium ions through leaching, plant uptake, drainage, and adsorption processes. This process disrupts the structure and contributes to the diffusion of soil particles. The displacement of magnesium and calcium ions promotes soil compaction, thus limiting water infiltration and making the soil less permeable. As a result, plants are unable to access the necessary amount of water, leading to a decrease in yield. This phenomenon is referred to as the “sodium hazard” and the prevalent situation leads to a decrease in the quality of water. Plants that are sensitive in nature are susceptible to the impacts of this circumstance. The most notable result of the sodium hazard is the occurrence of leaf burn and defoliation. Another factor connected to the sodium hazard is the percentage of sodium present. Elevated levels of sodium percentage contribute to the emergence of the sodium hazard (Bhatti et al., 2019).

2.4. Occurrence of anions and cations in freshwater environment

2.4.1. Major anions in water

2.4.1.1. Fluoride

As a result of rocks and minerals weathering, fluoride is frequently found in freshwater sources. The region's geology has a significant role in determining its concentration, although human activity can also have an impact. The breakdown of fluoride-rich rocks like fluorite is the cause of increased fluoride levels in groundwater. Fluoride levels in freshwater ecosystems can also be increased by human activities such industrial discharges, agricultural runoff, and the usage of chemicals that contain fluoride (Tufano and Salvestrini, 2018; Galindo-Miranda et al., 2019).

According to Babu et al. (2015) many areas of emerging nations have reported higher levels of fluoride in their groundwater, which is endemic in at least 25 nations worldwide. High groundwater temperatures have a considerable impact on human health and are a key cause of endemic fluorosis and a disabling disease may also develop slowly from an excessive intake of fluoride. Fluorosis is an incapacitating illness caused by the admission of F^- into the body. It affects all the body's organs, tissues, and cells and causes health concerns that share symptoms with various other diseases, such as gout and osteoporosis.

2.4.1.2. Chloride

One of the most frequently encountered anions in freshwater environments is chloride. It comes from several sources, including anthropogenic inputs, mineral leaching, and natural weathering. Chloride is associated with minerals including sylvite, gallite and carnallite (Galindo-Miranda et al., 2019) and can easily react with major cations to generate salts that are soluble in polar solvents (Matamoros et al., 2016). Rocks and salt deposits can dissolve naturally, adding chloride to the environment, but human activities like the use of road salt, discharging wastewater, and using industrial operations can greatly raise chloride concentrations (Kaushal et al., 2006; Starling et al., 2019). Freshwater plants and animals can suffer from high chloride concentrations, especially in areas with little room for dilution.

2.4.1.3. Nitrate

The chemical speciation of nitrogen in freshwater environment can be in the form of nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) (Gani et al., 2016). The presence of nitrate ions is from colloids and dissolved compounds. The biogenesis process transforms organic forms into mineral deposits whereby nitrogen regenerates and leads to ammonia (NH_3) being oxidized into NO_3^- and NO_2^- (Richards et al., 2021). Nitrates support growth of and reproduction of plants species. However, in higher concentration are harmful to aquatic environment as they can be easily transformed to NO_2^- (Dagestani et al., 2022). The freshwater environment is threatened by continuing increase of NO_3^- from different sources including cleaning reagents from households. groundwater may also be polluted by NO_3^- leaching from natural vegetation (Dagestani et al., 2022). WHO (2008) reported that most of scientific data collected in different countries highlighted that NO_3^- levels in drinking water collected from surface water were up to 10 mg/L and in well was greater than 50 mg/L.

2.4.1.4. Phosphate

Phosphate (PO_4^{3-}) strikes in the form of organic and inorganic compounds of suspended colloids. The chemical speciation of phosphate can be in the form of PO_4^{3-}, H_2PO_4 and HPO_4^{2-} (Verlicchi et al., 2012). The dominance of each phosphate species in a solution depends on the pH of the solution. Phosphorus is obtained in lower levels in natural water due to its low solubility and intensive depleted by hydro biotics (Rasheed et al., 2019). The sources of phosphates introduced to freshwater environment include sewage, industrial effluent, fertilizers, and many others (Richards et al., 2021). Orthophosphate is common inorganic phosphate in freshwater environments. High levels of phosphates in water result in eutrophication and due to excess growth of algae, oxygen is reduced in water and may lead to extinction of aquatic plants and fish.

2.4.1.5. Sulphates

Freshwater ecosystems naturally contain sulfate, which mostly results from the oxidation of sulfur-containing minerals in rocks and sediments (Dolar, 2012). Sulfate concentrations can also be influenced by microbial activity and the breakdown of organic substances. Sulfate levels in freshwater ecosystems can be increased by human activities such mining, industrial

discharges, and agricultural practices (Barnes and Kolpin, 2004). Some species are more vulnerable to sulfate toxicity than others, which can influence aquatic ecosystems when sulfate concentrations are high.

2.4.1.6. Bicarbonate ions

Bicarbonate ions (HCO_3^-) are a prevalent constituent of water and hold a crucial function in stabilizing the pH of water while exerting influence over diverse chemical and biological activities. Water abundant in HCO_3^- tends to facilitate the precipitation of insoluble calcium (Ca) and magnesium (Mg) in the soil, consequently leading to a greater presence of sodium (Na) available in solution. Although typical HCO_3^- levels are not inherently toxic, they have the potential to induce zinc (Zn) deficiency (Abbas et al., 2020).

2.4.2. Heavy and critical metals

Metals emerge as the environmental pollutants, imposing stress on the ecological community. They are unleashed into the environment through the erosion of rocks and human endeavours such as domestic discharges, industrial operations, and mining. These metals can be conveyed via rivers and airborne particles, eventually accumulating within lakes, seas, and oceans. Metals constitute a substantial proportion of sediment contaminants, attaining concentrations that induce environment toxicity. These metals can be categorized into three groups: macronutrients, micro/trace metals, and toxic metals.

Macronutrients such as calcium, sodium, magnesium, and potassium are necessary in larger amounts than other minerals. They supply energy and play vital roles in supporting growth, metabolism, and various bodily functions (Fellows, 2017).

Micronutrients like iron, manganese, copper, and zinc are crucial in specific quantities; an imbalance, either excessive or insufficient, can result in adverse effects.

Toxic/Trace metals: The prevalent metals typically detected in water include cadmium, mercury, nickel, arsenic, lead, and chromium. Common indicators of metal presence in water are discoloration and a metallic or salty taste Within aquatic ecosystems, these metals possess the ability to briefly exist as free ions in solution, assume colloidal state brought by adhering to inorganic compounds and organic materials. Monitoring their concentrations could serve as

a valuable gauge, facilitating accurate assessments of sediment contamination (Buccione et al., 2021).

2.5. Bioaccumulation of major cations and anions in the freshwater environment

The absorption of chemical constituents by organisms at faster rate compared to how is disoriented probably through excretion and catabolism mechanisms need much attention due emerging pollutants of concern (Rasheed et al., 2019). The chemical constituents (cations and anions) accumulate in soil, water, plants, and human bodies and this establishes serious health concerns (Richards et al., 2021). The main concern is ingestion of cations and anions dissolved in drinking water and accidentally from fishing and swimming. There is greater risk of chronic poisoning at a longer biological half-life of toxic chemical constituents (Zhao et al., 2018). The toxicity of anions and cations depends on exposure route, dose, chemical speciation of ions, bioaccumulation, and age group of consumers.

Due to their toxicity, trace metals have substantial ecological effects. They are important regulators of aquatic ecosystems and may pose a risk to humans and other living things. Environmentalists and biologists have seen heavy metal contamination as a serious hazard to the ecology inside the marine ecosystem.

According to studies done by Rubalingeswari et al., (2021) on the levels of trace metals in aquatic ecosystems and organisms, aquatic species have higher metal contents than their ecosystem. This results from the bioaccumulation process, in which the body takes in metal ions from the environment and stores them in various organs and tissues. The bioaccumulation factor (BAF), which is connected to biomagnification, depends on the mechanisms of tissue storage in addition to the organism's rate of intake and excretion. BAF can be calculated as the pollutant's cumulative concentration in the organs of the bioindicators divided by its dissolved concentration in water. The following equation can be used to determine BAF.

$$\text{BAF} = \frac{\text{metal concentration in the bioindicator's organs}}{\text{metal concentration in water}} \quad (1)$$

2.6. Environmental and health impacts of chemical constituents in freshwater environment

2.6.1. Environmental impacts of anions and cations in freshwater environment

Singh et al., (2020) indicated that scarcity of clean water due to anthropogenic activities polluting surface water pose a serious global environmental problem because it causes harm to aquatic ecosystems. Surface water is polluted by a variety of pollutant sources including discharged effluent (industrial and municipality wastewaters) and nutrients pollutants released from agricultural land use. Some of these NO_3^- or PO_4^{3-} pollutants may also be leached from natural commodities but their concentration becomes higher from discharged effluents including other major cations such as potassium (K), iron (Fe), manganese (Mn), calcium (Ca) etc. As concentration of NO_3^- and PO_4^{3-} increases, it negatively has impacts on flora (aquatic plants) and fauna (biota including fish). Due to algae that develops on surface water, it traps ultraviolet rays from the sun, and this can also cause oxygen-depletion.

It is critical to measure the turbidity of surface water as it reduces light intensity, inhibits plant growth, and clogs the gills of fish species. Ghangrekar and Chatterjee (2018) indicated that nutrient pollutant can be from point and non-point sources and high load of NO_3^- in lakes may result in eutrophication.

Pavlidis and Tsihrintzis (2018) highlighted that nutrients are beneficial to support plants growth, even though excessive nutrient concentrations can lead to algae on surface water that destroy the aquatic ecosystem. Due to respiration and degradation, algal blooms can significantly impair water quality by lowering the dissolved oxygen concentration in the water systems. Lack of dissolved oxygen may destroy both flora (indigenous species) and fauna (fish).

Conducting a geochemical analysis of water and sediment holds significant importance in comprehending the mechanisms behind the release of metals. The buildup of toxic metals in stream sediments can serve as a secondary contributor to water contamination when environmental conditions are altered. Consequently, sediments can also serve as a valuable environmental archive, capturing the historical presence of pollutants. Mining operations play a crucial role in the dissemination of heavy metals within the natural surroundings (Weleabzgi et al., 2022).

2.6.2. Health impacts of anions and cations in freshwater environment

WHO (2009) indicated that the ingestion of water with elevated fluoride levels (higher than 1 mg/L) may result in chronic disease (fluorosis), neurological damage and skin irritation. Though fluoride is essential in daily dietary, to minimize rate of dental cavities and prevent teeth decay. Calcium in teeth and bone strongly attracts fluoride due to its strong electronegativity.

Kelly et al., (2012) indicated that elevated levels of chloride pose a threat to infrastructure including industrial pipes and bridges. WHO (2008) highlighted that no health guideline assigned for chloride concentration in drinking water. However high levels of chloride up to 250 mg/L can be felt by taste in water. The excessive level of chloride poses a threat to human health if freshwater contains organic matter that can transform chlorine to chloramines.

Nitrate levels greater than 10 mg/L may result in methemoglobinemia. Methemoglobinemia (blue bay syndrome) is a health effect of nitrates that limits blood cells and circulation of oxygen, and this may result in fatal to infants. Other health effects may be gastric and intestinal cancer. High levels of sulphate greater than 500 mg/L makes water taste salty and this can corrode pipelines. The level of sulphates higher than 250 mg/L in drinking water may cause diarrhea.

Cations are introduced into aquifers through rainfall. The two most prevalent minerals causing water hardness are dissolved magnesium and calcium. Sodium (Na) is highly reactive and elevated concentrations can lead to a bitter taste and may also pose health risks to individuals with cardiac and kidney conditions. Iron can be introduced into water sources via industrial waste, corrosion, and the refinement of iron ore, existing in both ferrous and ferric forms. Nevertheless, an overabundance of iron can lead to harm to blood vessels, kidneys, and the liver, and result in fatal consequences. Both manganese and iron can lend a brownish tint in water, and an excessive concentration of manganese in drinking water can lead to neurological disorders. The excessive consumption of potassium can contribute to heart diseases, hypertension, kidney problems, diabetes and may also hinder proper kidney development in infants (Ogoamaka and Osarumwense, 2022).

Trace metals like arsenic (As), silver (Ag), barium (Ba), chromium (Cr), cadmium (Cd), mercury (Hg), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn), exhibit high toxicity levels even in low concentrations, posing a significant threat to both aquatic organisms and human beings. They can be extremely dangerous even in minute quantities, thus presenting a serious

health risk. Arsenic, for instance, is tasteless, colorless, and odorless in water, and can naturally occur in both water and soil due to weathering processes. Additionally, zinc and copper, when combined, can become toxic to various biological species in small amounts (Ogoamaka and Osarumwense, 2022).

2.7. Metal and anion analysis in water samples

2.7.1. Metal analysis

The metals in water samples were analysed using both an inductively coupled plasma optical emission spectrophotometer (ICP-OES) and an inductively coupled plasma mass spectrophotometer (ICP-MS). The ICP-OES possess a linear dynamic range capable of analysing metals from parts per million (ppm) to percent levels. This technique utilizes plasma as a source and relies on optical emission for analysis, primarily designed for liquid samples. These liquid samples undergo a process of nebulization to transform them into an aerosol before being introduced into the plasma. The extreme temperatures within the plasma effectively disintegrate the samples into atoms, providing the necessary energy for ionization and excitation.

ICP-MS utilizes argon (Ar) plasma to transform the sample into ions, which are quantified using a mass spectrometer. With significantly lower detection limits compared to ICP-OES, it proves to be a superior option for trace element analysis. An ICP-MS setup comprises a mass spectrometer (typically a scanning quadrupole mass filter), the ion source (the ICP), and a detector. The ICP operates at atmospheric pressure, while the MS and detector function within a vacuum chamber. Therefore, an ICP-MS necessitates a vacuum pump, a vacuum interface, and specific electrostatic ion "lenses" to precisely direct the ions through the system (Wilschefski and Baxter, 2019).

The ICP-OES and ICP-MS instruments underwent standardization using a multi-element calibration standard, and their analytical precision was validated by regular analyses of both standards and blanks. A multi standard solution served as a quality control measure, ensuring the precision of instrument calibration and the quantification of specific metals before and during sample analysis to continually monitor any potential drift (Luvhimbi et al., 2022).

2.7.2. Anions analysis

Ion chromatography was employed in the analysis of water chemistry to quantify the levels of primary anions including fluoride, chloride, nitrate, sulphate, and phosphate. The detection of these anions occurred through conductivity measurements within the parts-per-million (ppm) range. (Bauer and Gluhak 2019).

2.8. Metal and anion environmental standards in water bodies

Table 2.1 Desirable values for Zambia Bureau of Standards (ZABS), South African National Standard (SANS) (241-1) and World Health Organization (WHO) standards on water quality

Parameters	Unit	ZABS	WHO	SANS
pH		8.0	8.5	8.5
EC	µS/cm	1500	400	1700
TDS	mg/L	1000	1000	1200
F^-	mg/L	1.5	1.5	1.5
Cl^-	mg/L	250	300	300
NO_3^-	mg/L	10	50	11
SO_4^{2-}	mg/L	400	250	250
Ca	mg/L	200	100	-
K	mg/L	-	20	-
Mg	mg/L	150	50	-
Na	mg/L	200	200	200
As	mg/L	0.01	0.01	0.01
Fe	mg/L	0.3	0.3	0.3
Al	mg/L	0.2	0.2	0.3
Zn	mg/L	3	3	5
Mn	mg/L	0.1	0.4	0.1
Cu	mg/L	1	2	2
Cr	mg/L	0.05	0.05	0.05
Ni	mg/L	-	0.07	0.07

CHAPTER 3: AIM AND OBJECTIVES

This chapter establishes the study's goal and refines expectations by outlining the purpose's supporting objectives.

3.1. General Objective

Environmental science studies have shown that beneficial uses cannot be effectively preserved unless the levels of pollutants are monitored and regulated. Pollutant concentrations, whether physical or chemical, and water quality are frequently used to characterize these objectives. (Water Quality Division | "The California State Water Resources Control Board (2020). The primary aim of this study was to evaluate the water quality of Lake Kariba, influenced by various activities in and around the lake. This was achieved by measuring the physical properties of the water, the concentrations of metals and ions within the lake and its surrounding areas and investigating potential contributions between these elements and the land use practices around the lake.

3.2. Specific Objectives

- To measure the physicochemical properties of water from various parts of Lake Kariba.
- To identify and quantify different anions and metals in water from various parts of Lake Kariba.
- To identify the physicochemical properties, anions and metals in Lake Kariba's water, and then correlate these findings with human activities and land use practices in and around the lake.

3.3. Importance and Limitations of the study

This research is essential for understanding the interactions between land use practices and water quality in Lake Kariba. The study provides latest data on the presence and concentrations of anions and metals in the lake, highlighting their connections to ongoing activities in the surrounding area. Moreover, it contributes valuable insights into the impact of human activities on freshwater ecosystems, helping to address similar challenges worldwide.

However, the study faced a significant limitation due to the non-simultaneous sampling, driven by logistical constraints. This could lead to temporal variability, potentially affecting the comparability of data across different sites. Consequently, the findings may not be entirely generalisable to other time periods or locations. To validate the observed patterns and gain a more complete understanding of water quality dynamics in the area, future research should focus on synchronized sampling across sites. Enhancing logistical planning and coordination to achieve simultaneous sampling would improve data reliability and strengthen the study's conclusions.

CHAPTER 4: MATERIALS AND METHODS

This chapter describes the sample collection, preparation and analytical techniques used for the analysis.

4.1. Study area and sampling

The study was conducted from different parts of Lake Kariba from Zambia side, where it is surrounded by three districts well known for Kapenta fishing and aquaculture, Sinazongwe, Gwembe and Siavonga (Hasimuna et al., 2019; Simukoko et al., 2022). Siavonga district, one of Zambia's major aquacultures as a major fishery community (Hasimuna et al., 2019).Lake Kariba is the man-made confinement region of water bodies which is located between 17.97° S and 16.45° S and stretches across two longitudinal degrees, from 27.00° E to 29.05° E being shared by Zambia and Zimbabwe in equal proportions (Figure 4.1) (Tran et al., 2018; Njiru et al., 2018; Aura et al., 2018; Simukoko et al., 2022). The lake stretches beyond 223 kilometres (km) in length and extends up to 40 km in width and has been known as the largest man-made water reservoir across the globe due to its high-volume water-holding capability.

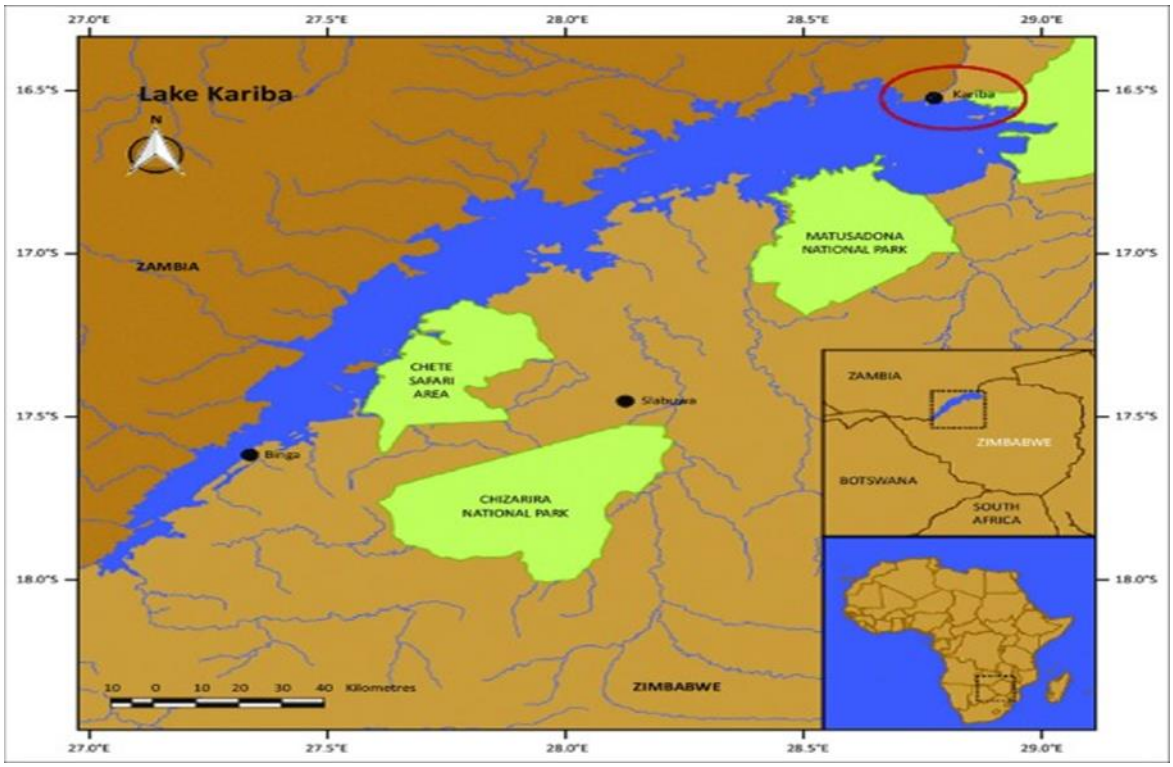


Figure 4.1 Study area showing geographical location of Lake Kariba, Siavonga

4.2. Sample collection Preparation

Water samples were taken from the upstream of the Lake near Sinazongwe and mostly from downstream in Siavonga areas. The following locations were examined: (i) Lower part close to the dam wall, (ii) Aquaculture farming regions (Yalelo, Banana Island, Kabyobyo, and ZamFresh cages) also lower end, and (iii) the sources of Kariba's tributaries (Muzuma, Kanzinze, Zongwe (both upper and downstream), and Malasha River) in the upstream part of the Lake.

4.2.1. First Sampling Points, Lake Kariba downstream in Siavonga

The initial sampling was carried out between the dam wall and Banana Island in October 2021 during the summer (dry season). A total of 27 water samples were taken from a boat, and sampling locations were determined (Table 4.1). The sampling area covered was considerably smaller than the extent of the lake depicted in Figure 4.2.

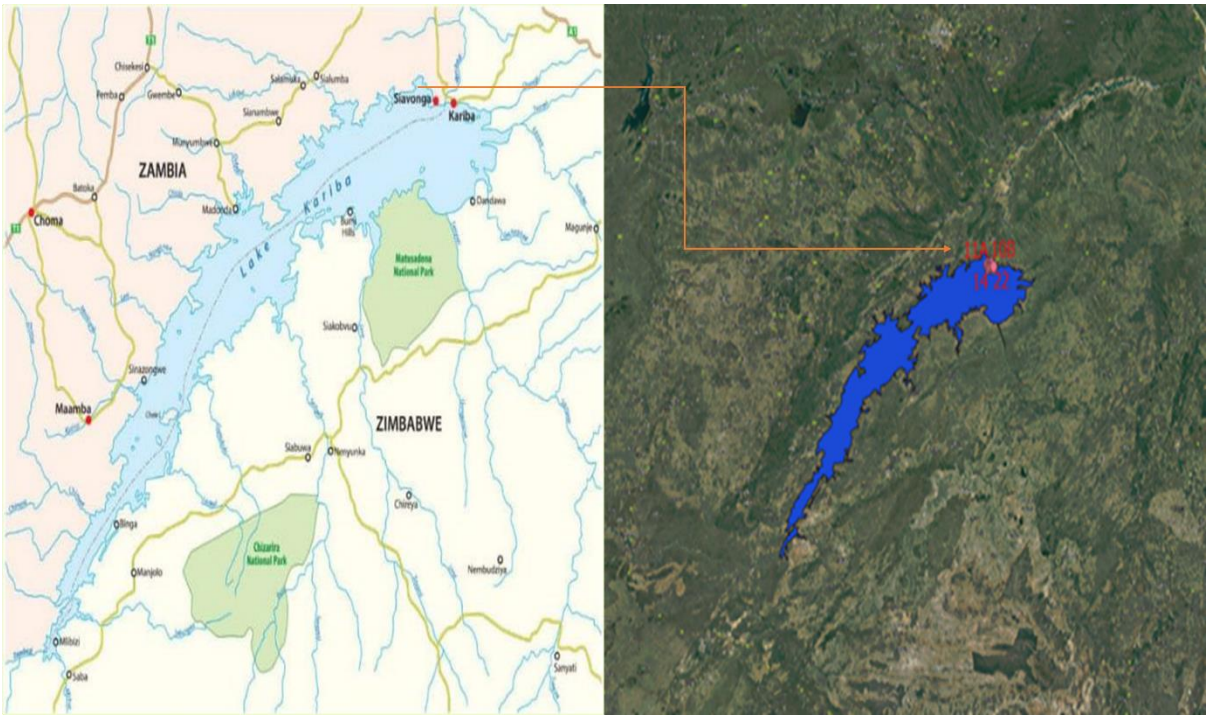


Figure 4.2 Geographical coordinates on Lake Kariba for the first sampling, October 2021

Table 4.1 Description of the first sampling sites and their GPS coordinates

Sample codes	Description	Coordinates	
		X (m)	Y (m)
DSL-1	Manchinchi – Laundry	684185,7	8170823,2
DSL-2	Eagle Rest – Shore	684459,2	8170919,0
DSL-3	Manchinchi – Harbour	684020,7	8170980,5
DSL-4	Bilharzia Bay – Chombo	683581,5	8171287,3
DSL-5	Harbour	682158,1	8170423,1
DSL-6	Lake Safari Lodge	682348,5	8170267,9
DSL-7	Fisheries	682227,1	8170875,8
DSL-8	Fresh View Hotel – Shore	681437,6	8170594,4
DSL-9	Fresh View Hotel	681398,2	8170519,1
DSL-10	Crocodile Farm, Kaliolio – Shore	681625,1	8172699,9
DSL-11	Crocodile Farm, Kaliolio	681658,0	8172690,4
DSL-12	Crocodile Farm, Kaliolio	681473,4	8172774,4
DSL-13	Crocodile Farm, Kaliolio	681369,0	8172801,0
DSL-14	Banana Island	679388,7	8172413,0
DSL-15	Fish Farming – Kabyobyo	678857,9	8172004,3
DSL-16	Fish Farming – Yalelo	678646,5	8171886,8
DSL-17	800m from the shore – 15minutes Intervals	678693,4	8170839,3
DSL-18	30 minutes	678937,7	8170242,7
DSL-19	45 minutes	679435,7	8169937,3
DSL-20	60 minutes	680004,1	8169462,9
DSL-21	75 minutes	680699,3	8169575,6
DSL-22	90 minutes	681394,6	8169829,3
DSL-23	105 minutes	682334,1	8169589,7
DSL-24	120 minutes	682592,4	8169740,0
DSL-25	135 minutes	683508,5	8169730,6
DSL-26	150 minutes	683936,0	8169857,5
DSL-27	165 minutes	684042,6	8170529,3

4.2.2 Second Sampling Points, Lake Kariba downstream (Siavonga) and upstream

A total of 21 water samples were taken, and sampling locations were established, during the second sampling, which took place in July 2022 during the cold season. The areas surveyed were primarily tributaries, both upstream and downstream (Table 4.2). Four further water samples were taken from the dam wall to the ZamFresh cages on a boat on Lake Kariba. Figures 4.3 show the sampling area that was covered.



Figure 4.3 Geographical coordinates on lake and river for second sampling, July 2022

Table 4.2 Description of the second sampling sites and their GPS coordinates

Sample codes	Description	Longitude	Latitude
USL-1	Muzuma River	S 17°11.367'	E 027°45.061'
USL-2	Kanzinze River	S 17°17.257'	E 027°19.995'
USL-3	Malasha River – A	S 17°35.903'	E 027°19.459'
USL-4	Malasha River – B	S 17°35.903'	E 027°19.459'
USL-5	Zongwe River – Upper	S 17°26.404'	E 027°36.101'
USL-6	Zongwe River – Downward	S 17°26.541'	E 027°36.260'
USL-7	Lake Kariba – Sinazongwe	S 17°26.833'	E 027°47.056'
USL-8	Dam on Muzuma River	S 16°54.201'	E 026°52.885'
USL-9	Yalelo Shore – 1	S 16°28.084'	E 028°38.786'
USL-10	Yalelo Shore – 0	S 16°28.076'	E 028°38.882'
USL-11	Yalelo Shore – 2	S 16°28.103'	E 028°38.826'
USL-12	Yalelo Shore – 3	S 16°28.168'	E 028°38.744'
USL-13	Siavonga Market		
USL-14	Fisheries		
USL-15	Saver Beach Resort (SBR)		
USL-16	Point 4 (close to SBR)		
DSL-28	Lake Kariba, Siavonga – Dam Wall	S 16°53.482'	E 028°74.719'
DSL-29	Banana Island – Behind	S 16°30.909'	E 028°40.302'
DSL-30	Fish Farming – Kabyobyo	S 16°29.946'	E 028°41.335'
DSL-31	Fish Farming – Yalelo	S 16°30.195'	E 028°38.705'
DSL-32	ZamFresh Cages	S 16°30.975'	E 028°35.841'

4.2.3. Final Sampling Points, Lake Kariba downstream in Siavonga

The last sampling was conducted in April 2023 during summer (rainy season). From the dam wall to the zamfresh cages, a total of 21 water samples were taken from a boat on Lake Kariba, and sampling locations were noted in Table 4.3. Figure 4.4 depicts the sampling area that was covered.

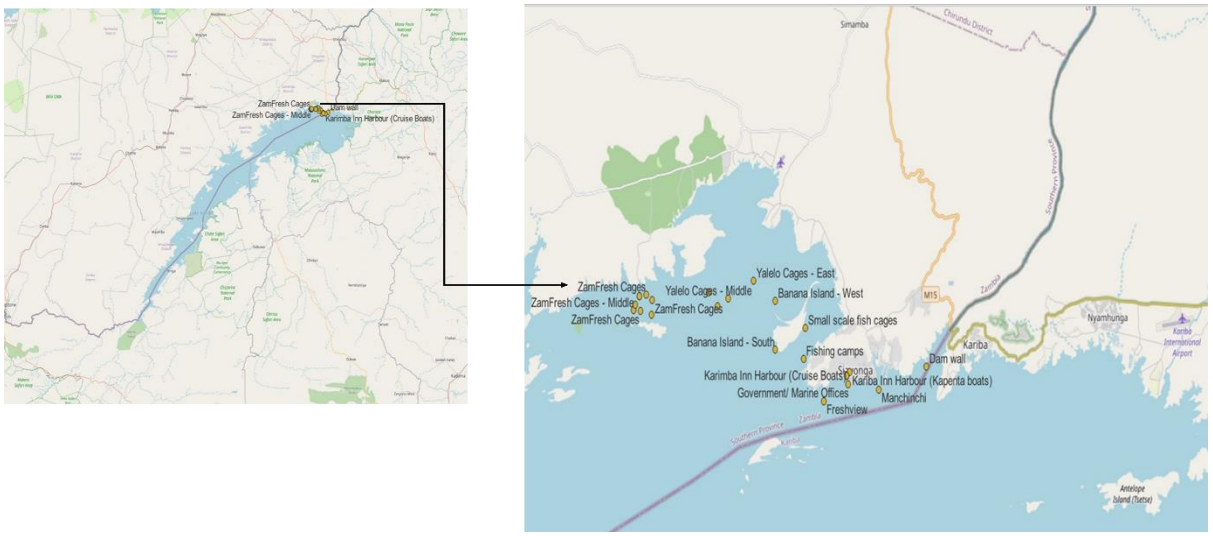


Figure 4.4 Geographical coordinates on the lake for the final sampling, April 2023



Figure 4.5 Illustrates the limited samples collected during (a) October 2021, (b) July 2022, and (c) April 2023

Forty-eight (48) samples, with an estimated volume of 500 ml each bottle, and 21 samples, with an estimated volume of 1 L per bottle, were collected in polyethylene bottles and stored in a refrigerator (5 °C) at the University of Zambia (UNZA) prior to being sent to South Africa for additional analysis (Figure 4.5).

With the aid of a portable multimeter from Hanna Instruments (Pty) Ltd., measurements of the parameters Electrical Conductivity, pH, TDS, and Temperature were made on-site. A sealed polypropylene plastic box containing ice bricks was used to transfer samples to the lab at the University of Witwatersrand in South Africa.

For anions analyses, samples were kept in polyethylene bottles that had been thoroughly cleansed with ultra-pure water. For cations (major and trace) analyses, samples were stored in polyethylene bottles that was cleaned prior with 10% HNO_3, rinsed thoroughly with deionized water. To prevent cation adsorption onto the wall of the bottles during cation studies, the unfiltered samples were acidified to pH 1 with 1 mol L^{-1} HNO_3. To prevent deterioration and for subsequent analysis, all samples were stored in the refrigerator at a temperature of 2 to 10 degrees.

Table 4.3 Description of the final sampling sites and their GPS coordinates

Sample codes	Description	Longitude	Latitude
DSL-33	Dam Wall	S 16° 32.127'	E 028° 44.927'
DSL-34	Manchinchi Bay Lodge	S 16° 32.587'	E 028° 43.419
DSL-35	Fresh View Hotel	S 16° 32.838'	E 028° 41.562'
DSL-36	Fishing Camps	S 16° 31.916'	E 028° 40.888
DSL-37	Small Scale Fish Cages	S 16° 31.313'	E 028° 40.924'
DSL-38	Banana Island – South	S 16° 31.734'	E 028° 39.956'
DSL-39	Banana Island – West	S 16° 30.674'	E 028° 39.953'
DSL-40	Yalelo Cages – East	S 16° 30.259'	E 028° 39.256'
DSL-41	Yalelo Cages – Middle	S 16° 30.641'	E 028° 38.449'
DSL-42	Yalelo Cages	S 16° 30.595'	E 028° 37.846'
DSL-43	Yalelo Cages	S 16° 30.818'	E 028° 38.128'
DSL-44	ZamFresh Cages – Entrance	S 16° 30.990'	E 028° 35.984'
DSL-45	ZamFresh Cages	S 16° 30.977'	E 028° 35.558'
DSL-46	ZamFresh Cages – Middle	S 16° 30.971'	E 028° 35.409'
DSL-47	ZamFresh Cages	S 16° 30.752'	E 028° 35.408'
DSL-48	ZamFresh Cages	S 16° 30.659'	E 028° 35.612'
DSL-49	ZamFresh Cages	S 16° 30.544'	E 028° 35.753'
DSL-50	ZamFresh Cages	S 16° 30.698'	E 028° 36.016'
DSL-51	Kariba Inn Harbour (Cruise Boats)	S 16° 32.282'	E 028° 42.302'
DSL-52	Kariba Inn Harbour (Kapenta Boats)	S 16° 32.281'	E 028° 42.352'
DSL-53	Government/Marine Offices	S 16° 32.511'	E 028° 42.372'

4.3. Reagents and Chemicals

For the analysis of cations and anions in trace quantities, only analytical grade or higher chemicals and reagents were utilized. Hydrogen peroxide (H_2O_2), 65% w/v concentrated pure nitric acid (HNO_3), 30% w/v and 98% w/v phosphoric acid (H_3PO_4) of supra pure grade were acquired from Merck Chemicals (PTY) Ltd. in Johannesburg, South Africa (SA). Commercial stock solutions (1000 g/ml) for IC, ICP-OES, and ICP-MS were obtained from de Bruyn Spectroscopic Solution, SA. For quality control, intermediate stock solutions of 1000 g/ml were purchased from Stargate Scientific, SA. A Milli-Q system purchased from Merck; SA produced de-ionized water (ultrapure, Type 1) with a resistivity of 18.2 MΩ-cm.

4.4. Instruments and Equipment

Total dissolved solids (TDS), Electrical conductivity (EC), pH, and temperature were measured using the Hanna multiparameter HI98194 (Hanna Instruments Pty Ltd, Johannesburg, SA). Multiwave Go (Anton Paar Southern Africa Pty Ltd, Johannesburg, South Africa) was used to digest water samples, Eco IC (Metrohm, Pty Ltd, Johannesburg, SA) to determine anions (F^-, Cl^-, NO_3^-, SO_4^{2-} and PO_4^{3-}), ICP-OES, Spectro Genesis (Spectro Analytical Instruments Pty Ltd, Johannesburg, South Africa) was used to analyse major cations (Ca, K, Mg, Na, Si, Fe and Al), and Nexion 2000 (PerkinElmer Pty Ltd, Johannesburg, SA) to analyse trace cations (As, Zn, Mn, Cu, Ni, Ti, and Cr). The 20 ml syringes, 0.22 µm, and 0.45 µm simple pure syringe filters from Anatech Instruments Pty Ltd (Johannesburg, SA) and micropipettes from Sciprofs Pty Ltd (Johannesburg, SA) ranging from 2 µl to 5000 µl for the preparation of calibration standards were used to filter water samples as additional tools.

4.5. Determination of major and trace cations in water

4.5.1. Preparation using Microwave Digestion

Water samples containing particles were digested using Multiwave GO (Figure 4.6). A volume of 10 ml of each sample were measured into various clean digestion vessels (lined with PTFE-TFM), and 5 ml of HNO_3 and 1 ml of H_2O_2 were then added to the vessels. The tubes were closed, put into a rotor, and digested using the program and conditions shown in Tables 4.4 and 4.5, respectively. The digested solution was then put into clean 25 mL volumetric flasks and diluted with ultrapure water to the appropriate concentration. To safeguard the nebulizer from any suspended particles, all digested solutions were subsequently filtered using 0.22 µm

SIMPLEPURE syringe filters before analysis. Before use, the vessels and volumetric flasks were cleaned with 10% (v/v) HNO_3 and were completely rinsed with ultrapure water. To control the level of contamination, the blank was made using the same steps as the samples.



Figure 4.6 Multiwave GO microwave system.

Table 4.4 Microwave Digestion Program

Ramp (min)	**Temperature (°C)**	**Hold (min)**
15	100	10

Table 4.5 Parameter conditions for Microwave Digestion

Application type	Digestion
Vessel mode	Multi-vessel
Temperature program mode	Average
Temperature limit (°C)	200

4.5.2. Measurements for major cations using the Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP - OES) technique.

The ICP - OES shown in Figure 4.7 was calibrated beforehand to obtain the best sensitivity using standards ranging from 0.1 mg/L to 10 mg/L that were made from a stock solution of 1000 mg/L. To manage the instrument stability and calibration drift, quality checks of 0.5 mg/L and 2 mg/L were also prepared using a 1000 mg/L stock solution (Stargate Scientific). Each standard was analyzed using a different metal wavelength to adapt for the metals' relative concentrations with increase in sensitivity. Additionally, blank was included in the calibration to keep track of any potential interferences. Table 4.6 displays the parameters that were optimized.

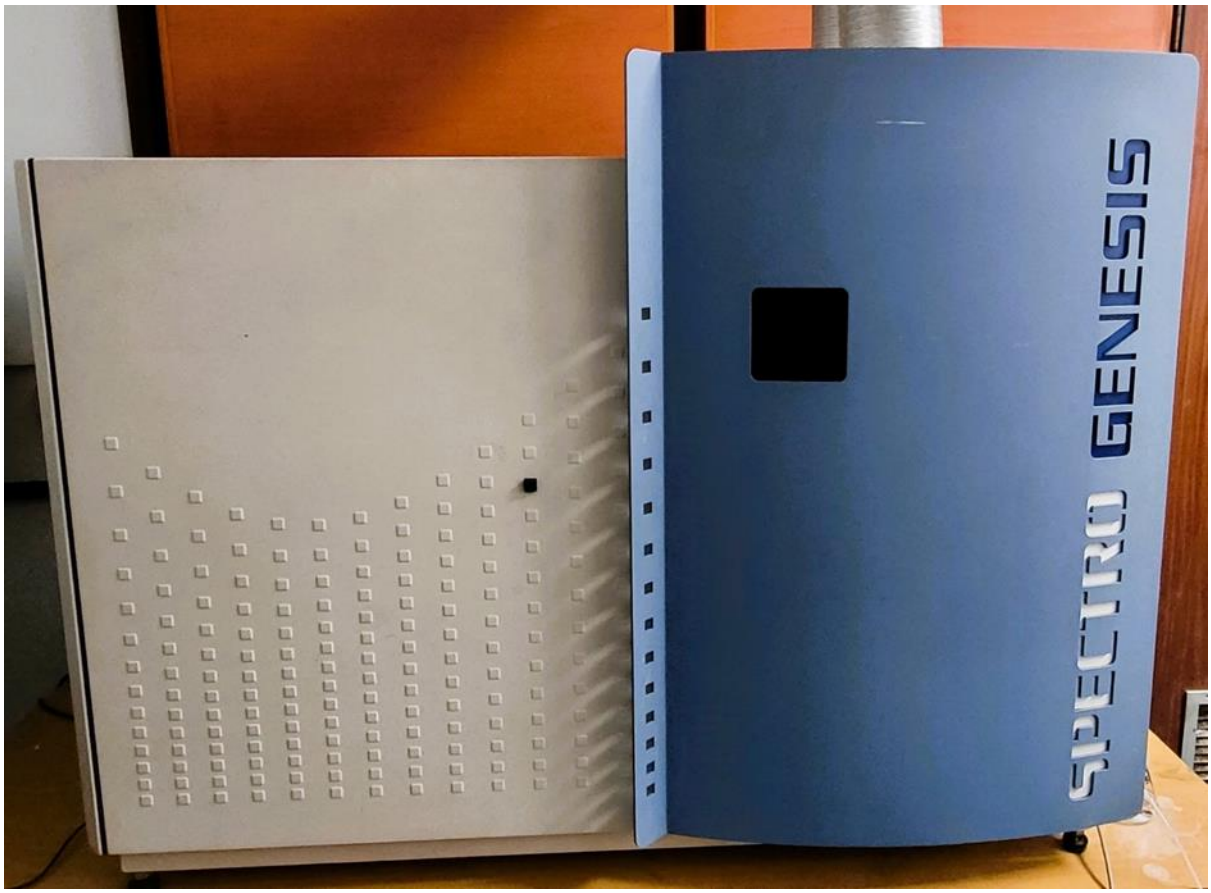


Figure 4.7 Inductively coupled plasma - optical emission spectroscopy.

Table 4.6 Operating parameters for ICP - OES

Parameters	Optimal condition
Coolant flow	14 ml /min
Auxiliary flow	1 ml /min
Plasma power	1400 W
Pump Speed	2 rpm
Nebulizer flow	1 ml /min
Nebulizer Pressure	3.00 bar
Argon Pressure	6.48 bar

4.5.3. Measurements for trace cations using the Inductively Coupled Plasma - Optical Mass Spectrometry (ICP - MS) technique.

The ICP - MS instrument shown in Figure 4.8 was used to quantify trace elements in the samples.



Figure 4.8 Inductively coupled plasma-mass spectrometry.

From a stock solution of 10 mg/L, multiple standard solutions ranging from 5 µg/L to 200 µg/L were prepared to generate a calibration curve and to achieve accurate and precise results, quality checks of 50 µg/L and 100 µg/L were made from a stock solution of 10 mg/L from Stargate Scientific. To keep an eye out for any potential interferences, blank was also incorporated into the calibration. The optimized settings are displayed in Table 4.7.

Table 4.7 Operating parameters for ICP - MS

Parameters	**Optimal condition**
RF power	1500 W
Vacuum pressure	1.50e-7 Torr
Plasma gas flow	17 L/min
Auxiliary gas flow	1.2 L/min
Nebulizer gas flow	0.98 L/min
Gas flow	5.6 L/min
Sweeps/Reading	20

4.6. Determination of anions in water

4.6.1. Sample preparation

Prior to the run, 15 ml of the sample was filtered through 0.45 µm disposable membrane filters into clean glass bottles to eliminate sediment and other particulate matter and to reduce the possibility of microbial modification. pH and electrical conductivity (EC) were then tested prior to checking for undesired levels of contaminants because excess ions contributing to higher conductivity can damage the column, processes, and/or product yield.

4.6.2. Measurements for anions using the Ion Chromatography (IC) technique

The analysis was performed on an ECO IC, automated with a compact autosampler (Figure 4.9). The column was running at a room temperature, which offered adequate separation for thermostability with less technical complexity. During separation, suppression using the Metrohm Suppressor Module (MSM) reduces background conductivity and raises the signal to noise (S/N) ratio. Anions were measured with a conductivity detector and quantification using MagIC Net software. The calibration was ranging from 0.5 – 100 mg/L including a blank to detect any possible interferences.



Figure 4.9 Eco IC with an 863 Compact Autosampler.

Table 4.8 Operating parameters for IC

Parameters	Optimal condition
Data source	Conductivity detector
Recording time	15.0 min
Column (150 x 4.0 mm)	Metrosep A Supp17
Eluent composition	5mM Na_2CO_3 & 0.1mM $NaHCO_3$
Flow	1.000 ml/min

4.7. Quality control (QC) and Quality assurance (QA) on analytical methods

Quality protocols were adhered to in order to guarantee the dependability and precision of the outcomes. Accredited analytical standards were used to calibrate all three methodologies. Ultra-pure water was utilized during all phases of the procedures. Blank samples were incorporated to rectify any potential interferences or impurities and to establish the limit of detection.

4.7.1. Limit of detection for the method

The Limit of Detection (LOD) is the minimum concentration of an analyte within a sample that can be reliably differentiated from the background noise or blank sample with a specified level of confidence. This parameter is particular to the matrix, method, and analyte being examined (Al-Hakkani, 2019). The following equation was used to ascertain the limit of detection.

$$LOD = 3\ x\ standard\ deviation\ of\ the\ blank\ samples \quad (2)$$

4.7.2. Accuracy

Certified solutions with established concentrations were used as quality controls to validate the attained outcomes.

4.7.3. Precision

To monitor the repeatability and reproducibility, three replicates' measurements were taken.

4.7.4. Internal standard

A pure compound with a known concentration, which was unrelated to the analysis of interest, was introduced to the sample prior to instrumental analysis. This allowed for the compensation of any inefficiencies.

4.8. Analysis of Statistical Data

The data was inputted into Microsoft Excel and transferred to a statical package. The mean and standard deviation of each parameter were calculated to compare with water quality standards set by WHO. To identify significant variations in water quality among different water sources, a One-way analysis of variance (ANOVA) was conducted. Graphical representation of the statistical data was accomplished using the OriginPro Graphing and Analysis Software.

4.8.1. Correlation matrix

A Pearson's correlation matrix was executed to examine the relationships between the parameters within the water (Das-Kangabam et al., 2017)

4.8.2. Water Quality Index (WQI) and Percent Sodium (%Na)

In evaluating water quality, the water quality index and the percentage of sodium were used to determine the classification level, identify potential health hazards, and assess the drinkability of the water (Karakus, 2019).

4.8.2.1. Water quality Index

The water quality index was formulated by utilizing the measured parameter values and applying the subsequent steps for calculation:

1. Allocate the weighted value (w_i) to each parameter according to the relative significance of drinking water quality as outlined in the WHO (2019) standard.
2. Calculate the relative weight (W_i)

$$W_i = \frac{w_i}{\sum w_i} \quad (3)$$

where W_i = relative weight, w_i = the weighted value of each parameter

3. Calculate the quality rating scale (Q_i)

$$Q_i = (C_i / S_i)100 \quad (4)$$

where Q_i = quality rating scale, C_i = concentration of the parameter, S_i = WHO (2019) drinking water standard for each parameter.

4. Calculate the subindex value (SI_i)

$$SI_i = W_i * Q_i \quad (5)$$

where SI_i = subindex, W_i = relative weight and Q_i = quality rating scale

5. Calculate the water quality index (WQI)

$$WQI = \sum SI_i \quad (6)$$

4.8.2.2. Sodium Percent

The percent sodium can be calculated using the subsequent formula:

$$\%Na = \frac{Na}{(Ca+Mg+K+Na)} \times 100 \quad (7)$$

Elevated sodium ratios can influence soil permeability (Ravikumar et al., 2013)

4.8.3. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a statistical method employed for dimensionality reduction in data analysis. It simplifies the complexity in multi-dimensional data while preserving patterns and trends, and to ascertain the factors or origins responsible for variations in water quality (Zeinalzadeh and Rezaei 2017).

CHAPTER 5: RESULTS AND DISCUSSION

This chapter presents the analytical findings from the water sample analyses, which are displayed as tables and graphs.

5.1. Quality Control (QC) and Quality Assurance (QA)

Table 5.1 presents the linear regression for the link between intensities and the metal (std) concentrations for ICP-OES, ICP-MS and IC was illustrated by the linear regression between area of peak vs. metals (std) concentration along with the coefficient (R^2), limit of detection (LOD) and limit of quantification (LOQ) (Alexander and Rohman 2019).

Table 5.1 Linearity, LOD and LOQ for cations and anions

Technique	Element	Concentration range	Regression equation	R^2	LOD	LOQ
ICP-OES	Ca	0.10 – 10 mg/L	y = 0.0212x + 0.0005	0.9998	0,112	0,341
	K	0.10 – 10 mg/L	y = 0.0115x - 0.0012	0.9997	0,125	0,379
	Mg	0.10 – 10 mg/L	y = 0.2295x + 0.0062	1.0000	0,043	0,132
	Na	0.10 – 10 mg/L	y = 0.1367x + 0.0164	0.9995	0,164	0,498
	Si	0.10 – 10 mg/L	y = 0.0166x - 0.00003	0.9995	0,178	0,538
	Fe	0.10 – 10 mg/L	y = 0.022x - 0.0004	1.0000	0,045	0,137
	Al	0.10 – 10 mg/L	y = 0.0219x - 0.0021	0.9997	0,137	0,416
	Mn	0.10 – 10 mg/L	y = 0.1026x +0.00009	0.9999	0,067	0,203
ICP-MS	Zn	5 – 200 µg/L	y = 0.0073x + 0.0489	0.9994	4,739	14.36
	Mn	5 – 200 µg/L	y = 0.0902x + 0.0919	0.9999	1.417	4.293
	Cu	5 – 200 µg/L	y = 0.0301x + 0.1104	0.9995	4.382	13.28
	Ni	5 – 200 µg/L	y = 0.0398x + 0.1214	0.9990	6.151	18.64
	Ti	5 – 200 µg/L	y = 0.0282x + 0.0616	0.9999	1.817	5.505
	Cr	5 – 200 µg/L	y = 0.0573x + 0.2504	0.9996	3.945	11.96
	As	5 – 200 µg/L	y = 0.0425x + 0.1525	0.9996	3.819	11.57
IC	F^-	0.50 – 100 mg/L	y = 0.1123x + 0.0356	0.9992	0,048	0,145
	Cl^-	0.50 – 100 mg/L	y = 0.0661x + 0.0183	0.9996	0,065	0,196
	NO_3^-	0.50 – 100 mg/L	y = 0.0166x - 0.1599	1.0000	0,143	0,435
	SO_4^{2-}	0.50 – 100 mg/L	y = 0.0589x - 0.0369	0.9996	1.489	4.512
	PO_4^{3-}	0.50 – 100 mg/L	y = 0.0213x - 0.0103	0.9996	1.516	4.593

To ensure quality control, a continuous calibration verification (CCV) analysis was performed for each run. A concentration of 3 mg/L Scandium (Sc) and 10 µg/L Rhodium (Rh) were used as internal standards for ICP-OES and ICP-MS respectively. Blank samples and a spiked solutions containing elements to be analysed at various concentrations served as references for

ICP-OES, ICP-MS and IC and the recovery percentages of these elements were then determined. Each sample was measured in triplicate, and calculated correlation coefficient values (R^2) for CCV at different concentrations. Limit of detection and limit of quantification were calculated using the following formulas: LOD = (3.3 × σ) / S and LOQ = (10 × σ) / S, where σ represents the standard deviation of the response, and S is the slope of the calibration curve. The percent recovery and relative standard deviation are shown in Table 5.2 and were calculated using the formulas: Recovery (%) = (experimental yield) / (theoretical yield) × 100. The percent relative standard deviation was calculated using the formula: RSD (%) = $(\frac{\sigma}{\bar{x}})$ X 100 with σ being the standard deviation and $\bar{x}$ representing the average of the analyte replicates.

Table 5.2 Percent Recoveries and Relative Standard Deviation (% RSD) for spiked samples

Technique	Element	Spiked Concentration	R1	R2	R3	Mean	SD	%RSD	%Recovery
ICP-OES	Ca	2 mg/L	2,02	2,03	2,02	2,02	0,004	0,22	101,1
	K	2 mg/L	2,02	2,04	1,99	2,02	0,023	1,12	100,8
	Mg	2 mg/L	2,02	2,02	2,03	2,02	0,003	0,16	101,1
	Na	2 mg/L	1,99	2,02	2,02	2,01	0,013	0,64	100,5
	Si	2 mg/L	1,99	1,98	2,00	1,99	0,011	0,54	99,52
	Fe	2 mg/L	2,02	2,02	2,06	2,03	0,020	1,00	101,6
	Al	2 mg/L	2,04	2,03	2,02	2,03	0,011	0,57	101,4
	Mn	2 mg/L	2,03	2,02	2,03	2,03	0,003	0,16	101,3
ICP-MS	Zn	50 µg/L	49,9	49,7	49,7	49,8	0,068	0,14	99,51
	Mn	50 µg/L	50,0	50,0	50,1	50,0	0,012	0,02	100,1
	Cu	50 µg/L	50,0	50,0	50,1	50,0	0,019	0,04	100,1
	Ni	50 µg/L	50,0	50,0	50,1	50,0	0,012	0,02	100,1
	Ti	50 µg/L	50,0	50,1	50,1	50,0	0,055	0,11	100,1
	Cr	50 µg/L	49,9	49,8	49,8	49,8	0,016	0,03	99,68
	As	50 µg/L	50,0	50,1	50,1	50,1	0,046	0,09	100,1
IC	F^-	20 mg/L	19,9	20,0	19,8	19,9	0,082	0,40	99,50
	Cl^-	20 mg/L	20,0	20,1	19,9	20,0	0,082	0,46	100,0
	NO_3^-	20 mg/L	19,9	20,0	20,1	20,0	0,068	0,34	100,1
	SO_4^{2-}	20 mg/L	19,9	19,9	19,9	19,9	0,014	0,07	99,34
	PO_4^{3-}	20 mg/L	20,2	20,1	20,1	20,1	0,047	0,16	100,8

R = replicate, SD = standard deviation, RSD = relative standard deviation

5.2. Physical-chemical parameters in the water

5.2.1. Mean and individual physical-chemical parameters in the water of Lake Kariba

The results of the mean physical chemical parameters found in the lake during the sampling periods of October 2021- (Hot and Dry season), July 2022 (Cool-Dry season) and April 2023 (Rainy season) comprising both downstream and upstream locations are shown in Tables 5.3 and 5.4.

There was a notable variation in pH levels in the Lake from downstream to upstream. Mean pH values ranged from 7.04 (upstream) to 7.97 (downstream), indicating that the water was predominantly neutral to slightly alkaline. However, the mean pH values do not give a true picture of actual of localised pH changes occurring due to land use activities around the lake. The upstream area of the lake exhibited a lower minimum pH value of 3.71 compared to 7.61, 7.32 and 7.55 of the downstream sampled areas. This lower pH signifies an acidic nature, likely attributed to the presence of acid-forming substances and could be linked to land use activities around this area especially Maamba Colliery Coal mine (Besa, 2001). In the same way the highest pH was recorded at 8.32 in one downstream area of the lake compared to 8.26, 7.89 and 7.75 in other areas. The maximum pH values could be attributed to the bicarbonate and carbonate chemistry of the lake. The mean pH levels observed in this study conform to the guidelines set forth by WHO and ZABS, ensuring the safety and quality of the drinking water but some individual samplings were below the maximum allowed pH which could be attributed to anthropogenic pollution mentioned above.

The mean electrical conductivity (EC) values in this study ranged from 88.0 (downstream) to 383.4 µS/cm (upstream). This just like mean pH reflect differences in land use activities in and around the lake impacting the water body. This is more reflected when one looks at the minimum and maximum of the EC values in Tables 5.1 and 5.2. The upstream showed huge differences between the minimum, mean and maximum with highest mean and maximum values higher than downstream samples. Seasonal fluctuations reveal an increased in EC downstream, with the lowest recorded value occurred in July 2022 at 88.0 µS/cm, and the highest recorded in October 2021 at 97.6 µS/cm. Conversely, the upstream region displayed markedly higher EC levels, reaching 383.4 µS/cm. Elevated EC values often signify a greater concentration of dissolved ions and increased levels of total dissolved solids (Pant et al., 2019).

This elevated EC is primarily attributed to extensive anthropogenic activities such especially mining activities since the increased EC values are also associated with low pH values (Table 5.3). However, downstream, the increase in EC values could be attributed to as household waste, waste disposal, and the runoff of chemicals from agricultural and apiculture practices. This is supported by highest pH of 8.32 recorded in downstream. The study reported EC levels were below the prescribed limits established by both the WHO and ZABS.

In the study area, the mean total dissolved solids (TDS) values spanned from 43.4 in one downstream to 191.7 mg/L in upstream. This variation is also influenced by various land use activities in and around the lake, similarly to pH and EC. TDS has also strong links to EC and pH in Table 5.3. The lowest minimum TDS value was recorded in July 2022 upstream which also recorded the maximum of 739 mg/L. Both minimum and maximum were not extreme in differences for the downstream samples in TDS values. Excessive TDS, which can stem from natural or anthropogenic sources, contributes to water coloration, overall alkalinity, or acidity (depending on the chemistry of the water) and electrical conductivity. As noted by Pant et al. (2019), elevated TDS levels typically have adverse implications for both human health and ecological well-being. TDS can originate from various sources, including natural processes, sewage, urban runoff, and agricultural runoff or mining activities. Land use activities in and around Siavonga town could contribute to high TDS significantly and EC in the water. In the same way, high TDS upstream could be linked to mining activities. The TDS measurements at all sites fall well below the recommended safety thresholds established by WHO and ZABS ensuring adherence to safety standards to drinking water.

Temperature stands as a crucial factor in aquatic habitats, exerting control over both biological and physicochemical processes. Warmer water notably accelerates the decomposition of organic matter within the lake (Pant et al., 2019). The mean temperatures for different sampling periods ranged from 22.4 °C upstream to 25.9 °C downstream. The minimum temperature was recorded in July 2022 (21.7 °C) sampling while the highest was from October 2023 sampling (26 °C). Results show that season controls much of the temperature. October is hot and dry season and thus average temperatures are higher than July which is part of winter though Zambia especially like Kariba never receives severe winters.

Upstream of the lake (USL)

The individual pH, EC, TDS and temperature exhibited variations across the survey locations along the lake and feeder rivers, as illustrated in Table 5.3. Although, these mean parameter

variations were within WHO acceptable drinking water safety standards, exceptions were observed. Specifically, USL-2 exhibited a pH of 6.01 and an EC of 878.0 µS/cm, USL-3 displayed a pH of 3.71 and an EC of 1035 µS/cm, and USL-4 had a pH of 4.81 and an EC of 1484 µS/cm. Some aquatic organisms experience sluggish growth due to the pH range below pH 6.50 (Saturday et al., 2021). These values did not meet the recommended WHO range. Notably, the total dissolved solids (TDS) were considerably elevated compared to other sample sites with USL-2, USL-3 and USL-4 measuring 439.0, 518.0, and 739.0 mg/L, respectively.

The elevated values compared to others could be associated with mining companies operating in the Maamba area, whose waste material may contribute to acid mine drainage finding its way into the lake. The exposed soil material encourages the production of acid mine drainage, which finally merges with the stream because Maamba coal and overburden material were linked to pyrite. These lands' surface runoff transports sediments that had silted and obstructed the Kanzinze River. Maamba Collieries Limited had seen significant environmental impacts because of the removal of loose soil. The exposed surfaces were susceptive to erosion, and runoff from these regions, which brings sediments with it and ended up in the Kanzinze River, reducing the water quality in the stream (Besa, 2001). So far, it’s impact of the this in the lake is minimum because of dilution of water but still creates localised environmental issues.

Table 5.3 Individual physical-chemical parameters for upstream during July 2022 (cool-dry) period

Sampling Point	pH	EC µS/cm	TDS mg/L	Temp °C
USL-1	7,56	124,0	62,0	22,7
USL-2	6,01	878,0	439,0	21,7
USL-3	3,71	1035	518,0	22,0
USL-4	4,81	1484	739,0	22,1
USL-5	7,09	123,0	61,0	22,6
USL-6	7,67	213,0	109,0	22,6
USL-7	7,57	81,0	40,0	23,0
USL-8	7,38	96,0	48,0	22,6
USL-9	7,82	90,0	45,0	22,5
USL-10	7,61	88,0	44,0	22,0
USL-11	8,26	86,0	43,0	22,0
USL-12	7,77	88,0	44,0	22,0
USL-13	7,59	781,0	390,0	22,8
USL-14	7,70	437,0	219,0	22,7
USL-15	6,81	248,0	124,0	23,1
USL-16	7,22	283,0	142,0	22,8
Mean	7,04	383,4	191,7	22,4
SD.	1,17	415,1	207,1	0,42
Min.	3,71	81,0	40,0	21,7
Max.	8,26	1484	739,0	23,1
ZABS	8,00	1500	1000	
WHO	6,50-8,50	400,0	1000	

Note: ZABS = Drinking water standard WHO = Drinking water standard

Downstream of the lake (DSL)

Table 5.4 displays the findings related to the physical-chemical parameters observed in the individual downstream water samples. The results indicated significant seasonal variations in most parameters during the sampling period as already started when discussing the mean values. The highest recorded values were observed in October 2021, (pH 7.61 to 7.89), (EC 89.0 to 122.0 µS/cm), (Temp 25.8 to 26.0 °C), and (TDS 44.0 to 61.0 mg/L) which corresponds to the hot and dry season, followed by April 2023 (pH 7.55 to 8.32), (EC 91.0 to 97.0 µS/cm), (Temp 24.8 to 25.0 °C), and (TDS 45.0 to 49.0 mg/L) during the end of rainy season and the lowest values were recorded in July 2022 (pH 7.32 to 7.75), (EC 87.0 to 90.0 µS/cm), (Temp 23.9 to 24.0 °C), and (TDS 42.0 to 48.0 mg/L), representing the cool dry season.

These fluctuations can be attributed to various factors. During the cool dry season, reduced temperatures tend to slow down biological activity in aquatic environments, affecting algae and bacteria. This, in turn, leads to a decrease in the production of carbon dioxide (CO_2)

through processes like photosynthesis and respiration, ultimately resulting in a decrease in pH levels. Additionally, the reduced evaporation rates during this season mean that fewer dissolved solids accumulate in the water. Furthermore, changes in land use practices can play a role in these variations. Such changes may result in decreased runoff of pollutants into water bodies, thereby contributing to lower concentrations of total dissolved solids (TDS) and electrical conductivity (EC) in the water.

The water exhibited a predominantly slightly alkaline nature, with noteworthy instances of elevated pH levels observed in multiple samples, including DSL-1, DSL-4, DSL-7, DSL-33-35, and DSL-51-53. In the case of DSL-1, DSL-33-35, and DSL-51-53, the elevated pH values may be attributed to improper disposal of wastewater or cleaning chemicals, which can introduce alkaline substances into the environment, subsequently affecting the pH of nearby water bodies. This is particularly notable as these sampling points were in proximity to hospitality zones in Siavonga town.

In contrast, for DSL-4, located near agricultural areas, the increased pH values may be linked to several factors, including the use of specific types of fertilizers in agriculture, the decomposition of crop residues, and the application of pesticides and herbicides. In the case of DSL-7, situated in aquatic environments (fish farms), the elevated pH values may be associated with factors like the presence of nutrient-rich waters, the application of lime as a water treatment measure to enhance water quality and provide essential calcium ions for aquatic organisms, and the presence of bottom sediments containing alkaline minerals. The measured parameters remained well below the recommended safety thresholds for drinking water established by WHO and ZABS. This adherence to safety standards ensures the maintenance of water quality within safe and acceptable limits.

Table 5.4 Individual physical chemical parameters for downstream during the period of October 2021, July 2022, and April 2023

2021 October (Hot and Dry)					2022 July (Cool-dry)					2023 April (Rainy)				
Sampling Point	pH	EC µS/cm	TDS mg/L	Temp °C	Sampling Point	pH	EC µS/cm	TDS mg/L	Temp °C	Sampling Point	pH	EC µS/cm	TDS mg/L	Temp °C
DSL-1	7,85	122,0	61,0	26,0	DSL-28	7,75	88,0	43,0	24,0	DSL-33	8,20	93,0	46,0	25,0
DSL-2	7,67	100,0	50,0	25,9	DSL-29	7,52	87,0	42,0	23,9	DSL-34	8,25	93,0	47,0	24,9
DSL-3	7,65	100,0	50,0	25,8	DSL-30	7,50	87,0	42,0	24,0	DSL-35	8,25	93,0	47,0	25,0
DSL-4	7,65	113,0	57,0	25,8	DSL-31	7,51	90,0	48,0	24,0	DSL-36	8,08	94,0	47,0	24,9
DSL-5	7,71	97,0	48,0	25,9	DSL-32	7,32	88,0	42,0	23,9	DSL-37	8,01	93,0	47,0	24,9
DSL-6	7,77	95,0	47,0	25,9						DSL-38	8,06	94,0	47,0	24,9
DSL-7	7,81	114,0	57,0	25,9						DSL-39	8,05	93,0	47,0	25,0
DSL-8	7,72	95,0	48,0	25,9						DSL-40	7,92	94,0	47,0	24,8
DSL-9	7,76	98,0	49,0	25,9						DSL-41	7,82	94,0	47,0	24,9
DSL-10	7,77	100,0	50,0	25,9						DSL-42	7,86	94,0	47,0	25,0
DSL-11	7,61	101,0	51,0	25,9						DSL-43	7,86	94,0	47,0	25,0
DSL-12	7,78	99,0	50,0	25,9						DSL-44	7,79	95,0	47,0	24,9
DSL-13	7,89	97,0	49,0	25,8						DSL-45	7,71	93,0	46,0	24,9
DSL-14	7,88	100,0	50,0	25,8						DSL-46	7,55	94,0	47,0	24,9
DSL-15	7,84	96,0	48,0	25,9						DSL-47	7,56	94,0	47,0	24,9
DSL-16	7,79	95,0	47,0	26,0						DSL-48	7,73	94,0	47,0	24,9
DSL-17	7,73	104,0	52,0	25,8						DSL-49	7,83	91,0	45,0	24,9
DSL-18	7,84	99,0	50,0	25,9						DSL-50	7,99	91,0	46,0	24,9
DSL-19	7,74	89,0	48,0	25,9						DSL-51	8,29	94,0	47,0	24,8
DSL-20	7,79	89,0	45,0	25,9						DSL-52	8,27	96,0	48,0	24,8
DSL-21	7,84	89,0	44,0	25,8						DSL-53	8,32	97,0	49,0	24,8
DSL-22	7,76	89,0	45,0	25,8										
DSL-23	7,85	90,0	45,0	25,9										
DSL-24	7,72	91,0	45,0	25,9										
DSL-25	7,81	90,0	45,0	25,9										
DSL-26	7,75	91,0	45,0	25,9										
DSL-27	7,75	93,0	48,0	25,9										
Mean	7,77	97,6	49,0	25,9		7,52	88,0	43,4	23,9		7,97	93,7	46,9	24,9
SD	0,071	7,99	3,97	0,043		0,137	1,10	2,33	0,055		0,231	1,31	0,750	0,064
Min	7,61	89,0	44,0	25,8		7,32	87,0	42,0	23,9		7,55	91,0	45,0	24,8
Max	7,89	122,0	61,0	26,0		7,75	90,0	48,0	24,0		8,32	97,0	49,0	25,0
ZABS	8,00	1500	1000											
WHO	6,50-8,50	400	1000											

5.3. Anions concentrations in the water of Lake Kariba

5.3.1. Mean and individual concentration of major anions in the water

The mean and individual concentrations of the anions detected in the lake from upstream and downstream of the lake are shown in Tables 5.5 and 5.6. The highest mean F^- concentration was detected in upstream samples at 0.278 mg/L with lowest as non-detected. The maximum amount detected was from upstream samples at 0.80 mg/L followed by one downstream sample at 0.179 mg/L. These findings suggest that certain areas of the lake, particularly upstream, may be more vulnerable to fluoride contamination, which could have implications for water quality and ecosystem health. Elevated fluoride levels could pose a risk to both aquatic life and human populations that depend on the lake for drinking water if they exceed safe limits.

Chlorine (Cl), an element highly soluble and primarily originating from non-lithological sources (Karakus 2018), exhibited varying average chloride levels downstream. The mean chloride ion concentration ranged from 9.54 mg/l in the upstream followed by 1.58, 1.25 and 1.51 mg/L in downstream samples. The highest concentration was thus reported in downstream samples. The maximum concentration reported was in upstream sample at 60.2 mg/L. The elevated chloride levels upstream could impact water quality, potentially increasing salinity, which may affect aquatic life, drinking water safety, and the overall health of the lake's ecosystem. The lower concentrations downstream might indicate dilution or reduced exposure to chloride sources.

The mean NO_3^- concentration ranged from 1.25 mg/L in the upstream samples to non-detected. NO_3^- concentrations were mostly non detected in many samples however few samples had high concentrations. The maximum concentration was reported upstream sample at 17.7 mg/L followed by downstream samples at 0.149, 0.558 and 0.288 mg/L for the October 2021, July 2022, and April 2023 sampling, respectively. The significant variation in nitrate concentrations, with a peak of 17.7 mg/L observed upstream, indicates a possible localized source of pollution, potentially from agricultural runoff, industrial discharge, or wastewater effluent. High nitrate levels can lead to eutrophication and decrease biodiversity. The detected concentration of 17.7 mg/L surpasses the maximum allowable limit for nitrates in drinking water, which is 10 mg/L, posing potential health risks.

A similar pattern emerged for sulphate (SO_4^{2-}), with average concentrations of 2.67 mg/L, 2.65 mg/L, and 2.15 mg/L in the downstream samples, while upstream recorded a notably higher level of 94.7 mg/L. The Sulphates were detected in most samples just like the chloride and fluoride ions. The highest sulphate concentration was recorded in the upstream of 561.5 mg/l which had also highest mean value. This was followed by 3.955, 3.37 and 2.20 mg/L in Oct 2021, April 2023, and July 2022 sampling periods in downstream respectively. High sulphate concentrations can lead to the development of acidic conditions, potentially harming aquatic life, diminishing water quality for human use, and disrupting the lake's ecological balance. The significant difference between upstream and downstream concentrations suggests that pollution sources, especially from mining activities, may be concentrated in upstream areas, resulting in localized contamination.

Phosphate (PO_4^{3-}) serves as a critically essential nutrient compound. Phosphate compounds primarily originate from natural reservoirs like soil erosion, animal waste, and plants weathering in aquatic environments (Fachrul et al.,2021). Concentration levels were largely minimal, with many areas in the study showing undetectable levels. Downstream, an average of 0.009 mg/L was recorded in 2021, while no detection was reported in 2022 and 2023. Conversely, upstream exhibited a mean concentration of 0.158 mg/L which was the highest. The highest phosphate concentration of 2.30 mg/L was reported in the upstream sample. Elevated phosphate levels can cause nutrient enrichment, which may trigger algal blooms that disrupt the aquatic ecosystem, lower oxygen levels, and degrade water quality. The mean and maximum anions detected despite their variations, all areas, based on the obtained values, remain within the drinking water standards outlined by WHO and ZABS.

Upstream of the lake (USL)

The results for the individual anions found in the water at different study points are shown in Table 5.5. Within this dataset, the concentration of fluoride ions (F^-) exhibited a range from 0.050 to 0.800 mg/L. Although the concentrations remained within acceptable water quality standards, there were areas of concern within the ranges of USL-2 to USL-4, USL-6 and USL-13 to USL-16. These specific regions displayed elevated values of 0.450, 0.800, 0.460, 0.370, 0.722, 0.393, 0.271, and 0.243 mg/L respectively. This indicates possible localized sources of contamination, such as industrial activities, natural mineral deposits, or improper waste management. Prolonged exposure to elevated fluoride levels can still pose health risks. Although acute toxicity is unlikely at these concentrations, chronic exposure could lead to

dental fluorosis, particularly in vulnerable populations like children. Elevated concentrations can also have ecological effects, potentially impacting aquatic life and soil health. Even within regulatory limits, the cumulative environmental impact might result in subtle yet significant changes in local ecosystems.

Similar trend emerged with chloride ions, where elevated concentrations of 9.36, 8.52, 9.83, 2.16, 60.2, 20.2, 14.5, and 16.8 mg/L were observed. The fluctuations in chloride levels may be driven by seasonal factors like precipitation, evaporation, and runoff. Additionally, human activities such as agricultural runoff and wastewater discharge can also temporarily raise chloride levels, but these increases are typically short-lived and within the lake's ability to handle without causing long-term damage.

The sulphate (SO_4^{2-}) individual concentrations ranged from 0.032 to 561.5 mg/L. With the exception of three sampling sites (USL-2 to USL-4), the sulphate levels fell within acceptable limits. However, at these specific sites, the SO_4^{2-} values were significantly elevated, measuring 355.2, 503.4, and 561.5 mg/L, respectively. It's worth noting that for USL-2, the sulphate concentration was below the limit established by ZABS, although it exceeded the WHO standard. Elevated levels of sulphates in the water source may result in an unpleasant taste (Kothari et al., 2021) and mostly upstream samples with high values could be linked to anthropogenic activities especially mining.

Among all the anions, phosphate exhibited the lowest concentrations, with values ranging from non-detected to 2.30 mg/L. A significant rise was noted in samples USL-13 (Siavonga Market) and USL-14 (Fisheries), measuring concentrations of 2.30 and 0.226 mg/L respectively. It's important to highlight that these readings exceeded the allowable limit established by the WHO for drinking water.

The concentrations of nitrate (NO_3^-) were found to be within the acceptable limits set by both the WHO and ZABS. However, it's worth noting that in one study area USL-13 (Siavonga Market), a higher concentration of 17.7 mg/L was recorded, surpassing the ZABS limit. Nitrate levels exceeding 5.0 mg/L typically indicate the presence of anthropogenic contamination originating from human activities and animal waste (Fachrul et al.,2021).

Table 5.5 Major anions observed in upstream water samples during July 2022 period

Sampling Point	F^- mg/L	Cl^- mg/L	NO_3^- mg/L	SO_4^{2-} mg/L	PO_4^{3-} mg/L
USL-1	0,170	1,63	nd	0,940	nd
USL-2	0,450	9,36	0,940	355,2	nd
USL-3	0,800	8,52	0,750	503,4	nd
USL-4	0,460	9,83	nd	561,5	nd
USL-5	0,195	1,19	nd	2,79	nd
USL-6	0,370	2,16	nd	39,3	nd
USL-7	0,050	1,21	nd	2,22	nd
USL-8	0,077	1,60	nd	0,032	nd
USL-9	0,058	1,29	nd	2,02	nd
USL-10	0,063	1,48	nd	2,27	nd
USL-11	0,063	1,28	nd	2,10	nd
USL-12	0,058	1,32	nd	2,05	nd
USL-13	0,722	60,2	17,7	27,5	2,30
USL-14	0,393	20,2	0,395	6,45	0,226
USL-15	0,271	14,5	0,113	5,25	nd
USL-16	0,243	16,8	0,173	2,72	nd
Mean	0,278	9,54	1,25	94,7	0,158
SD	0,231	14,5	4,25	186,0	0,555
Min	0,050	1,19	0,113	0,032	0,226
Max	0,800	60,2	17,7	561,5	2,30
ZABS	1,50	250,0	10,0	400,0	
WHO	1,50	300,0	50,0	250,0	0,020

nd=means non detected

The highlighted – Concentrations Elevated

Downstream of the lake (DSL)

The findings pertaining to the individual anions present at various study points are displayed in Table 5.6. The fluoride concentration displayed a wide range, with higher levels ranging from 0.066 to 0.179 mg/L in 2023, followed by a narrower range of 0.061 to 0.068 mg/L in 2021, and the lowest range of 0.056 to 0.057 mg/L in 2022. The peak concentration of 0.179 mg/L was recorded in sample DSL-34 (Manchinchi Bay Lodge, Restaurant), which may be

linked to human activities in the area such as the use of specific cleaning products or improper waste disposal can introduce fluoride into the local water system.

Chloride ion concentrations exhibited a wide range, with elevated levels ranging from 1.43 to 2.21 mg/L in 2023, followed by a slightly lower range of 1.34 to 2.14 mg/L in 2021, and the lowest range of 1.24 to 1.28 mg/L in 2022. These heightened concentrations were notably observed in samples DSL-8 (2.07 mg/L), DSL-9 (2.07 mg/L), DSL-24 (2.14 mg/L), and DSL-48 (2.21 mg/L), indicating potential pollution from wastewater discharges that contain chlorinated disinfectants, cleaning agents, and salts.

The sulphate ion (SO_4^{2-}) displayed a pattern of high concentrations, ranging from 2.26 to 3.96 mg/L in 2021, followed by 2.51 to 3.37 mg/L in 2023, and the lowest concentrations ranging from 2.13 to 2.20 mg/L in 2022. This trend was consistently observed in samples DSL-8 (3.96 mg/L), DSL-9 (3.93 mg/L), DSL-24 (3.24 mg/L), and DSL-48 (3.37 mg/L), where higher values were recorded. In contrast, phosphate concentrations were notably low, with a measured level found only in sample DSL-1 (Manchinchi Bay Lodge, Laundry), registering a concentration of 0.181 mg/L.

Nitrate (NO_3^-) levels displayed fluctuation over the years. In 2022, they peaked between 0.202 and 0.558 mg/L, followed by a narrower range of 0.057 to 0.288 mg/L in 2023 and the lowest range was observed in 2021, with levels ranging from 0.000 to 0.149 mg/L. The elevated concentrations were consistently recorded in samples DSL-28 to DSL-32, with values of 0.321 mg/L, 0.558 mg/L, 0.398 mg/L, 0.202 mg/L, and 0.253 mg/L respectively. Notably, all these sampling locations were associated with fish farming activities. These elevated nitrate levels can be attributed to various factors, including fish excretion, fish farming practices involving commercial feeds, aquaculture water management, and the influence of reduced rainfall and runoff during the sampling periods.

Table 5.6 Major anions observed in downstream water samples during the period of October 2021, July 2022, and April 2023

2021 October						2022 July						2023 April					
Sampling Point	F^- mg/L	Cl^- mg/L	NO_3^- mg/L	SO_4^{2-} mg/L	PO_4^{3-} mg/L	Sampling Point	F^- mg/L	Cl^- mg/L	NO_3^- mg/L	SO_4^{2-} mg/L	PO_4^{3-} mg/L	Sampling Point	F^- mg/L	Cl^- mg/L	NO_3^- mg/L	SO_4^{2-} mg/L	PO_4^{3-} mg/L
DSL-1	0,066	1,83	nd	2,47	0,181	DSL-28	0,057	1,28	0,321	2,16	nd	DSL-33	0,071	1,49	0,235	2,61	nd
DSL-2	0,065	1,65	nd	2,71	nd	DSL-29	0,056	1,24	0,558	2,20	nd	DSL-34	0,179	1,49	0,109	2,69	nd
DSL-3	0,064	1,53	nd	2,55	nd	DSL-30	0,056	1,24	0,398	2,15	nd	DSL-35	0,066	1,45	0,075	2,51	nd
DSL-4	0,066	1,48	nd	2,41	nd	DSL-31	0,057	1,25	0,202	2,13	nd	DSL-36	0,068	1,45	0,122	2,67	nd
DSL-5	0,068	1,87	0,149	2,88	nd	DSL-32	0,056	1,24	0,253	2,14	nd	DSL-37	0,069	1,44	0,104	2,64	nd
DSL-6	0,062	1,62	0,107	2,70	nd							DSL-38	0,070	1,46	0,098	2,63	nd
DSL-7	0,062	1,57	nd	2,72	nd							DSL-39	0,079	1,45	0,089	2,76	nd
DSL-8	0,066	2,07	0,124	3,96	nd							DSL-40	0,073	1,46	0,074	2,56	nd
DSL-9	0,065	2,07	0,118	3,93	nd							DSL-41	0,069	1,46	0,063	2,62	nd
DSL-10	0,063	1,76	0,138	2,83	nd							DSL-42	0,068	1,44	0,090	2,59	nd
DSL-11	0,063	1,38	nd	2,26	nd							DSL-43	0,067	1,43	0,161	2,56	nd
DSL-12	0,061	1,38	nd	2,32	nd							DSL-44	0,068	1,44	0,093	2,59	nd
DSL-13	0,061	1,48	nd	2,50	nd							DSL-45	0,068	1,45	0,057	2,64	nd
DSL-14	0,062	1,36	nd	2,31	nd							DSL-46	0,067	1,43	0,106	2,56	nd
DSL-15	0,061	1,37	nd	2,31	nd							DSL-47	0,068	1,46	0,095	2,63	nd
DSL-16	0,062	1,46	nd	2,52	nd							DSL-48	0,078	2,21	0,288	3,37	nd
DSL-17	0,061	1,34	nd	2,31	nd							DSL-49	0,070	1,53	0,101	2,78	nd
DSL-18	0,061	1,52	nd	2,58	nd							DSL-50	0,068	1,44	0,079	2,57	nd
DSL-19	0,061	1,53	nd	2,77	nd							DSL-51	0,070	1,53	0,069	2,62	nd
DSL-20	0,061	1,34	nd	2,31	nd							DSL-52	0,072	1,64	0,076	2,71	nd
DSL-21	0,061	1,40	nd	2,38	nd							DSL-53	0,070	1,55	0,167	2,70	nd
DSL-22	0,062	1,35	nd	2,32	nd												
DSL-23	0,061	1,36	nd	2,32	nd												
DSL-24	0,063	2,14	nd	3,24	nd												
DSL-25	0,062	1,54	nd	2,56	nd												
DSL-26	0,063	1,70	nd	2,86	nd												
DSL-27	0,065	1,56	nd	2,42	nd												
Mean	**0,063**	**1,58**	**0,024**	**2,65**	**0,009**		**0,056**	**1,25**	**0,346**	**2,15**	**nd**		**0,075**	**1,51**	**0,112**	**2,67**	**nd**
SD	0,002	0,233	0,050	0,433	0,036		0,001	0,015	0,125	0,025	nd		0,023	0,165	0,056	0,170	nd
Min	0,061	1,34	0,107	2,257	0,000		0,056	1,24	0,202	2,13	nd		0,066	1,43	0,057	2,51	nd
Max	0,068	2,14	0,149	3,955	0,181		0,057	1,28	0,558	2,20	nd		0,179	2,21	0,288	3,37	nd
ZABS	1,50	250	10,0	400													
WHO	1,50	300	50,0	250													

nd=means non detected

5.4. Major and Trace metals in the water of Lake Kariba

5.4.1. Mean and individual concentration of major elements in the water

The mean and individual concentration of major elements in the water are shown in Tables 5.7 and 5.8. The mean calcium (Ca) concentration in downstream water exhibited fluctuations over the observed years. It ranged from 10.4 mg/L in 2023, representing the lowest value, to 14.0 mg/L in 2022, marking the highest concentration during this period. In 2021, there was an intermediate value of 10.8 mg/L. Furthermore, the average calcium concentration in upstream water was measured at 41.4 mg/L. The drop in calcium levels to 10.4 mg/L in 2023 may be attributed to the dilution effect caused by increased rainfall. Conversely, the elevated Ca concentration observed in 2022, reaching 14.0 mg/L, likely resulted from geological contributions.

The mean magnesium (Mg) concentration exhibited variations, ranging from 3.34 to 3.91 mg/L. The highest value, 3.91 mg/L, was observed in the 2022 period, while the mean concentration remained consistent at 3.34 mg/L during both the 2021 and 2023 periods. Additionally, the upstream water displayed a higher magnesium level at 13.5 mg/L. This increase in concentration can be attributed to heightened evaporation processes.

The potassium (K) concentration exhibited a range from 1.15 to 4.39 mg/L, with the highest values observed in the upstream and downstream during the 2022 period, at 4.39 mg/L and 1.47 mg/L, respectively. In 2021, the downstream recorded a potassium concentration of 1.31 mg/L, while in 2023, it decreased to 1.15 mg/L. The elevated potassium levels, particularly in 2022, could be attributed to factors such as reduced dilution effect, urbanization, and industrial discharges.

Sodium (Na) exhibited significant variations across different sampling periods. In the downstream area, the recorded concentration values were 3.88 mg/L in 2021, 6.23 mg/L in 2022, and 2.74 mg/L in 2023, while upstream, a mean value of 14.6 mg/L was observed. The higher sodium values, especially upstream, can be attributed to factors such as agricultural runoff and reduced water flow. It's noteworthy that the overall chemistry of the lake water indicated that, despite seasonal fluctuations in major ion concentrations, the levels remained within acceptable limits set by WHO and ZABS.

The silicon (Si) concentration displayed a range of values across different years, measuring at 4.59 mg/L in 2021, 4.86 mg/L in 2022, and 4.36 mg/L in 2023. Upstream, the average silicon concentration was notably higher at 8.00 mg/L. Elevated silicon levels in rivers can be attributed to various factors, including geological characteristics and soil composition, biological activity, human activities, and changes in land use.

Iron (Fe) and aluminium (Al) were exclusively detected in upstream water, with mean concentrations of 8.34 mg/L and 1.01 mg/L, respectively. These occurrences can be attributed to a combination of various natural processes and human-related factors. Both elements can enter rivers through a combination of natural geological processes and human activities.

Upstream of the lake (USL)

The results concerning major elements present in the water are summarized in Table 5.7. The predominant elements were listed in the following order of concentration: Ca, with levels ranging from 11.7 to 134.7 mg/L, followed by Na, with concentrations ranging from 3.93 to 49.1 mg/L, Mg, with values ranging from 2.93 to 45.6 mg/L, Fe varying from 0.120 to 110.8 mg/L, Si ranging from 2.46 to 14.8 mg/L, K with levels spanning from 1.19 to 14.0 mg/L, and Al with concentrations ranging from 0.093 to 6.18 mg/L. The concentrations of Ca and Mg recorded at the study sites generally adhered to permissible limits, except for three locations (USL-2 to USL-4) where Ca surpassed the allowable threshold for WHO, measuring 115.6 mg/L, 130.5 mg/L and 134.7 mg/L. Elevated concentrations were also observed in the following areas: USL-2 to USL-4, USL-11, USL-13, USL-14 and USL-16 although they still remained within permissible limits established by WHO and ZABS.

Iron (Fe) concentrations, particularly in locations USL-1 to USL-13, exceeded the permissible limits set by both WHO and ZABS, which is 0.3 mg/L. The recorded values ranged from 0.415 mg/L to 110.8 mg/L, with the highest levels observed at USL-4 (110.8 mg/L), USL-3 (9.22 mg/L), and USL-8 (3.01 mg/L). It's worth noting that elevated levels of Fe can promote the growth of certain bacteria that have the potential to obstruct pipes and wells (Vetrimurugan et al. in 2017).

Furthermore, aluminium (Al) concentrations in the USL-2 to USL-4 and USL-9 to USL-13 areas also exceeded the established limits of 0.2 mg/L by both WHO and ZABS. The recorded values ranged from 0.252 mg/L to 6.18 mg/L, with the highest concentrations observed at USL-4 (6.18 mg/L) and USL-3 (4.17 mg/L). It's important to note that oral ingestion of aluminium

can have adverse effects on the kidneys and may potentially lead to bone and brain diseases, particularly at elevated levels (Maju-Oyovwikowhe and Emofurieta in 2021).

Table 5.7 Major elements present in upstream water samples during July 2022 period

Sampling Point	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	Si mg/L	Fe mg/L	Al mg/L
USL-1	12,6	1,78	3,30	10,4	8,47	1,90	0,503
USL-2	115,6	7,31	34,9	20,3	7,02	1,44	0,461
USL-3	130,5	9,45	43,2	15,0	12,5	9,22	4,17
USL-4	134,7	14,0	45,6	20,2	13,1	110,8	6,18
USL-5	13,7	1,93	6,33	11,2	8,12	1,75	0,809
USL-6	25,6	2,74	10,0	13,9	8,29	1,07	0,180
USL-7	17,2	1,39	3,71	5,29	5,18	0,80	0,608
USL-8	11,7	2,94	2,93	8,19	6,96	3,01	0,440
USL-9	13,9	1,35	4,39	4,27	2,46	0,49	0,384
USL-10	13,7	1,19	3,72	3,93	3,67	0,41	0,400
USL-11	33,2	1,27	6,50	5,03	3,95	0,57	0,252
USL-12	13,9	1,56	4,16	6,91	3,49	0,94	0,359
USL-13	52,6	13,7	22,2	49,1	14,8	0,49	0,481
USL-14	38,9	4,82	10,3	26,1	10,8	0,22	0,473
USL-15	13,9	1,56	7,02	15,9	10,5	0,13	0,292
USL-16	21,0	3,13	7,20	18,4	8,64	0,12	0,181
Mean	41,4	4,39	13,5	14,6	8,00	8,34	1,01
SD	42,7	4,24	14,2	11,0	3,56	26,6	1,62
Min	11,7	1,19	2,93	3,93	2,46	0,12	0,180
Max	134,7	14,0	45,6	49,1	14,8	110,8	6,18
ZABS	200,0	-	150,0	200,0		0,30	0,20
WHO	100,0	20,0	50,0	200,0		0,30	0,20

Downstream of the lake (DSL)

The presentation of results for major elements can be found in Table 5.8. Calcium (Ca) emerged as the dominant element, with silicon (Si), sodium (Na), magnesium (Mg), and potassium (K) following in terms of concentration. The observed concentrations fell within the following ranges: Ca (9.96 to 15.2 mg/L), Si (4.22 to 4.96 mg/L), Na (2.62 to 6.91 mg/L), Mg (3.19 to 4.26 mg/L), and K (1.09 to 1.66 mg/L).

The investigation also revealed a notable concentration of Ca compared to Mg levels. This observation could be linked to the specific chemical attributes of the soil and the geological source of the water. The levels of K showed a slight decrease compared to Na. Potassium tends

to bind with clay minerals and contributes to the creation of secondary minerals, which might account for the low K concentrations. Importantly, the metal concentrations detected at the study sites remained below the threshold deemed acceptable by WHO and ZABS.

Table 5.8 Major elements present in upstream water samples during the period of October 2021, July 2022, and April 2023

2021 October						2022 July						2023 April					
Sampling Point	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	Si mg/L	Sampling Point	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	Si mg/L	Sampling Point	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	Si mg/L
DSL-1	11,4	1,66	3,43	4,32	4,75	DSL-28	15,2	1,54	4,25	6,57	4,86	DSL-33	9,96	1,12	3,19	2,69	4,22
DSL-2	10,8	1,30	3,32	3,89	4,59	DSL-29	13,5	1,36	3,52	5,31	4,86	DSL-34	10,6	1,18	3,40	2,81	4,47
DSL-3	11,1	1,33	3,38	3,93	4,68	DSL-30	13,4	1,44	3,71	6,91	4,76	DSL-35	10,4	1,16	3,34	2,76	4,38
DSL-4	11,3	1,38	3,51	4,26	4,65	DSL-31	13,8	1,45	3,86	5,95	4,86	DSL-36	10,5	1,14	3,35	2,76	4,42
DSL-5	10,8	1,31	3,35	3,93	4,59	DSL-32	14,1	1,56	4,22	6,41	4,96	DSL-37	10,6	1,16	3,39	2,79	4,45
DSL-6	11,0	1,33	3,38	3,93	4,63							DSL-38	10,4	1,13	3,32	2,76	4,36
DSL-7	10,9	1,41	3,42	5,15	4,60							DSL-39	10,5	1,13	3,31	2,71	4,42
DSL-8	10,8	1,29	3,30	3,77	4,62							DSL-40	10,4	1,15	3,33	2,75	4,37
DSL-9	10,6	1,26	3,30	3,75	4,57							DSL-41	10,4	1,15	3,36	2,74	4,37
DSL-10	10,8	1,26	3,27	3,78	4,59							DSL-42	10,6	1,15	3,42	2,76	4,45
DSL-11	10,9	1,43	3,42	4,08	4,61							DSL-43	10,4	1,14	3,37	2,74	4,37
DSL-12	10,7	1,26	3,29	3,73	4,59							DSL-44	10,4	1,14	3,33	2,73	4,35
DSL-13	10,7	1,27	3,31	3,81	4,55							DSL-45	10,4	1,15	3,33	2,70	4,37
DSL-14	10,6	1,23	3,27	3,62	4,55							DSL-46	10,2	1,16	3,29	2,65	4,27
DSL-15	10,7	1,24	3,28	3,66	4,57							DSL-47	10,4	1,17	3,38	2,74	4,38
DSL-16	10,9	1,31	3,32	3,73	4,62							DSL-48	10,6	1,18	3,41	2,75	4,48
DSL-17	10,6	1,23	3,29	3,72	4,51							DSL-49	10,2	1,26	3,32	2,78	4,28
DSL-18	10,5	1,24	3,25	3,64	4,56							DSL-50	10,1	1,09	3,24	2,62	4,22
DSL-19	10,6	1,24	3,29	3,74	4,49							DSL-51	10,1	1,11	3,33	2,75	4,29
DSL-20	10,7	1,26	3,33	3,78	4,55							DSL-52	10,4	1,15	3,43	2,91	4,38
DSL-21	10,9	1,27	3,30	3,65	4,65							DSL-53	10,0	1,18	3,26	2,71	4,33
DSL-22	10,6	1,27	3,27	3,67	4,53												
DSL-23	11,0	1,28	3,37	3,78	4,71												
DSL-24	10,9	1,27	3,32	3,74	4,65												
DSL-25	11,0	1,37	3,56	4,23	4,63												
DSL-26	10,7	1,29	3,31	3,78	4,53												
DSL-27	10,7	1,35	3,30	3,77	4,43												
Mean	10,8	1,31	3,34	3,88	4,59		14,0	1,47	3,91	6,23	4,86		10,4	1,15	3,34	2,74	4,36
SD	0,221	0,087	0,074	0,310	0,066		0,637	0,072	0,288	0,555	0,062		0,195	0,033	0,060	0,058	0,074
Min	10,5	1,23	3,25	3,62	4,43		13,4	1,36	3,52	5,31	4,76		9,96	1,09	3,19	2,62	4,22
Max	11,4	1,66	3,56	5,15	4,75		15,2	1,56	4,25	6,91	4,96		10,6	1,26	3,43	2,91	4,48
ZABS	200,0	-	150,0	200,0													
WHO	100,0	20,0	50,0	200,0													

5.4.2. Mean and individual concentration of trace elements in the water

The mean and individual concentration of trace metals in both upstream and downstream water is shown in Tables 5.9 and 5.10. In the downstream water, arsenic was the sole trace metal detected, with the highest mean concentration of 0.428 µg/L recorded in 2023, followed by 0.396 µg/L in 2021, and the lowest at 0.165 µg/L in 2022. It's important to note that changes in water levels, flow rates, and residence times can impact the distribution and transport of arsenic. Seasonal variations in these hydrological factors can exert influence on arsenic concentrations.

In the case of upstream water, concentrations of trace metals, including manganese (Mn), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), titanium (Ti), and arsenic (As) were within the same order of magnitude. Among these Mn showcased the highest content, with an average of 485.0 µg/L in upstream water, surpassing the permissible limit set by the WHO and ZABS. In contrast, Zn, Cu, Cr, Ni, Ti, and As displayed the lowest contents, with average values of 119.2, 55.5, 48.0, 43.5, 28.7 and 0.332 µg/L, respectively. Generally, the levels of toxic elements in both upstream and downstream water remained low and within the acceptable limits.

Upstream of the lake (USL)

The results for trace metals in water are summarised in Table 5.9. The concentration ranges for these metals were as follows: Mn ranged from 0.176 to 3955 µg/L, Zn from 1.72 to 521.0 µg/L, Cu from 183.0 to 255.0 µg/L, Cr from 2.47 to 309.0 µg/L, Ni from 133.5 to 231.5 µg/L, Ti from 71.50 to 187.0 µg/L, and arsenic (As) from 0.149 to 1.12 µg/L. The elevated average Mn level stemmed from substantial concentrations in USL-3 and USL-4, reaching values of 3550 µg/L and 3955 µg/L respectively, exceeding the WHO and ZABS standards. Anthropogenic activities, such as mining, industrial discharges, and agricultural runoff, can introduce manganese into rivers. Moreover, the elevated levels of Zn, Cu, Cr, Ni, and Ti were attributed to the increased concentrations detected in USL-1 to USL-4, where both Ni and Cr exceeded the drinking water standards. Chromium is associated with allergic dermatitis. The adverse effects of Ni on humans are thought to be minimal, but it could be harmful to certain plant and animal (Vetrimurugan et al.,2017).

Table 5.9 Trace metals in upstream water samples during July 2022 period

Sampling Point	Zn µg/L	Mn µg/L	Cu µg/L	Ni µg/L	Ti µg/L	Cr µg/L	As µg/L
USL-1	268,5	65,0	255,0	144,0	109,5	101,0	0,250
USL-2	227,5	154,0	183,0	133,5	71,50	106,5	0,346
USL-3	436,0	3550	223,5	186,5	91,00	239,0	0,596
USL-4	521,0	3955	226,5	231,5	187,0	309,0	0,489
USL-5	120,1	1,26	nd	nd	nd	nd	0,230
USL-6	45,8	6,66	nd	nd	nd	nd	0,219
USL-7	58,8	1,61	nd	nd	nd	nd	0,149
USL-8	58,9	26,9	nd	nd	nd	nd	0,165
USL-9	47,0	nd	nd	nd	nd	nd	0,170
USL-10	35,4	nd	nd	nd	nd	nd	0,175
USL-11	52,5	nd	nd	nd	nd	nd	0,164
USL-12	28,6	nd	nd	nd	nd	nd	0,161
USL-13	1,76	2,64	nd	nd	nd	4,36	1,12
USL-14	nd	0,176	nd	nd	nd	2,67	0,491
USL-15	1,72	1,12	nd	nd	nd	2,87	0,293
USL-16	4,27	0,824	nd	nd	nd	2,47	0,296
Mean	119,2	485,3	55,5	43,5	28,7	48,0	0,332
SD	155,8	1238	97,0	77,7	54,3	92,6	0,243
Min	1,72	0,176	183,0	133,5	71.50	2,47	0,149
Max	521,0	3955	255,0	231,5	187,0	309,0	1,12
ZABS (mg/L)	3,00	0,100	1,00	-		0,050	0,010
WHO (mg/L)	3,00	0,400	2,00	0,070		0,050	0,010

Cd, Pb and Hg – not detected

Downstream of the lake (DSL)

The findings regarding arsenic levels are detailed in Table 5.10 showcasing concentrations ranging from 0.349 to 0.446 µg/L in 2021, 0.153 to 0.185 µg/L in 2022, and 0.399 to 0.471 µg/L in 2023. It is worth noting that the concentrations of this metal detected at the study sites consistently fell below the established thresholds considered safe according to the drinking water standards set by both the WHO and ZABS.

Table 5.10 Trace metal in downstream water samples during the period of October 2021, July 2022, and April 2023

2021 October		2022 July		2023 April	
Sampling Point	As µg/L	Sampling Point	As µg/L	Sampling Point	As µg/L
DSL-1	0,446	DSL-28	0,185	DSL-33	0,442
DSL-2	0,426	DSL-29	0,164	DSL-34	0,445
DSL-3	0,443	DSL-30	0,165	DSL-35	0,455
DSL-4	0,443	DSL-31	0,153	DSL-36	0,441
DSL-5	0,417	DSL-32	0,159	DSL-37	0,444
DSL-6	0,422			DSL-38	0,430
DSL-7	0,420			DSL-39	0,423
DSL-8	0,403			DSL-40	0,420
DSL-9	0,437			DSL-41	0,471
DSL-10	0,411			DSL-42	0,408
DSL-11	0,379			DSL-43	0,401
DSL-12	0,378			DSL-44	0,399
DSL-13	0,372			DSL-45	0,425
DSL-14	0,387			DSL-46	0,426
DSL-15	0,399			DSL-47	0,423
DSL-16	0,365			DSL-48	0,404
DSL-17	0,379			DSL-49	0,416
DSL-18	0,394			DSL-50	0,448
DSL-19	0,379			DSL-51	0,400
DSL-20	0,380			DSL-52	0,434
DSL-21	0,381			DSL-53	0,436
DSL-22	0,372				
DSL-23	0,392				
DSL-24	0,368				
DSL-25	0,378				
DSL-26	0,364				
DSL-27	0,349				
Mean	0,396		0,165		0,428
SD	0,027		0,011		0,019
Min	0,349		0,153		0,399
Max	0,446		0,185		0,471
ZABS	0,010				
WHO	0,010				

Zn,Cr,Cu,Mn,Cd,Pb and Hg – not detected

5.5. Correlation coefficient

5.5.1. Correlation coefficient between variables in upstream

Table 5.11 displays the Pearson correlation coefficients (Kangabam et al., 2017) for various water quality parameters measured in the upstream section in 2022. The parameters include pH, EC, TDS, temperature, and concentrations of various ions and metals such as fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), silicon (Si), iron (Fe), aluminium (Al), arsenic (As), zinc (Zn), manganese (Mn), copper (Cu), nickel (Ni), titanium (Ti), and chromium (Cr).

Negative Correlations

The table revealed negative correlations between pH and several ions, including EC (-0.817), TDS (-0.817), F^- (-0.672), SO_4^{2-} (-0.928), Ca (-0.864), K (-0.632), Mg (-0.879), Si (-0.548), Fe (-0.549), Al (-0.841), Zn (-0.846), Mn (-0.893), Cu (-0.716), Ni (-0.822), Ti (-0.722), and Cr (-0.884). These negative correlations indicate that lower pH levels (more acidic conditions) were associated with higher concentrations of these ions, potentially due to increased dissolution of minerals.

Positive Correlations

There was an almost perfect positive correlation (0.999) between electrical conductivity (EC) and total dissolved solids (TDS), which aligned with the downstream data. Additionally, EC showed positive correlations with several ions: F^- (0.801), SO_4^{2-} (0.907), Ca (0.944), K (0.927), Mg (0.971), Na (0.563), Si (0.714), Fe (0.714), Al (0.819), As (0.649), Zn (0.752), Mn (0.817), Cu (0.651), Ni (0.784), Ti (0.754), and Cr (0.851).

Calcium exhibited positive correlations with several ions: K (0.807), Mg (0.988), Si (0.534), Fe (0.606), Al (0.790), Zn (0.806), Mn (0.821), Cu (0.714), Ni (0.829), Ti (0.747), and Cr (0.870), indicating that these ions might share common sources or geochemical behaviours in the upstream section. Fluoride showed positive correlations with Cl^- (0.643), NO_3^- (0.537), SO_4^{2-} (0.640), PO_4^{3-} (0.510), Ca (0.742), K (0.836), Mg (0.803), Na (0.765), Si (0.852), Al (0.502), As (0.850), Mn (0.566), Ni (0.511), and Cr (0.557). Similarly, Cl^- exhibited positive correlations with NO_3^- (0.916), PO_4^{3-} (0.925), K (0.653), Na (0.949), Si (0.684), Al (0.502), and As (0.917). Additionally, NO_3^- revealed positive correlations with PO_4^{3-} (0.994), K (0.594), Na (0.830), Si (0.512), and As (0.859).

Sulphate showed positive correlations with multiple ions, including Ca (0.966), K (0.724), Mg (0.959), Fe (0.694), Al (0.878), Zn (0.895), Mn (0.903), Cu (0.765), Ni (0.888), Ti (0.822), and Cr (0.940). This suggests that these ions were influenced by similar environmental factors or sources. PO_4^{3-} showed positive correlations with K (0.572), Na (0.838), Si (0.513), and As (0.856). Likewise, potassium exhibited positive correlations with Mg (0.862), Na (0.759), Si (0.785), Fe (0.609), Al (0.686), As (0.845), Zn (0.574), Mn (0.671), Ni (0.605), Ti (0.594), and Cr (0.679). Additionally, Mg showed positive correlations with Si (0.619), Fe (0.625), Al (0.808), As (0.567), Zn (0.797), Mn (0.835), Cu (0.692), Ni (0.814), Ti (0.740), and Cr (0.869).

The upstream data revealed significant negative correlations with pH across numerous parameters, indicating that a decrease in pH might be associated with an increase in the concentrations of various ions. This highlights the importance of monitoring pH levels to assess the overall water quality in the upstream section.

Table 5.11 Correlation matrix between variables in upstream

Variables	pH	EC	TDS	Temp	F^-	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca	K	Mg	Na	Si	Fe	Al	As	Zn	Mn	Cu	Ni	Ti	Cr
pH	**1**	**-0.817**	**-0.817**	0.367	**-0.672**	-0.020	0.083	**-0.928**	0.137	**-0.864**	**-0.632**	**-0.879**	-0.165	**-0.548**	**-0.549**	**-0.841**	-0.334	**-0.846**	**-0.893**	**-0.716**	**-0.822**	**-0.722**	**-0.884**
EC	**-0.817**	**1**	**1.000**	-0.360	**0.801**	0.404	0.282	**0.907**	0.251	**0.944**	**0.927**	**0.971**	**0.563**	**0.714**	**0.714**	**0.819**	**0.649**	**0.752**	**0.817**	**0.651**	**0.784**	**0.754**	**0.851**
TDS	**-0.817**	**1.000**	**1**	-0.360	**0.803**	0.405	0.282	**0.907**	0.251	**0.945**	**0.927**	**0.971**	**0.564**	**0.714**	**0.712**	**0.818**	**0.650**	**0.751**	**0.817**	**0.651**	**0.784**	**0.753**	**0.850**
Temp	0.367	-0.360	-0.360	**1**	-0.106	0.288	0.194	**-0.551**	0.238	**-0.555**	-0.214	-0.482	0.209	0.251	-0.247	-0.341	0.082	-0.455	-0.381	-0.400	-0.452	-0.374	-0.439
F^-	**-0.672**	**0.801**	**0.803**	-0.106	**1**	**0.643**	**0.537**	**0.640**	**0.510**	**0.742**	**0.836**	**0.803**	**0.765**	**0.852**	0.244	**0.502**	**0.850**	0.464	**0.566**	0.452	**0.511**	0.409	**0.557**
Cl^-	-0.020	0.404	0.405	0.288	**0.643**	**1**	**0.916**	0.016	**0.925**	0.196	**0.653**	0.281	**0.949**	**0.684**	-0.006	-0.006	**0.917**	-0.166	-0.011	-0.099	-0.072	-0.073	-0.032
NO_3^-	0.083	0.282	0.282	0.194	**0.537**	**0.916**	**1**	-0.055	**0.994**	0.113	**0.594**	0.201	**0.830**	**0.512**	-0.083	-0.072	**0.859**	-0.172	-0.082	-0.117	-0.115	-0.119	-0.096
SO_4^{2-}	**-0.928**	**0.907**	**0.907**	**-0.551**	**0.640**	0.016	-0.055	**1**	-0.106	**0.966**	**0.724**	**0.959**	0.190	0.468	**0.694**	**0.878**	0.334	**0.895**	**0.903**	**0.765**	**0.888**	**0.822**	**0.940**
PO_4^{3-}	0.137	0.251	0.251	0.238	**0.510**	**0.925**	**0.994**	-0.106	**1**	0.066	**0.572**	0.153	**0.838**	**0.513**	-0.084	-0.093	**0.856**	-0.214	-0.111	-0.163	-0.159	-0.150	-0.134
Ca	**-0.864**	**0.944**	**0.945**	**-0.555**	**0.742**	0.196	0.113	**0.966**	0.066	**1**	**0.807**	**0.988**	0.365	**0.534**	**0.606**	**0.790**	0.487	**0.806**	**0.821**	**0.714**	**0.829**	**0.747**	**0.870**
K	**-0.632**	**0.927**	**0.927**	-0.214	**0.836**	**0.653**	**0.594**	**0.724**	**0.572**	**0.807**	**1**	**0.862**	**0.759**	**0.785**	**0.609**	**0.686**	**0.845**	**0.574**	**0.671**	0.484	**0.605**	**0.594**	**0.679**
Mg	**-0.879**	**0.971**	**0.971**	-0.482	**0.803**	0.281	0.201	**0.959**	0.153	**0.988**	**0.862**	**1**	0.445	**0.619**	**0.625**	**0.808**	**0.567**	**0.797**	**0.835**	**0.692**	**0.814**	**0.740**	**0.869**
Na	-0.165	**0.563**	**0.564**	0.209	**0.765**	**0.949**	**0.830**	0.190	**0.838**	0.365	**0.759**	0.445	**1**	**0.805**	0.125	0.121	**0.930**	0.012	0.110	0.076	0.110	0.106	0.134
Si	**-0.548**	**0.714**	**0.714**	0.251	**0.852**	**0.684**	**0.512**	0.468	**0.513**	**0.534**	**0.785**	**0.619**	**0.805**	**1**	0.393	**0.509**	**0.815**	0.404	**0.510**	0.380	0.442	0.434	**0.500**
Fe	**-0.549**	**0.714**	**0.712**	-0.247	0.244	-0.006	-0.083	**0.694**	-0.084	**0.606**	**0.609**	**0.625**	0.125	0.393	**1**	**0.864**	0.182	**0.714**	**0.774**	**0.498**	**0.668**	**0.782**	**0.772**
Al	**-0.841**	**0.819**	**0.818**	-0.341	**0.502**	-0.006	-0.072	**0.878**	-0.093	**0.790**	**0.686**	**0.808**	0.121	**0.509**	**0.864**	**1**	0.310	**0.885**	**0.982**	**0.655**	**0.813**	**0.823**	**0.930**
As	-0.334	**0.649**	**0.650**	0.082	**0.850**	**0.917**	**0.859**	0.334	**0.856**	0.487	**0.845**	**0.567**	**0.930**	**0.815**	0.182	0.310	**1**	0.188	0.322	0.202	0.250	0.215	0.301
Zn	**-0.846**	**0.752**	**0.751**	-0.455	0.464	-0.166	-0.172	**0.895**	-0.214	**0.806**	**0.574**	**0.797**	0.012	0.404	**0.714**	**0.885**	0.188	**1**	**0.887**	**0.909**	**0.970**	**0.946**	**0.974**
Mn	**-0.893**	**0.817**	**0.817**	-0.381	**0.566**	-0.011	-0.082	**0.903**	-0.111	**0.821**	**0.671**	**0.835**	0.110	**0.510**	**0.774**	**0.982**	0.322	**0.887**	**1**	**0.679**	**0.825**	**0.798**	**0.938**
Cu	**-0.716**	**0.651**	**0.651**	-0.400	0.452	-0.099	-0.117	**0.765**	-0.163	**0.714**	0.484	**0.692**	0.076	0.380	**0.498**	**0.655**	0.202	**0.909**	**0.679**	**1**	**0.967**	**0.928**	**0.877**
Ni	**-0.822**	**0.784**	**0.784**	-0.452	**0.511**	-0.072	-0.115	**0.888**	-0.159	**0.829**	**0.605**	**0.814**	0.110	0.442	**0.668**	**0.813**	0.250	**0.970**	**0.825**	**0.967**	**1**	**0.971**	**0.967**
Ti	**-0.722**	**0.754**	**0.753**	-0.374	0.409	-0.073	-0.119	**0.822**	-0.150	**0.747**	**0.594**	**0.740**	0.106	0.434	**0.782**	**0.823**	0.215	**0.946**	**0.798**	**0.928**	**0.971**	**1**	**0.946**
Cr	**-0.884**	**0.851**	**0.850**	-0.439	**0.557**	-0.032	-0.096	**0.940**	-0.134	**0.870**	**0.679**	**0.869**	0.134	**0.500**	**0.772**	**0.930**	0.301	**0.974**	**0.938**	**0.877**	**0.967**	**0.946**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

5.5.2. Correlation coefficient between variables in downstream over 3 years

Table 5.12 presents the Pearson correlation coefficients between various water quality parameters measured in the downstream section over three years. The parameters include pH, EC (Electrical Conductivity), TDS (Total Dissolved Solids), temperature, and concentrations of various ions such as fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), silicon (Si), and arsenic (As).

Negative Correlations

The table revealed negative correlations between pH and several major ions, including calcium (-0.537), potassium (-0.575), sodium (-0.609), and silicon (-0.610). This indicates that as pH decreases, the concentrations of these ions tend to increase. These inverse relationships are critical for understanding the geochemical interactions and potential acid-base reactions occurring in the water. Additionally, a negative correlation was observed between temperature and nitrate (-0.771) as well as magnesium (-0.572).

A significant negative correlation (-0.896) was observed between calcium and arsenic, suggesting that higher concentrations of calcium were associated with lower concentrations of arsenic. This potentially indicates competitive interactions in adsorption processes or co-precipitation mechanisms with arsenic possibly co-precipitating onto Fe colloids. Furthermore, negative correlations were found between nitrate and arsenic (-0.591), potassium and arsenic (-0.585), magnesium and arsenic (-0.758), and silicon and arsenic (-0.693). Similarly, sodium and arsenic also exhibit a negative correlation (-0.832), further supporting the idea of competitive interactions or different geochemical behaviours influencing these elements.

Positive Correlations

There was a near-perfect positive correlation (0.968) between electrical conductivity and total dissolved solids indicating that EC is a reliable indicator of the dissolved ionic content in water. The correlation between EC and TDS was expected since the dissolution of solids (e.g., minerals) increases ions in solution, thereby raising EC. Calcium showed positive correlations with magnesium (0.906), sodium (0.897), silicon (0.809) and potassium (0.732). Suggesting that these ions may originate from similar sources or undergo similar geochemical processes. A high positive correlation (0.876) between sodium and silicon implies that these ions could be derived from similar geological formations or influenced by similar environmental factors.

Additionally, positive correlations were observed between pH and arsenic (0.554), chloride and sulphate (0.786), nitrate and calcium (0.589) as well as magnesium (0.498), potassium and sodium (0.859), potassium and silicon (0.846) and magnesium (0.641), magnesium and sodium (0.760) as well as silicon (0.649).

These correlations indicate potential interdependencies between these parameters, suggesting that changes in one could significantly affect the others. Understanding these relationships is crucial for effective water quality management and predicting the impacts of various environmental and anthropogenic factors on water chemistry.

Table 5.12 Correlation matrix between variables in downstream over 3 years

Variables	pH	EC	TDS	Temp	F^-	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca	K	Mg	Na	Si	As
pH	**1**	0.039	0.074	-0.014	0.428	0.062	-0.176	0.134	0.016	**-0.537**	**-0.575**	-0.418	**-0.609**	**-0.610**	**0.554**
EC	0.039	**1**	**0.968**	0.453	-0.009	0.261	-0.387	0.076	**0.573**	-0.211	0.277	-0.202	-0.018	0.054	0.415
TDS	0.074	**0.968**	**1**	0.493	0.013	0.254	-0.466	0.088	**0.542**	-0.263	0.228	-0.256	-0.066	0.007	0.441
Temp	-0.014	0.453	0.493	**1**	-0.112	0.399	**-0.771**	0.269	0.149	-0.490	0.074	**-0.572**	-0.172	0.032	**0.496**
F^-	0.428	-0.009	0.013	-0.112	**1**	0.099	-0.001	0.165	-0.010	-0.237	-0.283	-0.130	-0.344	-0.271	0.305
Cl^-	0.062	0.261	0.254	0.399	0.099	**1**	-0.107	**0.876**	0.198	-0.320	-0.041	-0.308	-0.229	-0.076	0.390
NO_3^-	-0.176	-0.387	-0.466	**-0.771**	-0.001	-0.107	**1**	-0.044	-0.110	**0.589**	0.128	**0.498**	0.373	0.229	**-0.591**
SO_4^{2-}	0.134	0.076	0.088	0.269	0.165	**0.876**	-0.044	**1**	-0.053	-0.394	-0.276	-0.361	-0.348	-0.238	0.431
PO_4^{3-}	0.016	**0.573**	**0.542**	0.149	-0.010	0.198	-0.110	-0.053	**1**	0.061	0.455	0.026	0.090	0.185	0.107
Ca	**-0.537**	-0.211	-0.263	-0.490	-0.237	-0.320	**0.589**	-0.394	0.061	**1**	**0.732**	**0.906**	**0.897**	**0.809**	**-0.896**
K	**-0.575**	0.277	0.228	0.074	-0.283	-0.041	0.128	-0.276	0.455	**0.732**	**1**	**0.641**	**0.859**	**0.846**	**-0.585**
Mg	-0.418	-0.202	-0.256	**-0.572**	-0.130	-0.308	**0.498**	-0.361	0.026	**0.906**	**0.641**	**1**	**0.760**	**0.649**	**-0.758**
Na	**-0.609**	-0.018	-0.066	-0.172	-0.344	-0.229	0.373	-0.348	0.090	**0.897**	**0.859**	**0.760**	**1**	**0.876**	**-0.832**
Si	**-0.610**	0.054	0.007	0.032	-0.271	-0.076	0.229	-0.238	0.185	**0.809**	**0.846**	**0.649**	**0.876**	**1**	**-0.693**
As	**0.554**	0.415	0.441	**0.496**	0.305	0.390	**-0.591**	0.431	0.107	**-0.896**	**-0.585**	**-0.758**	**-0.832**	**-0.693**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

5.6. Water quality index and Sodium percent to assess the quality of water

Water Quality Index (WQI)

The water quality index utilised for evaluating water quality is depicted in Figure 5.1. Throughout the entire monitoring period from 2021 to 2023, samples collected downstream from the lake consistently met the criteria for "excellent" water quality, with respective mean Water Quality Index (WQI) values of 13.53, 13.11 and 13.63. Upstream sampling from the rivers generally demonstrated "excellent" and "good" water quality across most sampling stations with WQI values ranging from 10.00 to 79.00. However, a few exceptions were noted at sampling points USL-2 to USL-4, which did not meet the criteria for "very good" water quality. In these cases, the WQI values were notably higher (108.0, 372.0 and 2701 respectively), categorizing the water quality as "poor" for USL-2 and USL-3 and designating USL-4 as "water unsuitable for drinking". These instances of compromised water quality were attributed to wastewater discharges from the Maamba mine (Besa, 2001). The degradation in water quality for USL-2 to USL-4 was primarily attributed to elevated levels of EC, TDS, F^-, Cl^-, NO_3^-, SO_4^{2-}, Ca, K, Mg, Na, Fe and Mn.

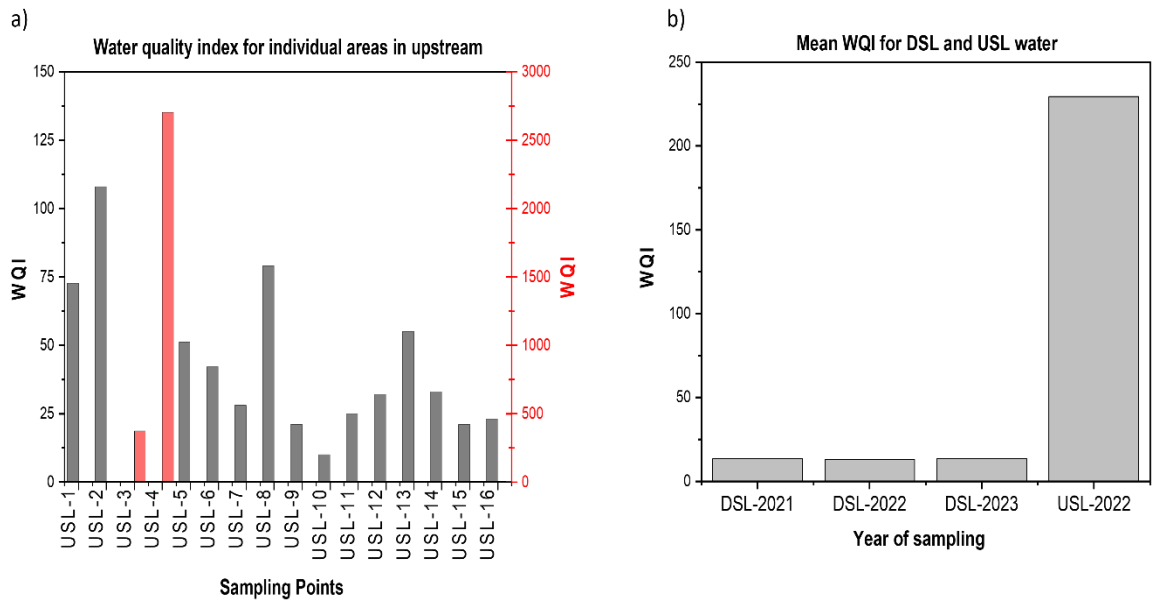


Figure 5.1 Water Quality Index, a) upstream water individual sites and b) comparison between downstream and upstream

Sodium Percent (Na %)

Figure 5.2 shows the sodium percentage values. The percentage of sodium (Na %) serves as an indicator of sodium-related concerns. For the downstream sampling locations, the Na % aligns with "excellent" water quality standards, demonstrating mean values of 20.06, 24.32 and 15.60 respectively. Across the upstream sampling sites, the Na % consistently meets both "excellent" and "good" water quality classifications, with values ranging from 7.59 to 37.0, except for a single study area (USL-15) where the Na % reaches 41.5, falling into the "permissible" range. Elevated levels of Na can have adverse effects on soil texture, hindering water and air permeation, ultimately reducing soil water availability and harming crop growth (Liu, 2020).

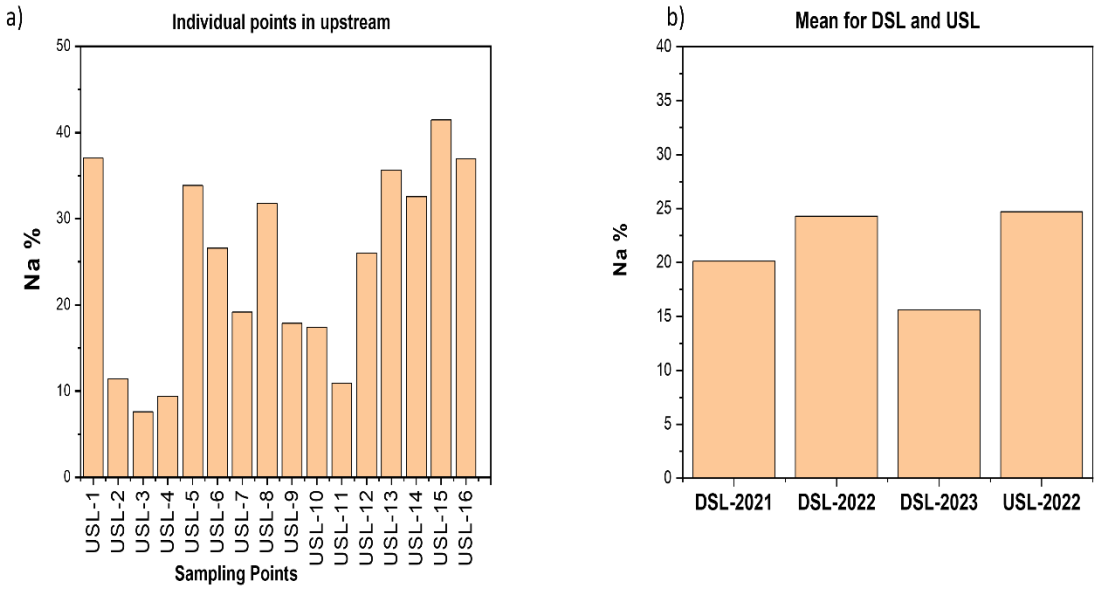


Figure 5.2 Sodium percent, (a) upstream water individual sites and (b) comparison between the downstream and upstream

5.7. Principal Component Analysis (PCA)

5.7.1 Correlation plot for upstream between variables (2022)

Principal Component Analysis correlation plot (Figure 5.3) visually represents the complex interdependencies among water quality parameters in the upstream section. It helps identify key factors driving variations in water chemistry. By reducing the dataset's dimensionality, PCA highlights the most significant variables and their interrelationships.

The PCA plot showed strong clustering of variables such as TDS, EC, and several metal ions like calcium (Ca), magnesium (Mg), and potassium (K). These clusters indicated high correlations among these parameters, suggesting that they might be influenced by similar sources or processes.

Negative correlations were depicted by variables positioned on opposite sides of the plot. For example, pH is positioned opposite to most other ions, reflecting the negative correlations observed in the correlation matrix. This visual representation highlights the inverse relationship between pH levels and the concentrations of various ions and metals.

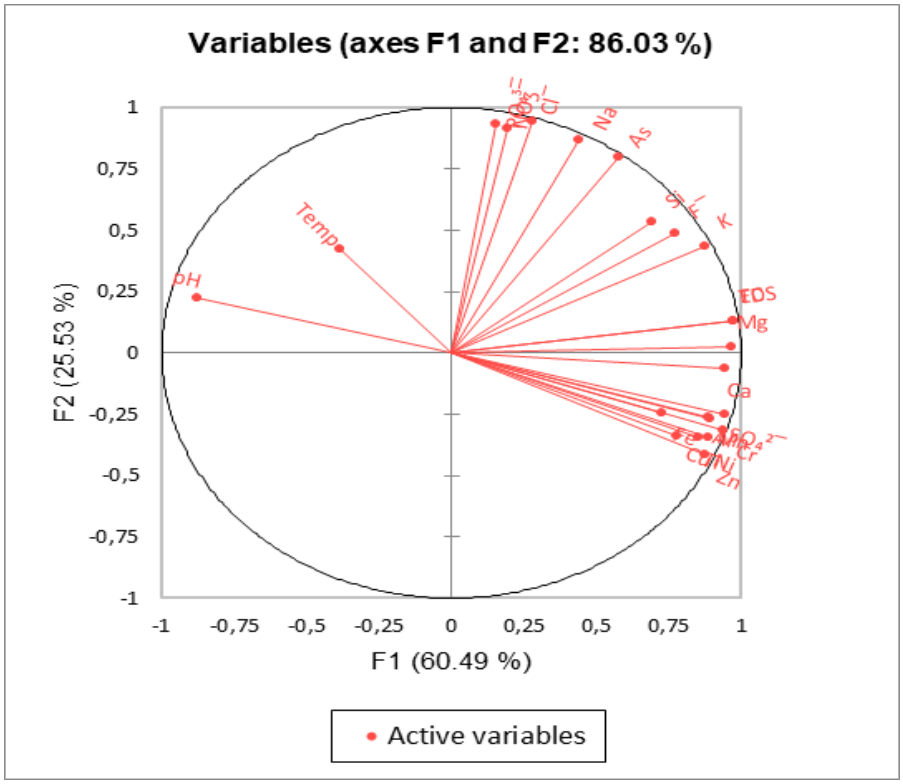


Figure 5.3 Correlation plot for upstream

5.7.1.1 Observations in upstream

Figure 5.4 shows the PCA observations for upstream water quality parameters. Each point in the plot represents a specific observation, with the biplot illustrating the distribution of observations based on the principal components. The biplot revealed distinct clusters of observations, indicating significant variability in water quality parameters. Total dissolved solids, electrical conductivity, sulphate, manganese, nickel, titanium, chromium, aluminium, iron, zinc, copper, temperature and pH significantly influenced the positioning of samples 55-57, 59, 67 and 68(USL-2 to USL-4, USL-6, USL-14 and USL-15). Meanwhile, phosphate, nitrate, chloride, sodium, arsenic, silicon, fluoride, potassium, total dissolved solids, electrical conductivity and magnesium influenced the positioning of sample 66 (USL-13).

These clusters suggest different environmental conditions or pollution sources affecting the upstream water quality. The separation of clusters highlights the heterogeneity in water quality, emphasizing the need for targeted monitoring and management strategies to address specific areas or sources of contamination.

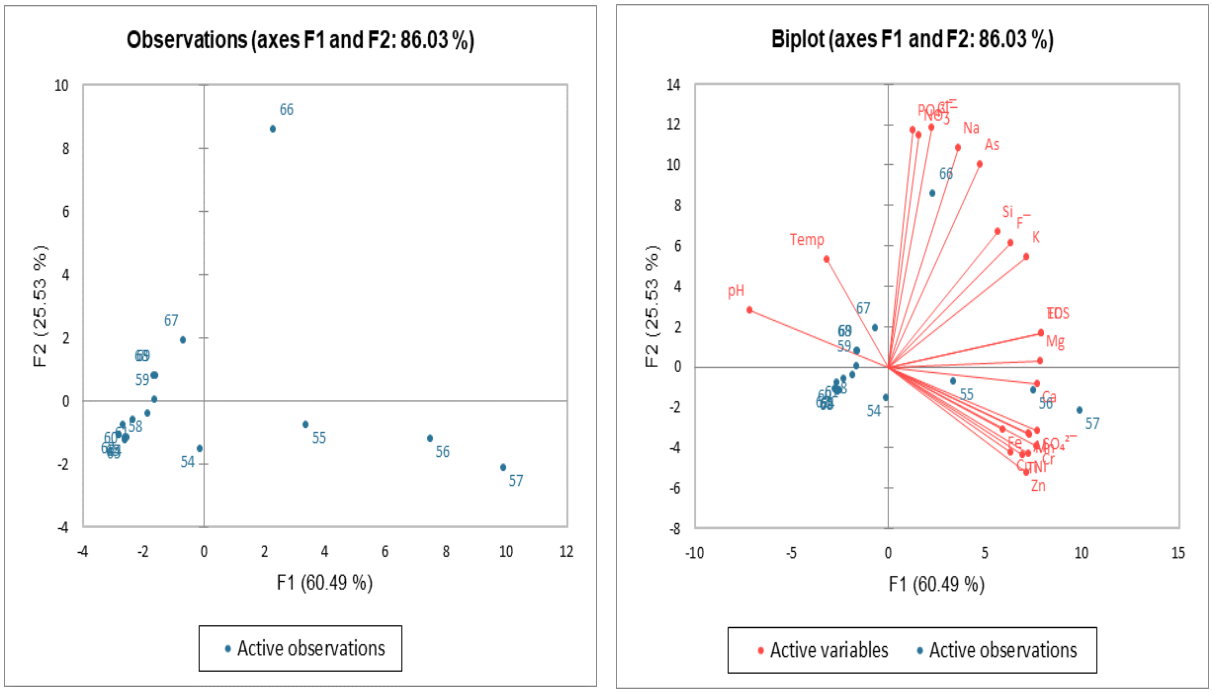


Figure 5.4 Observation plots for upstream

5.7.2 Correlation plot over 3 years (2021-2023) in downstream between variables

The correlation plot (Figure 5.5) visualises the relationships and variances between different water quality parameters in the downstream section over three years. The plot indicated that variables such as electrical conductivity (EC), total dissolved solids (TDS), and temperature were closely clustered, suggesting that these parameters share similar variance and exhibit strong correlations. This clustering can be attributed to their direct relationship, where higher ionic content (TDS) naturally increases EC, and both are influenced by temperature changes.

Negative correlations were depicted by variables positioned on opposite sides of the plot. For instance, pH is positioned opposite to major ions like potassium (K), sodium (Na), and silicon (Si), reflecting the strong negative correlations identified in the correlation matrix. This opposition highlights the inverse relationship between pH levels and ion concentrations.

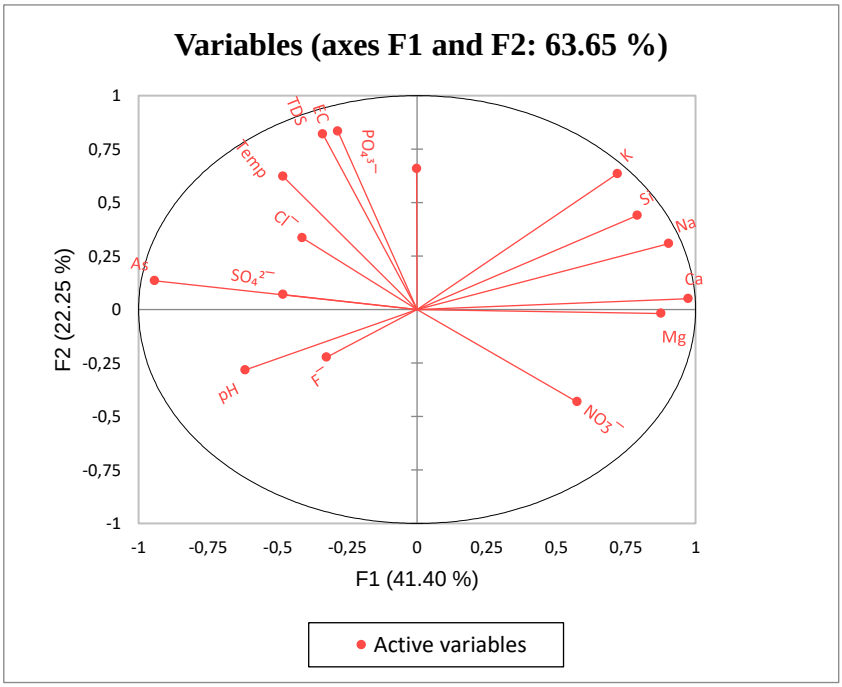


Figure 5.5 Correlation plot for downstream over three years

5.7.2.1 Observations over 3 years in downstream

Figure 5.5 shows the PCA observations, illustrating how different years cluster based on water quality parameters in the downstream section. Each point in the plot represents a specific observation, with the biplot showing the distribution of observations across three years: 2021, 2022, and 2023.

The biplot revealed distinct clusters for the years 2021, 2022, and 2023. Factors including sulphate, arsenic, magnesium, calcium, and nitrate notably influenced the positioning of samples 28 to 32 (DSL-28 to DSL-32). Conversely, nitrate, phosphate, chloride, conductivity, total dissolved solids and temperature influenced the positioning of samples 1, 4 and 7 (DSL-1, 4 and 7). This separation suggests significant variations in water quality parameters across these years, possibly due to changes in environmental conditions, pollution sources, or monitoring practices. Each year's observations form separate clusters, indicating that the water quality characteristics for each year were sufficiently different to be distinguishable in the PCA plot.

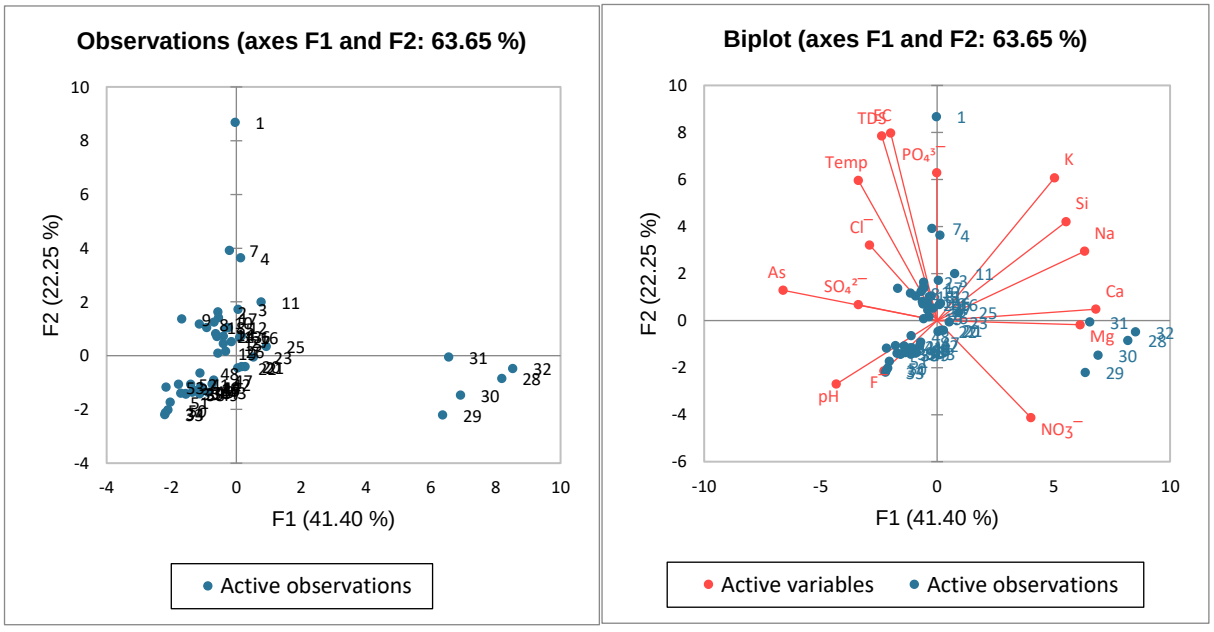


Figure 5.6 Observation plots for downstream over three years

5.8 Comparison with results from other studies

The average chemical composition of the water in this study was compared to that of other lakes (Table 5.13). The data showed that Lake Kariba was generally alkaline. The mean electrical conductivity (EC) in this study was lower than the levels recorded by Saturday et al. (2021) in Lake Bunyonyi, Uganda, das Kangabam et al. (2017) in Loktak Lake, India, and Kondowe et al. (2022) in Lake Kanyaboli, Kenya, but comparable to the findings of Khadka and Ramanathan (2013) in Begnas Lake, Nepal, and Anshumali and Ramanathan (2007) in Pandoh Lake, India. The study also showed lower levels of total dissolved solids (TDS), fluoride (F^-), chloride (Cl^-), calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) than those found by das Kangabam et al. (2017). TDS and F^- were not frequently analysed in other lakes.

Similar $NO3^-$ results, ranging from 0.02 mg/L to 0.11 mg/L, were recorded by Fachrul et al. (2021) in Maninjau Lake, West Sumatra, Indonesia, as well as by Saturday et al. (2021) and Kondowe et al. (2022). These values were lower than those reported by Khadka & Ramanathan (2013), Anshumali & Ramanathan (2007), and das Kangabam et al. (2017). Sulphate levels in this study were comparable to those reported by Anshumali & Ramanathan (2007), but lower than those found by Khadka & Ramanathan (2013) and higher than those reported by das Kangabam et al. (2017). This study found the lowest PO_4^{3-} content compared to other studies, except for das Kangabam et al. (2017), who obtained similar results.

The concentrations of Ca and K in this study were lower compared to those reported by Anshumali & Ramanathan (2007) and das Kangabam et al. (2017). Mg and Na levels were also lower compared to findings by Khadka & Ramanathan (2013) and das Kangabam et al. (2017). However, higher values for Ca and Mg were observed compared to Khadka & Ramanathan (2013). The results for K, Mg, and Na in this study were found to be comparable to those reported by Khadka & Ramanathan (2013), Anshumali & Ramanathan (2007), and das Kangabam et al. (2017). This study reported a mean arsenic level of 0.39 µg/L, which most other studies did not analyse.

Table 5.13 Average chemical composition of water from other studies

Parameters	Begnas Lake, Nepal	Pandoh Lake, India	Maninjau Lake, West Sumatra, Indonesia	Maninjau Lake, Indonesia	Lake Bunyonyi, Southwestern, Uganda	Loktak Lake, India	Lake Kanyaboli, Kenya	Lake Kariba, Zambia
References	Khadka & Ramanathan (2013)	Anshumali & Ramanathan, (2007)	Fachrul et al. (2021)	Syandri & Syandri (2015).	Saturday et al. (2021).	das Kangabam et al. (2017)	Kondowe et al. (2022)	This study
pH	7.27	7.13	-	6.56 – 6.80	7.4 – 7.9	6.43 – 7.34	7.05	7.83
EC, (µs/cm)	90.51	80.8	-	0.23 – 0.26	241.1 – 266.8	161.3 – 263.5	424.4	95.2
TDS, (mg/L)	-	-	-	12.4 – 22.8	-	69.8 – 179.1	-	47.7
Temp. (°C)	-	-	-	27.3 – 28.3	20.9 – 21.8	19.6 – 23.7	27.98	25.3
F^-, (mg/L)	-	-	-	-	-	0.20 – 0.22	-	0.070
Cl^-, (mg/L)	2.57	2.37	-	-	-	4.37 – 35.0	-	1.52
NO_3^-, (mg/L)	5.34	10.33	0.11 – 0.19	-	0.02 – 0.041	5.67 – 30.0	306.7µg/L	0.090
SO_4^{2-},(mg/L)	7.26	2.74	-	-	-	0.05 – 0.62	-	2.61
PO_4^{3-},(mg/L)	0.09	1.28	0.33 – 0.38	-	-	0.003 – 0.06	-	0.0034
Ca, (mg/L)	7.03	17.96	-	-	-	19.0 – 70.0	-	10.9
K, (mg/L)	1.42	2.06	-	-	-	3.82 – 12.1	-	1.26
Mg, (mg/L)	1.97	3.31	-	-	-	4.92 – 17.4	-	3.39
Na, (mg/L)	3.89	3.82	-	-	-	6.30 – 11.5	-	3.65
Fe, (mg/L)	-	-	-	0.02 – 0.07	-	-	-	-
Zn, (µg/L)	-	-	-	0.40 – 0.75 mg/L	-	-	-	-
Cu, (µg/L)	-	-	-	0.64 – 1.13 mg/L	-	-	-	-
Cd, (mg/L)	-	-	-	0.12 – 0.57	-	-	-	-
Pb, (mg/L)	-	-	-	0.58 – 0.93	-	-	-	-
As, (µg/L)	-	-	-	-	-	-	-	0.39

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This chapter provides a summary of the study's findings along with some recommendations that came from it.

6.1. Conclusion

The overall water quality of Lake Kariba was good, featuring low concentrations of nutrients, solutes, and suspended particles. From 2021 to 2023, it consistently falls within category I “excellent” of the water quality index (Karakus, 2018), with values ranging from 13.11 to 13.63 downstream. Although there have been no significant changes in the lake's overall water quality, NO_3^- concentrations have increased at the fish cages, ranging between 0.202 and 0.56 mg/L. These areas were the centre of fish farming activity, where fish feed accumulates in the water. The concentrations of all elements were within the recommended levels set by ZABS and WHO guidelines, indicating no possible risks to human health or ecosystem.

The water quality index upstream falls within categories I and II, ranging from "excellent" to "good," with values between 10.00 and 79.00. However, a few upstream sites exhibited poor to very poor water quality due to elevated levels of pollutants. These sites specifically showed low pH (acidic), increased electrical conductivity, and increased concentrations of cations and anions such as iron (Fe), aluminium (Al), manganese (Mn), nickel (Ni), chromium (Cr), and sulphates (SO_4^{2-}). These findings indicated pollution from various sources, possibly mining activities, which can release acidic drainage into water bodies, leading to pH reduction and dissolution of metals from surrounding rocks and soil.

The concentrations of these elements exceeded the recommended levels set by both ZABS and WHO guidelines, indicating possible risks to human health and the ecosystem. Therefore, a more comprehensive study is necessary to assess the environmental risks posed by these elevated metal concentrations in the water. Continued monitoring of water parameters is essential, along with interventions to mitigate the reported increases. Environmental risk assessments can provide valuable insights into the impact of these metals on aquatic ecosystems and human health, guiding future management strategies for Lake Kariba and its surrounding areas.

6.2. Recommendations

- Enhancing land use management strategies: To reduce the negative effects of human activity on the water quality in the Lake Kariba region. These actions include encouraging sustainable land use practices, creating and executing suitable land use plans, and using less fertilizers and other chemicals.
- Improving wastewater treatment: The study discovered that the release of untreated sewage and industrial effluents was a factor in the rise in anion and cation concentrations. To reduce the discharge of contaminants into the water body, it is necessary to improve wastewater treatment facilities in metropolitan areas.
- Monitoring water quality: It is crucial to regularly monitor and analyze the water quality to better understand how land use activities affect the aquatic ecosystem. Both chemical and biological analyses should be used in the monitoring, which should also include both point and non-point sources of pollution.
- Increasing awareness: It is important to inform local stakeholders and communities about the effects of land use patterns on water quality and the importance of sustainable practices. The decision-making process for water resource conservation and land use should engage the local communities.

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APPENDIX

APPENDIX A1: Physical-chemical parameters

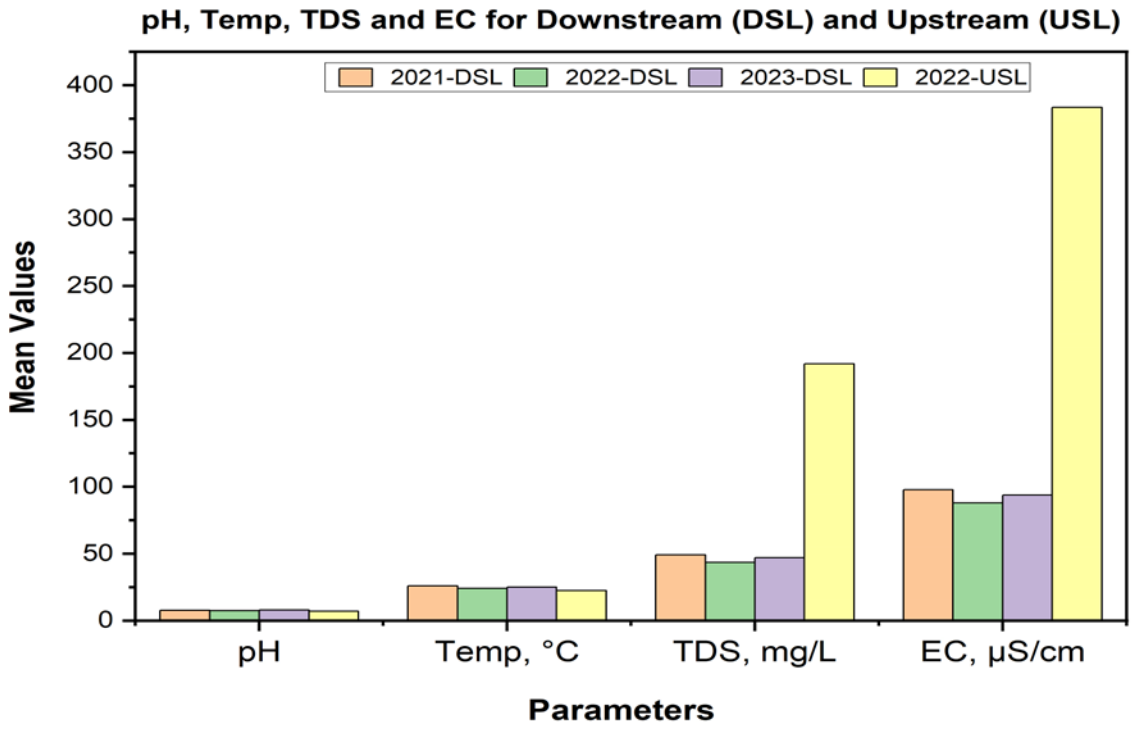


Figure A.1 Mean physical chemical parameters in downstream and upstream water according to the year of monitoring

APPENDIX A2: Anions

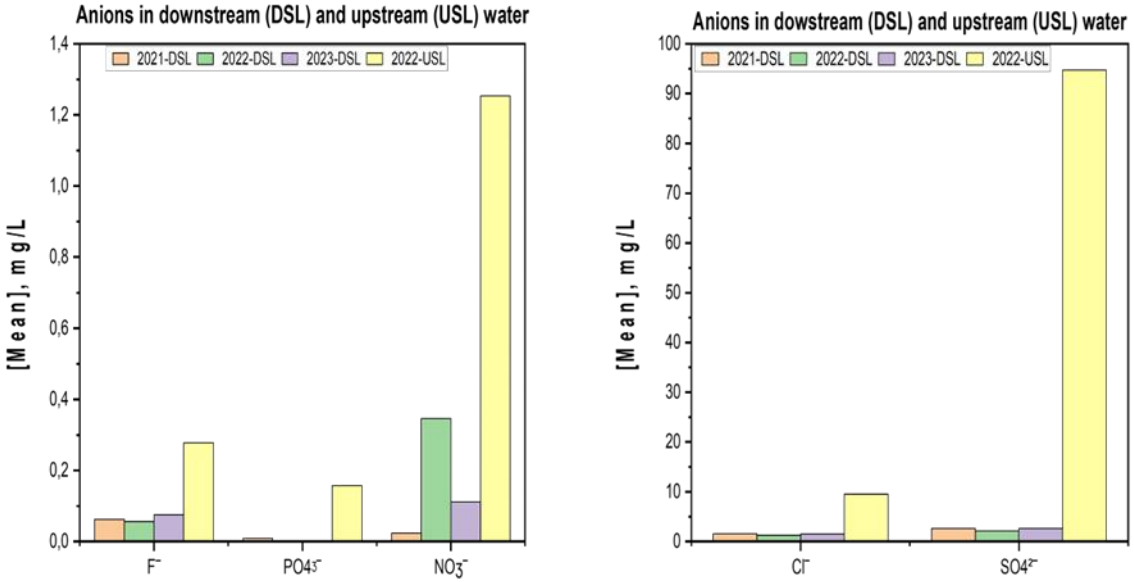
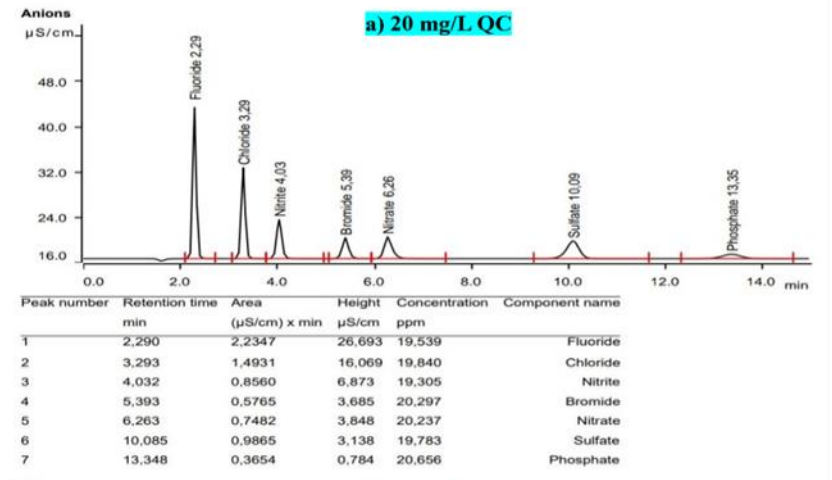
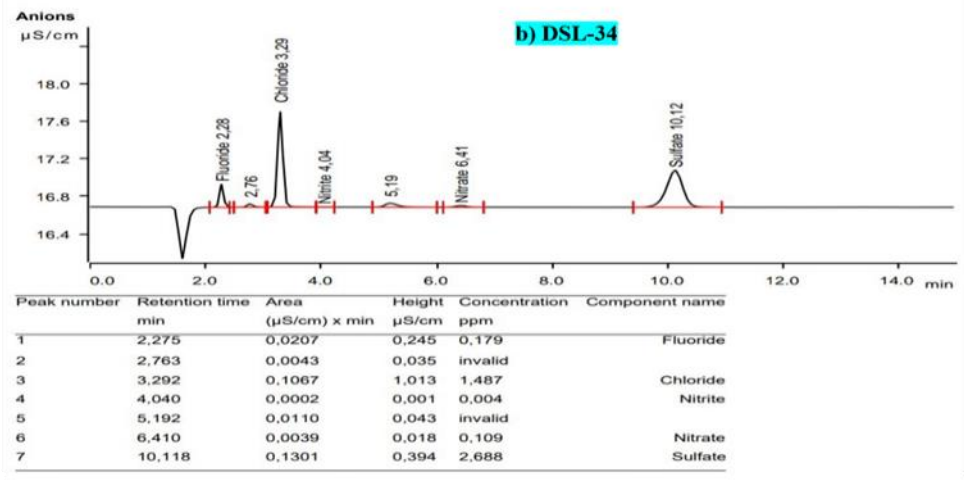


Figure A.2 Concentration of major anions detected in upstream and downstream water

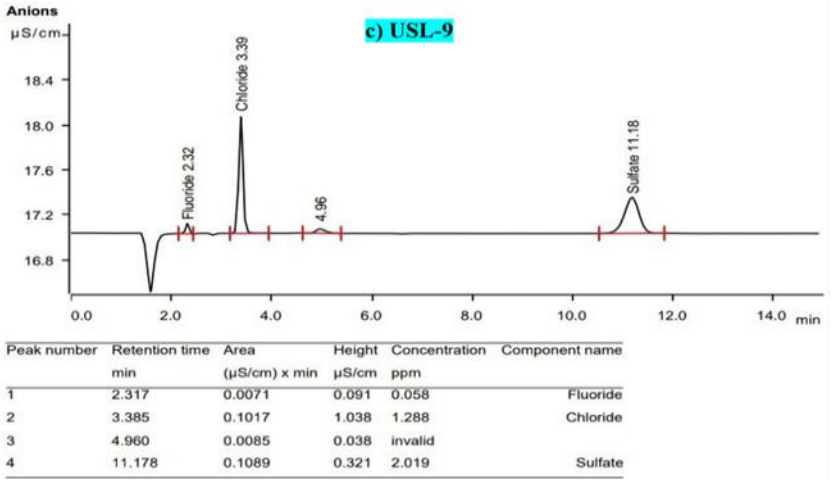
APPENDIX A3: Anions Chromatograms



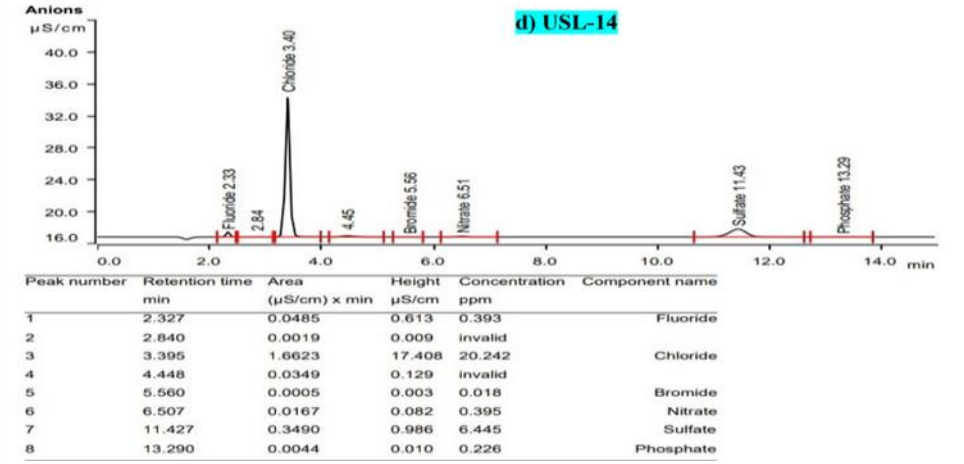
Peak number	Retention time	Area	Height	Concentration	Component name
	min	(µS/cm) x min	µS/cm	ppm	
1	2,290	2,2347	26,693	19,539	Fluoride
2	3,293	1,4931	16,069	19,840	Chloride
3	4,032	0,8560	6,873	19,305	Nitrite
4	5,393	0,5765	3,685	20,297	Bromide
5	6,263	0,7482	3,848	20,237	Nitrate
6	10,085	0,9865	3,138	19,783	Sulfate
7	13,348	0,3654	0,784	20,656	Phosphate



Peak number	Retention time	Area	Height	Concentration	Component name
	min	(µS/cm) x min	µS/cm	ppm	
1	2,275	0,0207	0,245	0,179	Fluoride
2	2,763	0,0043	0,035	invalid	
3	3,292	0,1067	1,013	1,487	Chloride
4	4,040	0,0002	0,001	0,004	Nitrite
5	5,192	0,0110	0,043	invalid	
6	6,410	0,0039	0,018	0,109	Nitrate
7	10,118	0,1301	0,394	2,688	Sulfate



Peak number	Retention time	Area	Height	Concentration	Component name
	min	(µS/cm) x min	µS/cm	ppm	
1	2.317	0.0071	0.091	0.058	Fluoride
2	3.385	0.1017	1.038	1.288	Chloride
3	4.960	0.0085	0.038	invalid	
4	11.178	0.1089	0.321	2.019	Sulfate



Peak number	Retention time	Area	Height	Concentration	Component name
	min	(µS/cm) x min	µS/cm	ppm	
1	2.327	0.0485	0.613	0.393	Fluoride
2	2.840	0.0019	0.009	invalid	
3	3.395	1.6623	17.408	20.242	Chloride
4	4.448	0.0349	0.129	invalid	
5	5.560	0.0005	0.003	0.018	Bromide
6	6.507	0.0167	0.082	0.395	Nitrate
7	11.427	0.3490	0.986	6.445	Sulfate
8	13.290	0.0044	0.010	0.226	Phosphate

Figure A.3 Chromatograms illustrating the occurrence of anions in samples for upstream (depicted as c and d), downstream (shown as b), and a quality control sample spiked with 20 mg/L (labelled as a)

APPENDIX A4: Major Cations

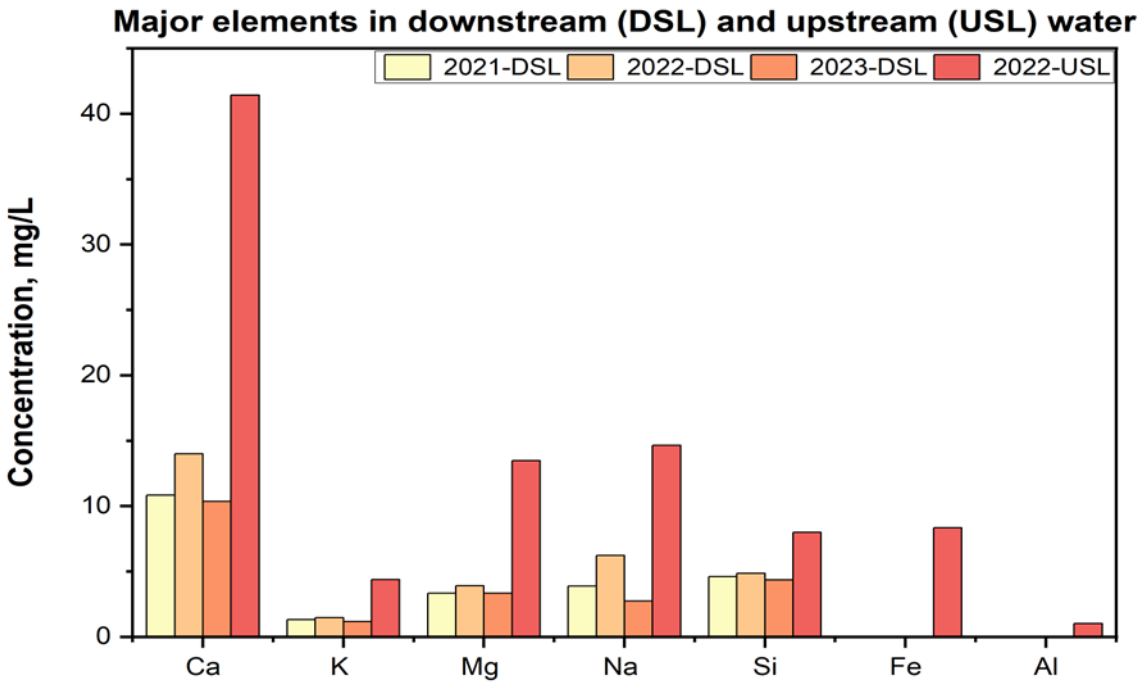


Figure A.4 Concentration of major elements detected in both study areas (downstream and upstream)

APPENDIX A5: Trace metals

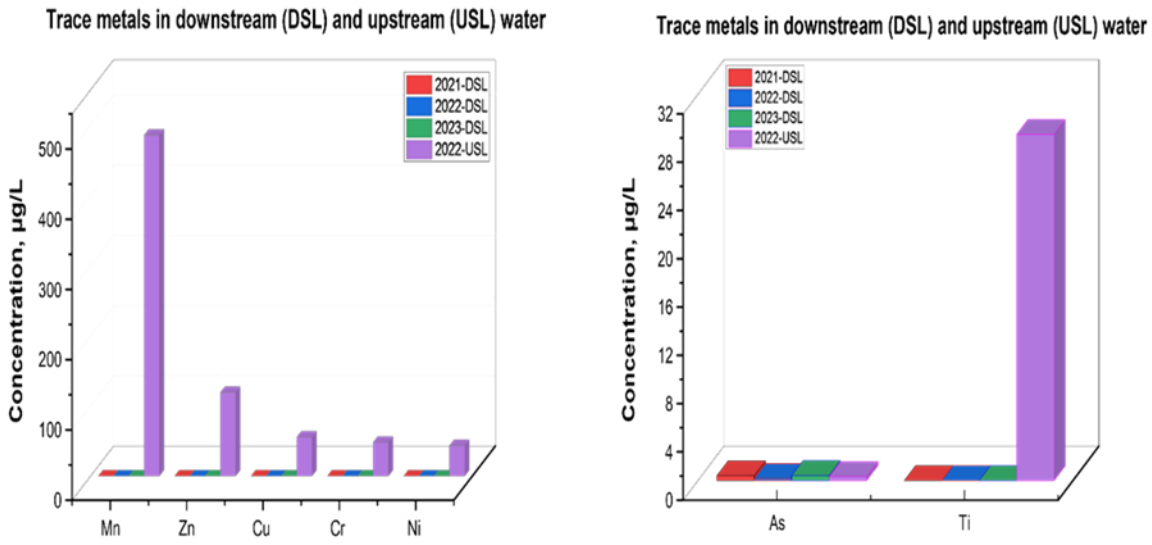


Figure A.5 Mean concentration of trace metals dominant in water

APPENDIX B: Water Quality Classification

Table B.1 The unit weight assigned to each of the physicochemical parameters utilized in calculating the WQI

Parameters	WHO desirable limit (WHO 2019)	Weight (w_i)	Relative weight (W_i)
pH	8,5	4	0,068
EC	400	5	0,085
TDS	1000	4	0,068
F^-	1,5	4	0,068
Cl^-	300	3	0,051
NO_3^-	50	5	0,085
SO_4^{2-}	250	5	0,085
Ca	100	3	0,051
K	20	2	0,034
Mg	50	3	0,051
Na	200	3	0,051
Fe	0,30	4	0,068
As	0,01	5	0,085
Mn	0,40	4	0,068
Cr	0,05	5	0,085
		$\sum w_i = 59$	$\sum W_i = 1.0$

Table B.2 Classification of water quality based on the WQI (Karakus, 2018)

WQI level	Classification
<50	Excellent water
50-100	Good water
100-200	Poor water
200-300	Very poor water
>300	Water unsuitable for drinking

Table B.3 Classification of water based on Sodium % (Ravikumar et al., 2013)

Na (%)	Water class
<20	Excellent
20-40	Good
40-60	Permissible
60-80	Doubtful
>80	Unsuitable

Table B.4 Parameters of water quality and their impact on human health, (WHO, 2019; Ogoamaka and Osarumwense, 2022)

Parameters	Unit	Maximum Allowable according to WHO	Effects on Health
pH	-	6.5-8.5	Low-pH water is characterized by acidity, softness, and the potential for corrosiveness. Such water has the capacity to release metal ions like iron, manganese, copper, lead, and zinc into the aquifer, plumbing fixtures, and pipes. This water may also contain elevated levels of toxic metals, which can pose cancer risks and harm to health.
Total Dissolved Solids	mg/L	1000	Water with TDS concentration exceeding 1000 mg/L can lead to gastrointestinal discomfort.
Conductivity	µS/cm	400	None
Total Hardness (as $CaCO_3$)	mg/L	150	Water surpassing the 300 mg/L threshold is classified as extremely hard and can potentially contribute to heart disease and kidney-related issues.
Arsenic (As)	mg/L	0.01	Skin cancer, lung cancer, bladder cancer, kidney cancer, diabetes, gastrointestinal issues, cardiovascular disorders, swift poisoning, and fatality.
Chloride (Cl)	mg/L	300	None
Chromium (Cr^{6+})	mg/L	0.05	Cancer
Copper (Cu)	mg/L	2	Gastrointestinal disturbance: Elevated copper levels in water sources can result in symptoms such as nausea, diarrhoea, and irritation of the eyes, nose, and mouth. In severe cases, it may even progress to kidney failure and potentially be fatal

Parameters	Unit	Maximum Allowable according to WHO	Effects on Health
Fluoride (F^-)	mg/L	1.5	Fluorosis leads to morbidity in skeletal tissues, affecting bones and teeth. Dental caries, or tooth decay, occurs due to the absence of fluoride in drinking water.
Magnesium (Mg)	mg/L	50	Elevated levels of magnesium in drinking water can induce a laxative effect and lead to osmotic diarrhoea.
Manganese (Mn)	mg/L	0.4	Disorder of the nervous system.
Nickel (Ni)	mg/L	0.07	Potentially developing carcinogenic properties.
Nitrate (NO_3^-)	mg/L	50	Cyanosis and asphyxia, known as "blue-baby syndrome," can occur in infants below three months of age.
Sodium (Na)	mg/L	200	Elevated levels of sodium in water can impact individuals with heart, kidney, or circulatory conditions, potentially leading to increased blood pressure.
Sulphate (SO_4^{2-})	mg/L	250	An excessive quantity of sulphate in water can induce laxative effect on those who consume it.
Zinc (Zn)	mg/L	3	High levels of zinc exposure can lead to cholesterol and anaemia issues in adults, as well as nausea and vomiting in children.

APPENDIX C: Water Sampling Period

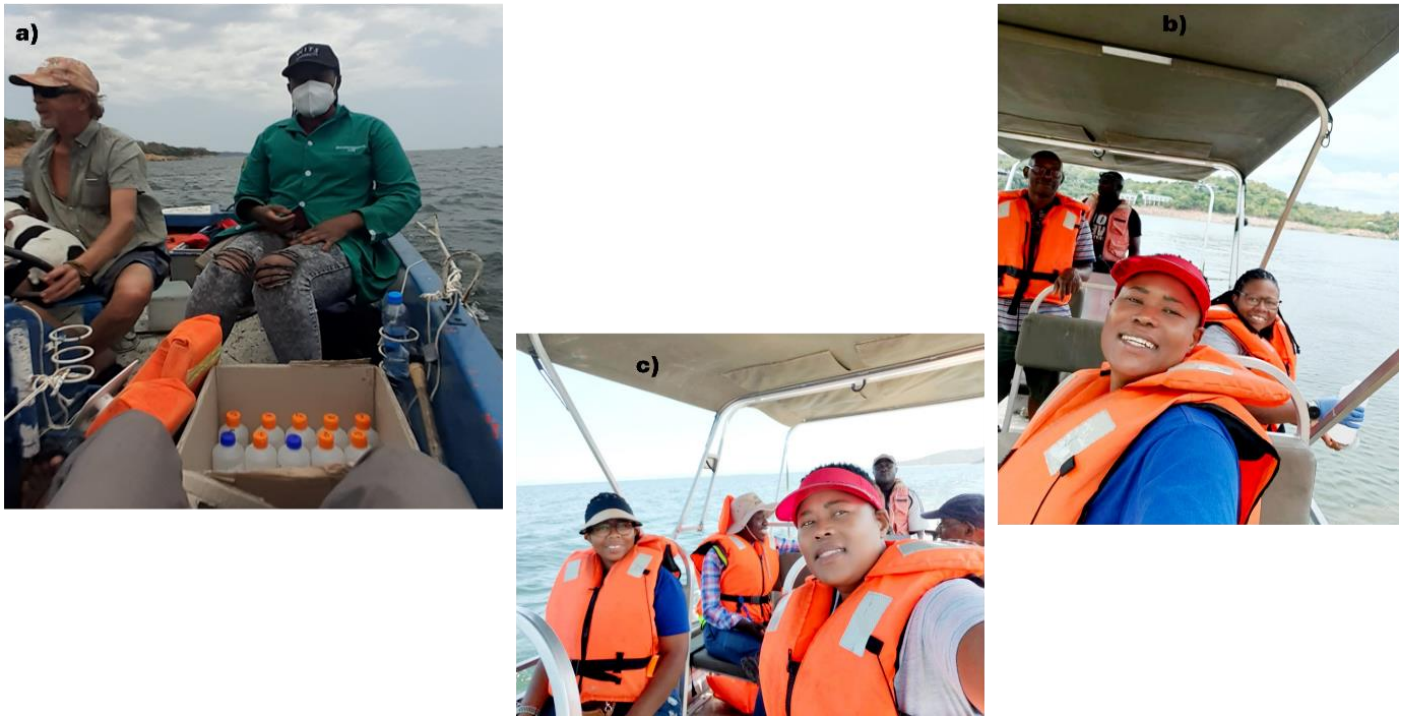


Figure C.1 Downstream water sampling in Siavonga, a) October 2021, b) and c) April 2023



Figure C.2 Water sampling, a), b) and c) upstream in July 2022 and d) downstream in July 2022



Figure C.3 Some of the few sampling areas, Kapenta Boats Harbour (Top Left), Siavonga market (Top Right), Fish farming (Bottom Left), and Dam wall (Bottom Right)

APPENDIX D: WELCOME (Water, Energy, Livelihoods and eCOsysteM hEalth) Project Workshop



Figure D.1 WELCOME Project workshop with Zambian stakeholders in October 2021 and August 2022