

**UNIVERSITY OF EDUCATION, WINNEBA**



**ASSESSMENT OF HEAVY METAL CONTAMINATION IN DRINKING  
WATER SOURCES AT TAPA ABOTOASE COMMUNITY IN THE OTI  
REGION OF GHANA**



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**UNIVERSITY OF EDUCATION, WINNEBA**



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WATER SOURCES AT TAPA ABOTOASE COMMUNITY IN THE OTI  
REGION OF GHANA**



**A thesis submitted to the school of graduate studies in  
partial fulfilment of the requirement for the award of  
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(Integrated Science Education)**

**DEPARTMENT OF INTEGRATED SCIENCE EDUCATION  
FACULTY OF SCIENCE EDUCATION  
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**OCTOBER, 2025**

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## DECLARATION

### Candidate's Declaration

I, **Richard Holy Mawuko**, here by declare that this thesis, with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or whole, for another degree elsewhere.

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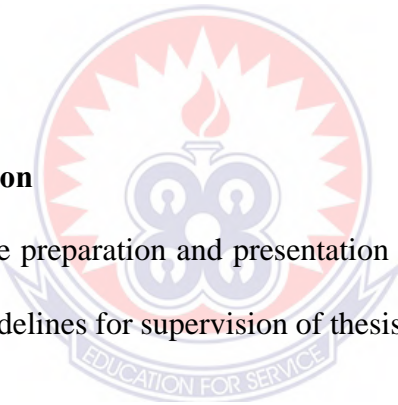
### Supervisor's Declaration

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of thesis as laid down by the University of Education, Winneba.

Supervisor' Name: Prof. Charles Kwesi Koomson

Signature: .....

Date: .....



## **DEDICATION**

I dedicated this work to my lovely wife Mrs. Vicentia Otimpong Mawuko for her dedicated support and encouragement.



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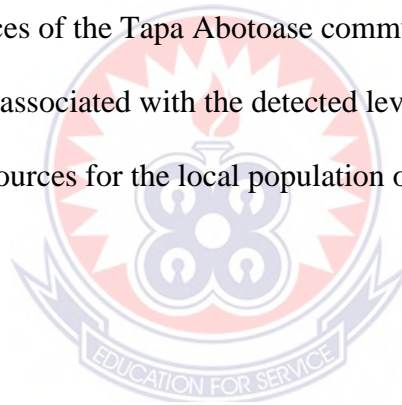
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## LIST OF ABBREVIATIONS/ACRONYMS

<b>AAS</b>	Atomic Absorption Spectroscopy
<b>ACT</b>	Act (Legal Document)
<b>APHA</b>	American Public Health Association
<b>ASGM</b>	Artisanal and Small-Scale Gold Mining
<b>BOD</b>	Biochemical Oxygen Demand
<b>BW</b>	body weight
<b>Cd</b>	Cadmium
<b>Cr</b>	Chromium
<b>Cu</b>	Copper
<b>CWSA</b>	Community Water and Sanitation Agency
<b>DO</b>	Dissolved Oxygen
<b>EC</b>	Electrical Conductivity
<b>Ed</b>	Exposure dose
<b>EPA</b>	Environmental Protection Agency
<b>GMSWR</b>	Ghana Ministry of Sanitation and Water Resources
<b>Hg</b>	Mercury
<b>HQ</b>	hazard quotient
<b>ICP-MS</b>	Inductively Coupled Plasma Mass Spectrometry
<b>ICP-OES</b>	Inductively Coupled Plasma Optical Emission Spectrometry
<b>IR</b>	ingestion rate or water intake rate
<b>IWRM</b>	Integrated Water Resources Management
<b>MESTI</b>	Ministry of Environment, Science, Technology, and Innovation
<b>MWRWH</b>	Ministry of Water Resources, Works, and Housing

<b>NEP</b>	National Environmental Policy
<b>NGO</b>	Non-Governmental Organization
<b>Ni</b>	Nickel
<b>NWP</b>	National Water Policy
<b>ORP</b>	Oxidation-Reduction Potential
<b>Pb</b>	Lead
<b>QA/QC</b>	Quality Assurance/Quality Control
<b>Rfd</b>	reference dose
<b>Sf</b>	Slope factor
<b>TDS</b>	Total Dissolved Solids
<b>UNDP</b>	United Nations Development Programme
<b>UNEP</b>	United Nations Environment Programme
<b>UNICEF</b>	United Nations Children's Fund
<b>USEPA</b>	United States Environmental Protection Agency
<b>WHO</b>	World Health Organization
<b>WRC</b>	Water Resources Commission
<b>WSSSP</b>	Water Supply and Sanitation Sector Programme

## ABSTRACT

Access to safe drinking water is critical to human health and sustainable development. This study aimed to identify heavy metals present in the drinking water sources at Tapa Abotoase Community in the Oti Region of Ghana. The Abotoase Community relies primarily on the Volta River and boreholes for domestic water supply. The study employed an experimental research design using a quantitative analytical approach to identify heavy metals, to examine their concentration levels and to evaluate their potential health risks to consumers. The water samples were collected from eight sampling points, comprising five boreholes and three points along the Volta River (upstream, midstream, and downstream). Sampling was conducted twice during the dry season and twice during the wet season, making a total of 32 samples. The samples were analyzed in the laboratory following the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Heavy metals such as iron (Fe), lead (Pb), copper (Cu), cadmium (Cd), mercury (Hg), and arsenic (As) were identified. The results were compared with the World Health Organization (WHO, 2022) and Ghana Water Quality Standards to determine compliance levels. The findings revealed that concentrations of some heavy metals, such as iron and lead, exceeded the WHO permissible limits in certain sampling locations, indicating localized contamination likely associated with anthropogenic activities such as waste disposal, small-scale mining, and agricultural runoff. Seasonal analysis also revealed that concentrations of most heavy metals were higher during the wet season compared to the dry season. However, only mercury (Hg) exhibited a statistically significant variation ( $p = 0.016$ ; Cohen's  $d = 0.903$ ), suggesting that its mobilization was strongly influenced by rainfall and runoff. Health risk assessment showed potential non-carcinogenic risks for children due to prolonged exposure. The study concluded that while most water sources in the area remain suitable for domestic use, periodic monitoring and proper management are required to prevent health hazards. It was recommended that local authorities strengthen water quality surveillance, promote safe waste disposal practices, and educate residents on household water treatment methods. Further studies should also investigate other potential contaminants such as microbial pathogens, organic pollutants, and emerging contaminants that may affect drinking water quality in the area.

## CHAPTER ONE

### INTRODUCTION

#### 1.0 Overview

This section of the study highlights the background that informed the research. It discusses the problem, purpose of the study, the research objectives and questions that had arisen from the objectives. The organisation of this report for the subsequent chapters are outlined at the end of this section.

#### 1.1 Background to the Study

Heavy metals are metallic elements with high atomic weights and densities that are at least five times greater than that of water. They are naturally occurring in the earth's crust but can become toxic to living organisms when present in elevated concentrations. Heavy metals commonly associated with water contamination include lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), and nickel (Ni) (Ali *et al.*, 2023). These metals are non-biodegradable, persist in the environment, and can bioaccumulate in the food chain, posing significant health risks. Heavy metals, which are defined as metallic elements with relatively high atomic weights and densities significantly higher than that of water, include substances such as lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni), and copper (Cu), and are among the major environmental pollutants with significant implications for public health (Alloway, 2013).

To comprehensively assess water quality, it is necessary to evaluate physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), turbidity, temperature, and dissolved oxygen (DO). These physicochemical parameters are crucial as they provide insights into the

water's chemical balance, potential contaminants, and overall ecosystem health (Adekunle *et al.*, 2007). Studies have shown that heavy metals pose significant health risks, including neurological effects such as cognitive deficits, memory loss, attention disorders, and developmental issues, including reduced intelligent quotient (IQ) and developmental delays in children (WHO, 2017). These parameters can be influenced by various sources, including agricultural runoff, industrial discharges, wastewater effluents, and natural processes such as weathering and erosion (WHO, 2017). Heavy metals such as lead, mercury, arsenic, and cadmium persist in the environment and accumulate in living organisms over time, posing long-term ecological and human health risks. Their non-biodegradable nature makes them particularly hazardous, as they remain in water, soil, and biological systems for years, gradually entering the food chain and accumulating in vital organs of humans and animals (Cabrera *et al.*, 2010).

According to Asare-Donkor *et al.*, (2016), systematic monitoring and risk assessment of drinking water sources are crucial for identifying contamination hotspots and implementing control measures. They further emphasized that even low concentrations of heavy metals, if consumed continuously, can lead to chronic health conditions such as kidney damage, neurological disorders, and developmental issues in children. In response to growing concerns over water safety and contamination, particularly from heavy metals, the Ghanaian government has implemented several policies and regulatory frameworks aimed at improving water quality and accessibility. One of the key frameworks is the National Water Policy (NWP), which provides strategic direction for sustainable water resources management and aims to enhance equitable access to clean water across the country (GMSWR, 2021). In addition, the Community Water and Sanitation Agency (CWSA) has spearheaded efforts to improve rural water supply systems and sanitation infrastructure, particularly in underserved areas (GMSWR,

2021). Complementing these efforts, the Water Supply and Sanitation Sector Programme (WSSSP) was launched to further expand access to safe drinking water and improve sanitation nationwide (GMSWR, 2021). Beyond governmental efforts, non-governmental organizations (NGOs) and international development agencies have played a vital role in addressing water quality challenges.

Organizations such as the World Bank have supported initiatives involving water quality testing and public education to raise awareness about the health risks associated with heavy metal contamination (World Bank, 2020). Furthermore, NGOs such as WaterAid and World Vision have partnered with government institutions to monitor and improve water quality through the testing of key physicochemical parameters in both rural and urban water sources (WaterAid, 2020). A pollutant is any substance that, when introduced into the environment, causes harm or undesirable effects to living organisms and ecosystems. Pollutants may be physical, chemical, or biological, with heavy metals classified as chemical pollutants due to their toxicity and persistence in water bodies (WHO, 2022). Pollution refers to the introduction of harmful substances into the environment, causing adverse effects on human health, ecosystems, and natural resources. In the context of water, pollution occurs when contaminants such as heavy metals exceed safe thresholds, rendering water unfit for consumption or use (UNICEF, 2023). Industrial, agricultural, and mining wastes are major contributors to heavy metal contamination, as these wastes often contain significant concentrations of toxic metals that leach into water sources (Mensah *et al.*, 2023). Access to clean and safe drinking water is a fundamental human right and a critical determinant of public health; however, drinking water quality is increasingly threatened by contamination from both natural and anthropogenic activities (WHO, 2022).

Heavy metal contamination of drinking water sources is a growing global concern, particularly in developing countries where regulatory frameworks and enforcement mechanisms are often weak (Ali *et al.*, 2023). Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are toxic at low concentrations and can accumulate in the human body over time, leading to chronic health issues including kidney damage, neurological disorders, and cancers (Kumar *et al.*, 2022). In Ghana, water quality issues have attracted considerable attention due to their implications for public health and socio-economic development. Communities that rely on surface water sources such as rivers, lakes, and streams are particularly vulnerable to heavy metal contamination, often arising from mining, agricultural activities, and improper waste disposal (Opoku *et al.*, 2023). The River Volta, one of Ghana's major water bodies, has been identified as a contamination hotspot due to its proximity to industrial and agricultural activities (Mensah *et al.*, 2023).

Physicochemical parameters remain critical indicators of water quality, encompassing physical and chemical properties that determine water suitability for human consumption. Key parameters include pH, turbidity, temperature, dissolved oxygen, electrical conductivity, and concentrations of specific ions such as nitrates, chlorides, and sulfates (WHO, 2022). These parameters influence both the aesthetic quality of water and the mobility and bioavailability of pollutants, including heavy metals. For example, low pH levels can increase the solubility of metals such as lead and cadmium, thereby enhancing their toxicity (Kumar *et al.*, 2022). In communities such as Tapa Abotoase, where residents depend on untreated surface and groundwater sources, monitoring physicochemical parameters is essential for assessing water quality. Deviations from recommended limits often indicate contamination from anthropogenic activities such as agriculture and mining (Boateng *et al.*, 2022). High turbidity may

result from agricultural runoff carrying sediments, while elevated electrical conductivity may indicate contamination from industrial discharges.

Governments and non-governmental organizations (NGOs) therefore play critical roles in ensuring access to safe drinking water, particularly in areas where water quality is compromised. In Ghana, policies such as the National Water Policy (NWP) and the Water Resources Commission Act (Act 522 of 1996) provide a framework for sustainable water resource management and protection (Ministry of Water Resources, Works, and Housing, 2023). These policies emphasize integrated water resource management (IWRM) and promote initiatives to monitor and mitigate contamination in drinking water sources. However, enforcement of these policies is often challenged by limited resources, inadequate monitoring, and weak institutional coordination, especially in rural communities such as Tapa Abotoase (Mensah *et al.*, 2023).

NGOs and international agencies have complemented governmental efforts by supporting water quality testing, community education, and infrastructure development. Organizations such as the World Health Organization (WHO), WaterAid, and the United Nations Children's Fund (UNICEF) have been instrumental in raising awareness about the risks associated with contaminated water and improving access to safe drinking water (UNEP, 2010). Despite these efforts, significant gaps remain in addressing heavy metal contamination, which requires more targeted and localized interventions. Tapa Abotoase, located in the Oti Region of Ghana, is one such community that relies heavily on the River Volta and boreholes for drinking water due to limited access to treated municipal water systems. However, these water sources are increasingly threatened by agricultural runoff, improper waste disposal, and small-scale mining activities in surrounding areas, which introduce heavy metals into the aquatic

environment (Boateng et al., 2022). The presence of these contaminants poses serious health risks to residents, particularly children and pregnant women, who are more vulnerable to the toxic effects of heavy metals (Yeboah, *et al.*, 2022).

## **1.2 Statement of the Problem**

Access to safe drinking water is a fundamental human right and a critical determinant of public health. However, in the Tapa Abotoase community, the safety of available drinking water sources remains a major concern. During a visit to the community, noticeable changes in the colour of water from boreholes and the nearby River Volta were observed, raising concerns about possible contamination. Community members, including children and the elderly, were also seen relying directly on these untreated water sources for drinking and domestic use, increasing potential health risks.

Agricultural activities along the riverbanks further heighten concerns about water quality in the community. The extensive use of herbicides, pesticides, and other agrochemicals, particularly during the rainy season, increases the likelihood of runoff and leaching into surface and groundwater sources. These practices create conditions that may facilitate the accumulation of heavy metals in drinking water over time, posing health risks through prolonged exposure. Such observations underscore the need for a systematic assessment of drinking water quality in Tapa Abotoase, with specific attention to heavy metal contamination.

Prolonged exposure to heavy metals in drinking water is associated with serious health effects, including neurological disorders, kidney damage, developmental problems in children, and increased cancer risks (WHO, 2022). Vulnerable groups such as pregnant women and children are particularly at risk due to the long-term consequences of exposure during critical developmental stages (Yeboah, 2023). Beyond health

implications, contaminated water also contributes to increased healthcare costs and reduced socio-economic productivity, undermining sustainable development efforts (UNDP, 2022).

Although Ghana has established policies such as the National Water Policy to promote safe water access and integrated water resource management, enforcement remains weak in many rural communities (MWRWH, 2023). While NGOs and international agencies provide support, these interventions are often limited in coverage and sustainability, highlighting the need for location-specific data to guide effective decision-making (Ali *et al.*, 2023).

Heavy metals such as lead (Pb), mercury (Hg), and arsenic (As) are among the most toxic water contaminants due to their persistence and bioaccumulative nature. Exposure to these metals has been linked to neurological damage, kidney dysfunction, and various cancers (Ali *et al.*, 2023). Despite these risks, there is limited empirical data on the concentrations of these heavy metals in the drinking water sources of Tapa Abotoase, constraining accurate health risk assessment and targeted intervention planning (Mensah *et al.*, 2023).

Anthropogenic activities including agricultural runoff, improper waste disposal, and small-scale mining in surrounding areas are potential contributors to heavy metal contamination in the River Volta and local boreholes (Opoku *et al.*, 2023). Rural communities such as Tapa Abotoase remain underrepresented in water quality studies despite their heavy dependence on untreated water sources. This gap necessitates focused research to generate evidence that can inform public health protection and water resource management.

To fill this gap, this study aimed to identify heavy metals present in the drinking water sources and systematically evaluate their concentrations in the drinking water sources of Tapa Abotoase using advanced analytical techniques, including Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to provide critical data for public health interventions and the development of effective water quality management strategies tailored to the specific needs of the Tapa Abotoase community.

### **1.3 Purpose of the Study**

The purpose of this study is to determine the presence and levels of heavy metals in the drinking water sources of Tapa Abotoase community in the Oti Region of Ghana.

### **1.4 Objectives of the Study**

The study was guided by the following objectives. Specifically, the study seeks to:

- 1.** identify heavy metals present in the drinking water sources of the Tapa Abotoase community.
- 2.** examine the concentration levels of the heavy metals present in the drinking water sources of the Tapa Abotoase community.
- 3.** investigate the seasonal variations in heavy metal concentrations in the drinking water sources of the Tapa Abotoase community in one year.
- 4.** evaluate the potential health risks associated with the detected level of the heavy metals for the local population using USEPA standard guideline values.

### **1.5 Research Questions**

The following research questions were formulated to guide the study:

1. which heavy metals are present in the drinking water sources of the Tapa Abotoase community?
2. what are the concentration levels of the heavy metals present in the drinking water sources of the Tapa Abotoase community?
3. what are the seasonal variations in the concentration of the heavy metals in the drinking water sources of the Tapa Abotoase community?
4. what are the potential health risks associated with the detected level of the heavy metals for the local population using the USEPA standards guideline values?

### **1.6 Significance of the Study**

The outcome of this study would be significant for the following:

1. this study will provide essential data on the quality of drinking water in the Tapa Abotoase community and highlighting areas with high contamination levels.
2. again, the findings will support local authorities and policymakers in developing targeted interventions to improve water quality and protect public health of the people in the Tapa Abotoase community.
3. additionally, this research will contribute to the broader understanding of environmental health risks in the Biakoye District and similar areas.
4. finally, the study will evaluate the potential health risks associated with the detected levels of heavy metals, offering valuable insights for community awareness and preventive health measures to mitigate exposure risks.

### **1.7 Delimitations of the Study**

- The study focused exclusively on drinking water sources within the Tapa Abotoase community.
- Only quantitative approach was employed for this study relying on numerical data and laboratory analysis.
- Only heavy metals were analyzed, excluding other possible contaminants

### **1.8 Limitations of the Study**

- The study was limited by financial constraints, which affected the smooth conduct of laboratory analysis and fieldwork activities.
- Again, the distance between the sampling sites and the laboratory made the transportation of samples difficult and time-consuming.
- Furthermore, weather fluctuations, especially during rainy the rainy season, affected accessibility to some sampling areas that delayed data collection.

### **1.9 Organisation of the Study**

The chapter two of this study covers existing relevant literature. Chapter three discusses the methodology which comprises the design of the study, study area, populations, sample size and sampling technique, instruments and data collection procedure as well as the method of data analysis. Chapter four presents the results and the discussions of the findings whereas chapter five presents the summary of the key findings of the study. It also entailed conclusion, recommendations and suggestions for further studies

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.0 Overview**

This chapter present a review of related literature that underpins the study.

#### **2.1 Heavy Metals in Drinking Water sources**

Heavy metals are natural components of the Earth's crust and are introduced into water sources through both natural and anthropogenic activities. These metals, including lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), and chromium (Cr), are considered toxic when they accumulate in water sources at concentrations exceeding permissible limits (Ali *et al.*, 2023). The presence of these heavy metals in drinking water sources is a critical concern because they are non-biodegradable, persist in the environment, and bioaccumulate in the food chain, posing significant risks to human health and ecosystems (Mensah *et al.*, 2023).

Natural processes such as weathering of metal-bearing rocks and volcanic activity can contribute to the release of heavy metals into water sources (Kumar *et al.*, 2022). However, human activities are the dominant contributors to heavy metal contamination in drinking water. Key sources include agricultural runoff containing fertilizers and pesticides, industrial discharges, mining operations, and improper waste disposal (Mensah *et al.*, 2023). These activities introduce metals like lead, mercury, and arsenic into water bodies, often in concentrations harmful to both humans and aquatic life.

Lead contamination in water is primarily attributed to corrosion of plumbing materials, industrial effluents, and atmospheric deposition from mining and smelting activities (Kumar *et al.*, 2022). Once ingested, lead can accumulate in the bones, liver, and

kidneys, causing neurological and developmental issues, particularly in children (Boateng *et al.*, 2022). The World Health Organization (WHO) recommends a maximum allowable concentration of 10 µg/L for lead in drinking water, but levels exceeding this limit have been reported in many parts of Ghana, including rural communities (WHO, 2022).

Mercury contamination often results from artisanal and small-scale gold mining (ASGM) activities, where mercury is used to extract gold. This practice leads to direct mercury release into water bodies, where it is converted to methylmercury, a highly toxic form that can bioaccumulate in fish and other aquatic organisms (Mensah *et al.*, 2023). Long-term exposure to mercury through contaminated water and food can cause severe damage to the nervous system and kidneys.

Arsenic contamination is frequently associated with groundwater sources, particularly in areas with arsenic-rich geological formations. It can also result from industrial processes and the use of arsenic-containing pesticides in agriculture (Ali *et al.*, 2023). Chronic exposure to arsenic has been linked to skin lesions, cardiovascular diseases, and several cancers. The WHO guideline value for arsenic in drinking water is 10 µg/L, but studies indicate that levels in some regions exceed this limit, necessitating urgent intervention (UNICEF, 2023).

Cadmium enters water bodies primarily through industrial discharges, electroplating, and runoff from agricultural lands treated with phosphate fertilizers. Even at low concentrations, cadmium is toxic to human health, causing kidney dysfunction, skeletal damage, and cardiovascular problems (Kumar *et al.*, 2022).

Chromium contamination, particularly hexavalent chromium (Cr<sup>6+</sup>), arises from industrial activities such as leather tanning and electroplating. It is highly toxic and

classified as a human carcinogen. Chronic exposure can lead to skin ulcers, respiratory issues, and increased risk of lung cancer (Opoku *et al.*, 2023).

In Ghana, the presence of heavy metals in drinking water is a growing concern, especially in rural areas where reliance on untreated water sources is prevalent. Studies by Mensah *et al.*, (2023) reported elevated levels of lead, arsenic, and mercury in the Volta Basin, posing significant health risks to communities. Similarly, Boateng *et al.*, (2022) highlighted the impact of agricultural runoff and mining activities on water quality in the Oti Region, where the Tapa Abotoase community is located. Despite these findings, data on the specific concentrations of heavy metals in drinking water sources in Tapa Abotoase remain scarce, leaving a critical gap in understanding the extent of contamination and its health implications.

Efforts to mitigate heavy metal contamination in drinking water have been limited by inadequate monitoring, lack of infrastructure for advanced water treatment, and weak enforcement of environmental regulations. This underscores the need for comprehensive studies to quantify heavy metal levels and assess their seasonal variations, as well as the associated health risks. Advanced analytical techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) are increasingly being recommended for accurate detection and quantification of heavy metals in water sources (Ali *et al.*, 2023). These methods can provide the data necessary for developing targeted interventions and policies to protect water quality and public health.

## **2.2 Sources and Pathways of Heavy Metal Contamination**

Heavy metal contamination in drinking water sources arises from a variety of natural and anthropogenic activities. These metals can enter water systems through multiple

pathways, including direct discharge from industrial activities, runoff from agricultural lands, leaching from mining sites, and natural weathering processes (Ali *et al.*, 2023). Understanding these sources and pathways is critical for designing effective mitigation strategies to safeguard water quality and public health (Mensah *et al.*, 2023).

### **2.2.1 Natural Sources of Heavy Metal Contamination**

Heavy metals are naturally present in the Earth's crust and can enter water systems through geological processes such as weathering, erosion, and volcanic activity. These natural pathways contribute to baseline levels of metals like arsenic, lead, and cadmium in groundwater and surface water. For example, groundwater in regions with arsenic-rich rock formations often exhibits elevated arsenic concentrations due to geochemical interactions (Kumar *et al.*, 2022). Similarly, the dissolution of metal-bearing minerals in sedimentary and igneous rocks can introduce heavy metals into aquifers and surface water bodies (Ali *et al.*, 2023).

Natural processes, while contributing to heavy metal contamination, are often exacerbated by human activities, which amplify metal concentrations in water sources beyond safe thresholds. This synergy between natural and anthropogenic factors makes it challenging to isolate the exact sources of contamination in affected communities like Tapa Abotoase.

Heavy metals are naturally occurring elements found in the Earth's crust, and they can enter water bodies through a variety of geogenic processes. Unlike anthropogenic contamination, which results from human activities such as mining or industrial discharge, natural sources of heavy metals are linked to the geological and geochemical characteristics of an environment. Understanding these natural contributions is essential,

as they often form the baseline concentration of metals in water bodies, against which pollution from human activities is assessed (Alloway, 2013).

One of the primary natural sources of heavy metals in water is rock weathering. During the physical, chemical, or biological breakdown of rocks and soils, trace metals such as arsenic, lead, cadmium, and chromium can be released into surface water and groundwater systems. For instance, the weathering of sulfide-bearing minerals, such as pyrite ( $\text{FeS}_2$ ), often leads to the release of iron, arsenic, and other associated metals into water sources (Smedley and Kinniburgh, 2017).

Another natural pathway is through volcanic activity. Volcanic eruptions emit large amounts of gases, ash, and particulate matter containing heavy metals such as mercury, cadmium, lead, and arsenic. These contaminants are deposited onto land and water surfaces either directly or through atmospheric transport and precipitation (Nguyen *et al.*, 2023). Volcanic geothermal systems, including hot springs and fumaroles, also release metal-laden fluids into nearby water bodies, contributing to localized heavy metal contamination.

Soil erosion and sediment mobilization represent another natural mechanism. During intense rainfall or seasonal flooding, sediments enriched with trace metals from mineralized zones are washed into rivers, lakes, and reservoirs. The mobility of these sediments can significantly increase the concentration of metals in aquatic environments, particularly in areas where soils naturally contain higher levels of metals such as chromium, cobalt, or nickel (Gaillardet *et al.*, 2014).

In addition, atmospheric deposition of dust from arid and semi-arid regions can serve as a natural source of heavy metals in water. Wind-blown dust particles, often containing

iron, manganese, and zinc, eventually settle into rivers and lakes, influencing the geochemistry of these ecosystems. For example, Saharan dust storms have been shown to deposit considerable amounts of trace metals into the Atlantic Ocean and nearby freshwater systems (Goudie and Middleton, 2006).

It is important to note that the bioavailability and toxicity of heavy metals from natural sources are influenced by physicochemical parameters such as pH, redox potential, and temperature. Even when metals are naturally derived, changes in environmental conditions can alter their solubility and increase the risk of exposure to humans and aquatic organisms (Tchounwou *et al.*, 2012).

### **2.2.2 Anthropogenic Sources of Heavy Metal Contamination**

Industries such as mining, electroplating, tanning, and manufacturing are significant contributors to heavy metal contamination. Effluents from these industries often contain metals such as lead, chromium, and cadmium, which are discharged directly into nearby water bodies without adequate treatment (Mensah *et al.*, 2023). These discharges not only elevate the concentration of heavy metals but also alter the physicochemical parameters of the water, further facilitating the mobility and bioavailability of the metals.

Small-scale and artisanal gold mining, which is prevalent in many parts of Ghana, including areas near Tapa Abotoase, is a major source of mercury contamination. Mercury is used in gold extraction processes and is often released into water bodies, where it is transformed into its more toxic organic form, methylmercury (Boateng *et al.*, 2022). Additionally, mining tailings and waste rock piles can leach heavy metals such as arsenic, lead, and cadmium into surrounding water systems through rainwater runoff and groundwater infiltration. The use of fertilizers, pesticides, and herbicides in

agriculture introduces heavy metals such as arsenic, cadmium, and chromium into water systems. These agrochemicals often contain trace amounts of heavy metals, which are washed into rivers, lakes, and groundwater through surface runoff during rainfall (Opoku *et al.*, 2023). Agricultural runoff is particularly concerning in areas where farming activities are conducted near water sources, as it not only contaminates the water but also affects aquatic ecosystems. Unregulated disposal of solid and liquid waste, including e-waste, is a growing concern for water quality. Electronic waste, for instance, contains metals like lead, mercury, and cadmium, which can leach into soil and water sources from landfills and dumpsites. Similarly, untreated domestic and municipal wastewater often contains heavy metals that find their way into nearby rivers and streams (Ali *et al.*, 2023).

Urbanization contributes to heavy metal contamination through construction activities and urban runoff. Materials used in construction, such as paints, pipes, and roofing, often contain lead and other metals that leach into water systems over time. Urban runoff during rainfall events also carries heavy metals from roads, vehicles, and industrial areas into surface water bodies (Kumar *et al.*, 2022).

### **2.2.3 Pathways of Heavy Metal Contamination in Water Systems**

Heavy metal contamination in water sources is significantly influenced by anthropogenic activities, which introduce high concentrations of toxic metals into the environment. These activities, driven by human development and industrialization, often exacerbate the natural occurrence of heavy metals and lead to severe environmental and public health challenges (Mensah *et al.*, 2023). The primary anthropogenic contributors to heavy metal contamination include industrial processes,

mining activities, agricultural practices, urbanization, and improper waste disposal (Opoku *et al.*, 2023).

Erosion of contaminated soil further contributes to this process, carrying sediment-bound metals into surface water bodies (Mensah *et al.*, 2023).

Leaching occurs when heavy metals from solid waste, industrial residues, and mining tailings dissolve in rainwater and percolate into the soil. This process allows the metals to infiltrate into groundwater systems, making them a significant source of contamination for communities relying on wells and boreholes (Boateng *et al.*, 2022).

Heavy metals released into the atmosphere from industrial activities, mining, and combustion processes settle onto land and water surfaces through wet and dry deposition. This pathway is particularly relevant for metals like mercury, which are emitted into the air during gold mining and coal combustion (Opoku *et al.*, 2023). In water bodies, heavy metals often accumulate in sediments. Disturbances caused by natural events like floods or human activities such as dredging can resuspend these sediments, releasing the metals back into the water column (Ali *et al.*, 2023).

Heavy metals can enter aquatic ecosystems and accumulate in the tissues of plants and animals. Through the food chain, these metals can reach humans, posing significant health risks. Methylmercury, for example, bioaccumulates in fish, which are then consumed by humans (Kumar *et al.*, 2022).

### **2.3 Anthropogenic activities associated with heavy metal contamination**

Industries such as electroplating, battery manufacturing, paint production, and leather tanning release substantial quantities of heavy metals into the environment. Effluents from these industries often contain metals like lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), which are discharged into nearby rivers, lakes, or groundwater without

adequate treatment (Ali *et al.*, 2023). Industrial discharges not only elevate heavy metal concentrations in water sources but also alter the physicochemical properties of the water, facilitating metal mobility and bioavailability (Kumar *et al.*, 2022). The high cost of advanced waste treatment systems and weak regulatory enforcement in developing regions further exacerbate industrial contributions to heavy metal pollution.

Again, anthropogenic activities are the primary contributors to heavy metal contamination in water sources. These activities, which include mining, industrial processes, agricultural practices, urbanization, and improper waste disposal, significantly elevate the levels of toxic metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) in water systems. Their impact is particularly severe in developing countries like Ghana, where regulatory frameworks and enforcement mechanisms are often inadequate (Mensah *et al.*, 2023).

### **2.3.1 Mining and Heavy Metal Contamination**

Mining activities, particularly artisanal and small-scale gold mining (ASGM), are a leading source of heavy metal contamination in Ghana. Mercury is widely used in ASGM for gold extraction, leading to its release into rivers and streams. Once in the aquatic environment, mercury is converted into methylmercury, a highly toxic form that bioaccumulates in fish and shellfish (Boateng *et al.*, 2022). Arsenic is another heavy metal commonly associated with mining due to its natural presence in ore deposits. Opoku *et al.*, (2023) reported that mining activities in Ghana's Oti Region have resulted in elevated arsenic and mercury concentrations in nearby water sources, often exceeding World Health Organization (WHO) permissible limits. The unregulated nature of many mining operations exacerbates this problem, as tailings and waste materials are often disposed of directly into water bodies without treatment.

### **2.3.2 Industrial Discharges**

Industries such as electroplating, tanning, and chemical manufacturing release significant quantities of heavy metals into the environment. Effluents from these industries often contain high levels of cadmium, chromium, and nickel, which contaminate nearby water sources when untreated or inadequately treated effluents are discharged into rivers and streams (Ali *et al.*, 2023). Chromium, particularly in its hexavalent form, is a common pollutant from tanning and electroplating industries and poses significant health risks due to its carcinogenic properties. Nguyen *et al.*, (2023) highlighted that, industrial effluents are the major source of water contamination in urban areas, where high concentrations of heavy metals accumulate due to poor wastewater management systems.

### **2.3.3 Agricultural Practices**

Agricultural activities contribute to heavy metal contamination primarily through the use of fertilizers, pesticides, and animal manure. These agrochemicals often contain trace amounts of metals such as arsenic, cadmium, and lead. During rainfall, surface runoff carries these metals into rivers, lakes, and groundwater systems, significantly impacting water quality (Boateng *et al.*, 2022). Additionally, irrigation using contaminated water sources further amplifies the cycle of heavy metal contamination. Osei *et al.*, (2022) observed that agricultural runoff is a significant contributor to cadmium and lead pollution in the Volta Basin, especially during the rainy season when erosion and runoff rates are highest.

### **2.3.4 Urbanization and Urban Runoff**

Urbanization leads to increased heavy metal contamination through construction activities, vehicular emissions, and improper waste disposal. Urban runoff during

rainfall events carries heavy metals such as lead and zinc from roads, parking lots, and construction sites into water bodies (Mensah *et al.*, 2023). Construction materials, including paints and pipes, often contain lead, which can leach into water systems over time. Nguyen *et al.* (2023) emphasized that the rapid urbanization in developing countries has significantly increased the pressure on water resources, as untreated wastewater and urban runoff introduce heavy metals into rivers and lakes.

### **2.3.5 Improper Waste Disposal**

Improper disposal of solid and liquid waste is another major anthropogenic activity contributing to heavy metal pollution. Landfills and dumpsites containing electronic waste (e-waste) release metals such as lead, cadmium, and mercury into soil and groundwater through leaching (Ali *et al.*, 2023). Municipal waste, including household cleaning products and batteries, also contains heavy metals that contaminate water sources when disposed of in unregulated landfills. In rural areas, the lack of waste management infrastructure exacerbates this issue, as open dumping and burning of waste are common practices.

### **2.3.6 Atmospheric Deposition**

Industrial activities, fossil fuel combustion, and mining also contribute to atmospheric deposition of heavy metals. Metals such as mercury and lead are released into the atmosphere as particulates or gases during industrial processes and are subsequently deposited onto land and water surfaces through rainfall (Nguyen *et al.*, 2023). This pathway is particularly significant in regions near industrial and mining operations, where atmospheric deposition can significantly elevate heavy metal concentrations in nearby water bodies.

### **2.3.7 Mining Activities**

Mining, particularly small-scale and artisanal mining, is a significant source of heavy metal contamination in many parts of the world, including Ghana. The use of mercury (Hg) in gold extraction and the improper disposal of mining tailings contribute to mercury pollution in water systems. Mercury from mining activities can convert to methylmercury in aquatic environments, a highly toxic form that bioaccumulates in fish and other organisms (Mensah *et al.*, 2023). In addition to mercury, arsenic (As) and lead (Pb) are commonly released from mining operations, either through direct discharge or leaching from waste rock piles and tailings during rainfall.

### **2.3.8 Agricultural Practices**

Agricultural activities introduce heavy metals into water sources through the use of fertilizers, pesticides, and herbicides. These agrochemicals often contain trace amounts of heavy metals like cadmium, arsenic, and copper, which can leach into nearby water systems through surface runoff (Opoku *et al.*, 2023). The impact of agricultural runoff is particularly pronounced during rainy seasons, where large volumes of water carry contaminants from farmlands into rivers and lakes. Additionally, the intensive use of livestock manure, which may contain elevated levels of metals from animal feed, further contributes to the contamination of water sources near agricultural areas.

### **2.3.9 Urbanization and Urban Runoff**

Urbanization leads to increased heavy metal contamination through construction activities, vehicular emissions, and urban runoff. Construction materials such as paints, roofing sheets, and pipes often contain heavy metals like lead and zinc, which leach into water systems over time (Boateng *et al.*, 2022). Furthermore, they postulated that, urban runoff during rainfall events carries contaminants from roads, parking lots, and

industrial sites into surface water bodies. In urban areas without proper stormwater management systems, heavy metals such as chromium, nickel, and cadmium accumulate in drainage systems and eventually pollute rivers and lakes.

### **2.3.10 Improper Waste Disposal**

Improper disposal of solid and liquid waste is a major contributor to heavy metal pollution in water sources. Landfills and dumpsites containing electronic waste (e-waste) release metals like lead, cadmium, and mercury into the soil and groundwater through leaching (Ali *et al.*, 2023). Municipal and domestic wastewater, which often contains heavy metals from household products and cleaning agents, is another significant source of contamination when discharged untreated into nearby water bodies. In rural areas, the absence of regulated waste management systems exacerbates this issue, leading to localized hotspots of heavy metal pollution.

### **2.3.11 Industrial Combustion and Atmospheric Deposition**

Combustion of fossil fuels in power plants, vehicles, and industrial facilities releases heavy metals like mercury, lead, and arsenic into the atmosphere. These metals are deposited onto land and water surfaces through wet and dry deposition processes, contributing to secondary contamination of water sources (Kumar *et al.*, 2022). The impact of atmospheric deposition is often underestimated, but studies have shown that it plays a significant role in heavy metal contamination, especially in regions downwind of industrial and urban areas.

## **2.4 Physicochemical parameters**

Physicochemical parameters are crucial indicators of water quality, providing insights into the physical and chemical characteristics of water that determine its suitability for consumption, industrial use, and ecological sustenance. Monitoring these parameters is

essential for understanding the overall condition of water sources, as they can influence the presence, behavior, and toxicity of pollutants, including heavy metals (Ali *et al.*, 2023).

The pH of water measures its acidity or alkalinity, ranging from 0 to 14, with 7 being neutral. Acidic water ( $\text{pH} < 7$ ) can increase the solubility of heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As), making them more bioavailable and toxic. Conversely, alkaline water ( $\text{pH} > 7$ ) may precipitate certain metals, reducing their mobility but possibly causing scaling in water systems (Kumar *et al.*, 2022). The World Health Organization (WHO) recommends a pH range of 6.5–8.5 for drinking water to minimize these effects and ensure safe consumption (WHO, 2022).

Electrical conductivity is a measure of water's ability to conduct electricity, which is directly related to the concentration of dissolved ions, including heavy metals. High EC values indicate elevated levels of dissolved salts and metals, often resulting from industrial effluents, agricultural runoff, or mining activities. EC is a critical parameter for assessing the ionic composition of water and identifying potential contamination sources (Mensah *et al.*, 2023).

Turbidity refers to the cloudiness or haziness of water caused by suspended particles, including silt, organic matter, and microorganisms. Elevated turbidity levels can indicate contamination from runoff or industrial discharges and may interfere with the detection of dissolved pollutants like heavy metals (Opoku *et al.*, 2023). Turbid water often requires filtration before testing to ensure accurate results.

Total dissolved solids represent the combined content of inorganic and organic substances dissolved in water. High TDS levels are typically associated with industrial

pollution, agricultural runoff, or leaching from contaminated soils and sediments. While TDS itself may not be harmful, excessive levels can affect the taste and palatability of water and indicate the presence of harmful substances (Boateng *et al.*, 2022). Dissolved oxygen is essential for the survival of aquatic life and serves as a key indicator of water quality. Low DO levels often result from organic pollution and can create anoxic conditions that promote the release of heavy metals from sediments into the water column (Ali *et al.*, 2023). The interaction between DO and metal solubility highlights its importance in assessing the risk of heavy metal contamination.

Water temperature affects the solubility and reaction rates of chemical species, including heavy metals. Higher temperatures increase the solubility of many metals and enhance the metabolic activities of aquatic organisms, potentially leading to bioaccumulation (Kumar *et al.*, 2022). Temperature also influences the stratification of water bodies, which can affect the distribution of contaminants.

ORP measures the tendency of water to either gain or lose electrons, which determines its oxidative or reductive capacity. Heavy metals like chromium (Cr) and arsenic (As) exist in multiple oxidation states, with some forms being more toxic than others. Monitoring ORP helps in understanding the chemical speciation of these metals and their potential health impacts (Mensah *et al.*, 2023).

#### **2.4.1 Importance of physicochemical parameters**

Physicochemical parameters play a critical role in the mobility, speciation, and bioavailability of heavy metals in water sources. For example, low pH and high conductivity conditions can increase the solubility of heavy metals, enhancing their toxicity to humans and aquatic life (Ali *et al.*, 2023). Conversely, high turbidity levels

may indicate the presence of suspended particles that can adsorb heavy metals, reducing their immediate availability but posing risks during sediment resuspension.

Regular monitoring of physicochemical parameters is essential for assessing the suitability of water for human consumption and other uses. Deviations from recommended values often indicate contamination sources, enabling timely interventions. For instance, high TDS and conductivity values can signal industrial pollution, while low DO levels may reflect organic contamination that indirectly affects metal release (Kumar *et al.*, 2022).

Understanding the physicochemical properties of water is critical for designing effective treatment strategies. For example, pH adjustments are often used in coagulation and filtration processes to remove heavy metals. Similarly, managing turbidity and TDS is essential for improving the efficiency of water treatment systems (Boateng *et al.*, 2022).

### **2.5 Health Impacts of Heavy Metal Contamination**

Heavy metal contamination in drinking water poses severe health risks to humans due to the toxic nature and persistence of these elements in the environment. Metals such as Lead (Pb), Mercury (Hg), Arsenic (As), Cadmium (Cd), and Chromium (Cr) are of particular concern as they are non-biodegradable, bioaccumulative, and can interfere with biological processes even at low concentrations (Ali *et al.*, 2023). Prolonged exposure to heavy metals through contaminated water can result in acute and chronic health effects, ranging from organ damage to developmental disorders and increased risk of cancers.

### **2.5.1 Lead (Pb): Neurological and Developmental Effects**

Lead is a potent neurotoxin that adversely affects the central nervous system, particularly in children. Prolonged exposure to lead can impair cognitive function, reduce IQ, and cause developmental delays in children. In adults, lead exposure can lead to hypertension, kidney dysfunction, and reproductive issues (Mensah *et al.*, 2023). The World Health Organization (WHO) has stated that no safe level of lead exposure exists, emphasizing the need for stringent measures to minimize its presence in drinking water (WHO, 2022).

### **2.5.2 Mercury (Hg): Nervous System and Renal Damage**

Mercury contamination, often associated with artisanal gold mining, poses significant risks due to its transformation into methylmercury in aquatic environments. Methylmercury bioaccumulates in fish and is neurotoxic to humans. Ingesting mercury-contaminated water or fish can result in tremors, memory loss, vision impairment, and, in severe cases, coma or death (Boateng *et al.*, 2022). They further highlighted that, pregnant women and infants are particularly vulnerable, as mercury can cross the placental barrier and disrupt fetal development.

### **2.5.3 Arsenic (As): Carcinogenic and Systemic Effects**

Arsenic exposure through drinking water is a global health concern, particularly in regions with high arsenic concentrations in groundwater. Chronic arsenic exposure has been linked to skin lesions, cardiovascular diseases, and cancers of the skin, lungs, and bladder (Kumar *et al.*, 2022). Additionally, long-term exposure can cause peripheral neuropathy, diabetes, and respiratory disorders. The International Agency for Research on Cancer (IARC) classifies arsenic as a Group 1 carcinogen, underscoring its severe health risks.

#### **2.5.4 Cadmium (Cd): Renal and Skeletal Toxicity**

Cadmium exposure primarily affects the kidneys and skeletal system. Prolonged intake of cadmium-contaminated water can result in tubular proteinuria, a condition where the kidneys lose their ability to reabsorb proteins effectively. Cadmium also interferes with calcium metabolism, leading to bone demineralization, osteoporosis, and increased risk of fractures (Ali *et al.*, 2023). Additionally, cadmium is considered a carcinogen, with evidence linking it to lung and prostate cancers.

#### **2.5.5 Chromium (Cr): Carcinogenic Effects**

Chromium contamination, particularly in the form of hexavalent chromium (Cr<sup>6+</sup>), is highly toxic and carcinogenic. Ingesting water contaminated with Cr<sup>6+</sup> can cause gastrointestinal distress, liver and kidney damage, and an elevated risk of lung and stomach cancers (Mensah *et al.*, 2023). Chronic exposure can also result in skin ulcers and respiratory issues due to its corrosive nature.

#### **2.5.6 Cumulative and Synergistic Effects**

In many contaminated areas, exposure to multiple heavy metals occurs simultaneously, compounding the health risks. For instance, the co-presence of lead and arsenic in water can exacerbate neurotoxic effects and increase the overall carcinogenic risk (Opoku *et al.*, 2023). The cumulative toxicity of heavy metals poses significant challenges for risk assessment and underscores the need for comprehensive mitigation strategies.

#### **2.5.7 Public Health Implications**

The health impacts of heavy metal contamination extend beyond individual well-being to broader public health concerns. Contaminated water sources contribute to increased healthcare costs, loss of productivity, and reduced life expectancy in affected communities. For instance, arsenic-related cancers and cadmium-induced kidney

diseases place a significant burden on healthcare systems in regions with high contamination levels (Ali *et al.*, 2023). Furthermore, the intergenerational effects of heavy metal exposure, such as developmental delays in children, can perpetuate cycles of poverty and poor health in vulnerable populations.

Heavy metal contamination in water sources has profound and long-lasting effects on human health. Exposure to metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) is associated with a wide range of acute and chronic health conditions. These metals, being non-biodegradable and highly toxic, accumulate in the human body over time, exacerbating their harmful effects. The health impacts are particularly severe in communities with limited access to safe drinking water, where untreated water sources are heavily relied upon (Nguyen *et al.*, 2023).

## **2.6 Neurological Effects**

Neurological damage is one of the most well-documented effects of heavy metal exposure. Lead, for instance, interferes with the development of the central nervous system, making children especially vulnerable. Chronic exposure to lead can result in reduced IQ, cognitive impairments, attention disorders, and behavioral issues (Ali *et al.*, 2023). Mercury, particularly in its methylmercury form, also poses significant risks to the nervous system. Prenatal exposure to mercury through maternal consumption of contaminated water or fish can result in developmental delays, motor dysfunction, and learning disabilities in children (Boateng *et al.*, 2022).

### **2.6.1 Carcinogenic Risks**

Several heavy metals, including arsenic, cadmium, and chromium (hexavalent form), are classified as human carcinogens by the International Agency for Research on Cancer (IARC). Chronic exposure to arsenic in drinking water is associated with cancers of the

skin, bladder, lungs, and liver. Studies have shown that cadmium exposure increases the risk of prostate and lung cancer, while hexavalent chromium is linked to gastrointestinal cancers (Mensah *et al.*, 2023). These metals induce carcinogenesis by causing oxidative stress, DNA damage, and interference with cellular repair mechanisms.

### **2.6.2 Renal and Hepatic Toxicity**

The kidneys and liver are primary targets of heavy metal toxicity due to their role in filtration and detoxification. Cadmium accumulates in the kidneys, leading to nephrotoxicity, proteinuria, and chronic kidney disease (Osei *et al.*, 2022). Mercury exposure also damages renal tissues, impairing kidney function over time. Arsenic and lead, on the other hand, are known to cause hepatotoxicity, manifesting as liver inflammation, fibrosis, and impaired detoxification processes (Nguyen *et al.*, 2023). These conditions are exacerbated in populations with prolonged exposure to contaminated water.

### **2.6.3 Cardiovascular Impacts**

Heavy metals are also linked to various cardiovascular diseases. Long-term exposure to lead has been shown to elevate blood pressure and increase the risk of hypertension, stroke, and heart disease. Arsenic exposure is associated with vascular disorders, including atherosclerosis and peripheral artery disease, as well as an increased risk of heart attacks (Boateng *et al.*, 2022). These effects are attributed to the ability of heavy metals to induce oxidative stress and disrupt normal cellular functions in cardiovascular tissues.

### **2.6.4 Reproductive and Developmental Effects**

Reproductive health is significantly affected by heavy metal exposure. Mercury and lead are known to impair fertility in both men and women by disrupting hormonal balances

and damaging reproductive organs (Ali *et al.*, 2023). Pregnant women exposed to high levels of arsenic or lead are at increased risk of preterm birth, low birth weight, and developmental abnormalities in their offspring. Prenatal exposure to heavy metals can also result in long-term developmental delays and neurological deficits in children, making maternal and fetal health a critical area of concern.

### **2.6.5 Gastrointestinal and Metabolic Disorders**

Exposure to heavy metals like chromium and arsenic is associated with gastrointestinal issues, including stomach ulcers, nausea, and abdominal pain. These metals can irritate the lining of the digestive system, leading to chronic inflammation and discomfort (Mensah *et al.*, 2023). In addition, heavy metals such as cadmium and lead disrupt normal metabolic processes, impairing glucose metabolism and increasing the risk of diabetes and obesity.

### **2.6.6 Immune System Suppression**

Heavy metals are known to weaken the immune system by disrupting the normal functioning of immune cells. Arsenic and lead, for example, suppress the production of antibodies and impair the activity of T-cells, making individuals more susceptible to infections and reducing the effectiveness of vaccines (Nguyen *et al.*, 2023). This immunosuppressive effect poses a significant public health challenge, particularly in regions with high prevalence of infectious diseases.

### **2.6.7 Health Impacts on Vulnerable Populations**

Vulnerable populations, including children, pregnant women, the elderly, and individuals with pre-existing health conditions, are disproportionately affected by heavy metal contamination. Children absorb heavy metals more readily than adults and are more susceptible to their toxic effects due to their developing organs and systems.

Pregnant women are at risk of transferring heavy metals to their unborn children, leading to developmental and birth defects. The elderly, with age-related declines in organ function, are more vulnerable to the cumulative effects of heavy metal exposure (Boateng *et al.*, 2022).

## **2.7 Environmental and Public Health Policies in Ghana**

Ghana has implemented several environmental and public health policies aimed at protecting natural resources, safeguarding public health, and promoting sustainable development. These policies are crucial in addressing challenges such as water pollution, including heavy metal contamination, which poses significant risks to ecosystems and human well-being. This section highlights key policies, frameworks, and initiatives in Ghana that govern environmental protection and public health, particularly in the context of water quality management (MESTI, 2019).

### **2.7.1 National Environmental Policy**

The National Environmental Policy (NEP) serves as the cornerstone of Ghana's environmental management efforts. Established in the 1990s and revised over the years, this policy emphasizes sustainable development through the integration of environmental considerations into national planning (Ministry of Environment, Science, Technology, and Innovation (MESTI, 2022)). The policy addresses issues such as pollution control, resource conservation, and waste management. In the context of water quality, the NEP mandates the regulation of industrial and agricultural practices that contribute to pollution, including heavy metal contamination.

### **2.7.2 National Water Policy**

Ghana's National Water Policy (NWP) provides a comprehensive framework for the sustainable management of water resources. Adopted in 2007, the policy focuses on

ensuring access to safe and affordable water for all while maintaining the ecological integrity of water bodies (WRC, 2023). The NWP emphasizes integrated water resource management (IWRM) as a strategy for addressing water pollution, including heavy metal contamination. Key objectives include, Promoting the protection of water bodies from pollutants such as industrial discharges, mining effluents, and agricultural runoff, strengthening institutional frameworks for water quality monitoring and enforcement of standards, enhancing community participation in water resource management to ensure sustainable practices. The policy also aligns with Sustainable Development Goal 6, which aims to ensure the availability and sustainable management of water and sanitation for all by 2030 (UNDP, 2022).

### **2.7.3 Water Resources Commission Act (Act 522 of 1996)**

The Water Resources Commission Act establishes the Water Resources Commission (WRC) as the principal authority responsible for the regulation and management of water resources in Ghana. The WRC is tasked with granting water use permits, monitoring water quality, and enforcing regulations to prevent pollution (WRC, 2023). Under this act, the WRC collaborates with other agencies to address heavy metal contamination, particularly in mining-affected regions where water pollution is prevalent.

### **2.7.4 Environmental Protection Agency Act (Act 490 of 1994)**

The Environmental Protection Agency (EPA) Act establishes the EPA as the regulatory body for environmental protection in Ghana. The EPA is responsible for enforcing environmental standards and guidelines, conducting environmental impact assessments (EIAs) for industrial and mining projects, monitoring and mitigating pollution from various sources, including heavy metals (EPA Ghana, 2023).

The EPA's role in regulating industrial effluents and agricultural practices is critical for minimizing heavy metal contamination in water sources. The agency also collaborates with local governments to implement pollution control measures and raise public awareness about environmental issues.

### **2.7.5 Mining and Minerals Act (Act 703 of 2006)**

The Mining and Minerals Act governs mining activities in Ghana, including artisanal and small-scale mining (ASM). While mining is a major contributor to Ghana's economy, it is also a significant source of heavy metal pollution, particularly mercury and arsenic (Mensah *et al.*, 2023). The act requires mining companies to adhere to environmental regulations, including the proper disposal of mining waste and the rehabilitation of mined areas. The EPA and the WRC work together to monitor compliance with these regulations to prevent water contamination.

### **2.7.6 Public Health Act (Act 851 of 2012)**

The Public Health Act focuses on the protection and promotion of public health in Ghana. It includes provisions for water quality management, emphasizing the prevention of waterborne diseases and the regulation of pollutants in drinking water sources (Ministry of Health, 2022). The act mandates regular water quality monitoring and the implementation of measures to address contamination, including heavy metals.

### **2.7.7 Non-Governmental and International Contributions**

In addition to governmental policies, non-governmental organizations (NGOs) and international agencies play a crucial role in addressing environmental and public health issues in Ghana (WHO, 2022). Organizations such as WaterAid, UNICEF, and the World Health Organization (WHO) collaborate with the government to fund water quality monitoring programs, provide infrastructure for safe water access, such as

boreholes and filtration systems, conduct community education campaigns to raise awareness about the risks of water pollution and heavy metal contamination (UNICEF, 2023).

## **2.8 Technological and Methodological Approaches for Monitoring Heavy Metal Contamination**

Effective monitoring of heavy metal contamination in water sources is essential for safeguarding public health and ensuring environmental sustainability. Over the years, advancements in technology and methodology have significantly enhanced the detection, quantification, and analysis of heavy metals in water.

These approaches, ranging from traditional wet chemistry techniques to advanced instrumental methods, provide valuable insights into the sources, concentrations, and health risks associated with heavy metal pollution (Wang *et al.*, 2021).

### **2.8.1 Wet chemistry techniques**

Traditional methods such as titration and gravimetric analysis have historically been used for heavy metal detection. These techniques involve chemical reactions that result in measurable changes, such as color changes or precipitate formation. For instance, gravimetric analysis is commonly used for detecting metals like lead (Pb) and chromium (Cr). However, these methods are often labor-intensive, time-consuming, and less sensitive compared to modern techniques (Kumar *et al.*, 2022).

### **2.8.2 Spectrophotometry**

Spectrophotometry measures the absorption of light by a sample to determine the concentration of specific metals. While relatively simple and cost-effective, this method has limitations in sensitivity and selectivity for trace metal detection (Ali *et al.*, 2023).

### **2.8.3 Atomic Absorption Spectroscopy (AAS)**

AAS is one of the most widely used methods for detecting and quantifying heavy metals in water. The technique measures the absorption of light by free atoms in the gaseous state, providing highly accurate results for metals such as lead, cadmium, and mercury (Mensah *et al.*, 2023). AAS is particularly useful for monitoring low concentrations of metals and is relatively cost-effective compared to other advanced methods.

### **2.8.4 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)**

ICP-MS is a cutting-edge technique for detecting trace levels of heavy metals. It uses an inductively coupled plasma to ionize the sample and a mass spectrometer to separate and quantify ions based on their mass-to-charge ratio. ICP-MS is ideal for simultaneous multi-element analysis and is highly sensitive, capable of detecting metals at parts per trillion (ppt) levels (Boateng *et al.*, 2022).

### **2.8.5 Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)**

ICP-OES is similar to ICP-MS but measures the emission of light from ionized elements. It is less sensitive than ICP-MS but is still effective for quantifying heavy metals in water sources. ICP-OES is commonly used for metals like arsenic and chromium (Ali *et al.*, 2023).

### **2.8.6 X-Ray Fluorescence (XRF)**

XRF is a non-destructive technique that uses X-rays to determine the elemental composition of a sample. It is widely used for rapid screening of heavy metals in sediments and solid wastes. However, its application in water analysis is limited due to challenges in detecting trace metal concentrations (Kumar *et al.*, 2022).

### **2.8.7 Nanotechnology-Based Sensors**

Nanotechnology has revolutionized heavy metal monitoring by enabling the development of highly sensitive and selective sensors. These sensors use nanoparticles to detect specific metals through changes in electrical conductivity, optical properties, or fluorescence (Mensah *et al.*, 2023). For instance, gold nanoparticles are used in the detection of mercury in water sources.

### **2.8.8 Biosensors**

Biosensors leverage biological molecules, such as enzymes or antibodies, to detect heavy metals. These devices offer rapid and on-site monitoring capabilities, making them suitable for remote areas like Tapa Abotoase. Biosensors are particularly effective for detecting metals like arsenic and lead (Boateng *et al.*, 2022).

### **2.8.9 Portable Analytical Devices**

Portable devices, such as handheld XRF analyzers and field spectrometers, provide rapid, on-site analysis of heavy metals in water. These tools are increasingly used in environmental assessments due to their ease of use and cost-effectiveness (Ali *et al.*, 2023).

## **2.9 Methodological Approaches**

### **2.9.1 Sample Collection and Preservation**

Proper sample collection and preservation are critical for ensuring the accuracy of heavy metal analysis. Guidelines provided by organizations like the World Health Organization (WHO) recommend the use of acid-washed containers to minimize contamination and acidification of samples to prevent metal precipitation during storage (WHO, 2022).

### **2.9.2 Assurance and Quality Control (QA/QC)**

Assurance and Quality Control (QA/QC) procedures, including the use of certified reference materials, calibration standards, and replicate analysis, are essential for ensuring data reliability. These procedures help minimize errors and improve the accuracy of results (Opoku *et al.*, 2023).

### **2.9.3 Data Analysis and Interpretation**

Statistical tools and software are used to analyze heavy metal concentrations and identify contamination patterns. Techniques such as principal component analysis (PCA) and cluster analysis are employed to determine the sources and pathways of contamination (Mensah *et al.*, 2023).

### **2.9.4 Risk Assessment Approaches**

Health risk assessments, including exposure dose and hazard quotient calculations, are used to evaluate the potential health impacts of detected heavy metal concentrations. These assessments provide critical insights into the level of risk posed to local populations and guide mitigation strategies (Boateng *et al.*, 2022).

### **2.9.5 Seasonal Variations in Heavy Metal Concentrations**

Seasonal variations in heavy metal concentrations in water sources are a critical factor in understanding the dynamics of water quality. These variations are influenced by natural hydrological cycles and human activities, which interact to either increase or dilute the presence of heavy metals in surface and groundwater systems. Monitoring these variations provides valuable insights into the behavior of heavy metals under different environmental conditions, guiding effective water quality management strategies (Mensah *et al.*, 2023).

Heavy rainfall during the rainy season significantly increases surface runoff, which mobilizes heavy metals from agricultural lands, mining sites, industrial zones, and urban areas into water bodies. Agricultural runoff is a major contributor, carrying pesticides, fertilizers, and manure containing trace amounts of metals such as arsenic (As), cadmium (Cd), and lead (Pb) (Boateng *et al.*, 2022). Similarly, runoff from mining sites often introduces mercury (Hg) and arsenic into rivers and streams, raising their concentrations significantly during the wet season. Additionally, surface runoff transports suspended sediments that act as carriers of adsorbed heavy metals. When these sediments enter water bodies, they release metals into the water column, increasing dissolved metal concentrations (Ali *et al.*, 2023). This process is particularly pronounced in areas with steep slopes, degraded vegetation, or unregulated mining activities.

In contrast, the dry season is characterized by reduced water flow rates and higher evaporation, which lead to the concentration of dissolved substances, including heavy metals (Opoku *et al.*, 2023). The lower dilution capacity during this period exacerbates contamination from point sources, such as industrial discharges and untreated wastewater. Metals such as chromium (Cr) and nickel (Ni), commonly associated with industrial effluents, show marked increases in concentration during the dry season. Seasonal variations also influence groundwater systems. During the rainy season, increased recharge can dilute heavy metal concentrations, whereas in the dry season, reduced recharge and higher extraction rates may concentrate metals in groundwater. Additionally, fluctuations in redox conditions caused by seasonal changes can alter the chemical speciation and mobility of metals like arsenic, making them more bioavailable under specific conditions (Kumar *et al.*, 2022).

Studies conducted in Ghana provide insights into these seasonal patterns. Research in the Volta Basin, has revealed significant variations in heavy metal concentrations. Mensah *et al.* (2023) reported elevated levels of mercury and arsenic during the rainy season due to runoff from small-scale mining sites. Conversely, lead and cadmium concentrations were higher in the dry season, attributed to evaporation and reduced water flow. Agricultural areas in Ghana also exhibit seasonal trends. Boateng *et al.* (2022) found that cadmium and arsenic concentrations peaked during the rainy season due to runoff from farmlands treated with fertilizers and pesticides. Similarly, urban and industrial regions experience increased concentrations of chromium and nickel during the dry season when reduced rainfall limits the dilution of industrial effluents (Ali *et al.*, 2023).

Understanding these seasonal variations is critical for effective water quality management. Monitoring during both wet and dry seasons ensures a comprehensive assessment of heavy metal concentrations and helps identify periods of peak contamination (WHO, 2022). Mitigation strategies must also account for seasonal patterns. For example, controlling agricultural runoff during the rainy season through buffer zones and erosion control measures can significantly reduce heavy metal inputs into water bodies (Opoku *et al.*, 2023). Increasing water treatment efforts during the dry season can mitigate the effects of concentrated pollutants. Community awareness campaigns are another essential component, emphasizing the importance of using treated water during periods of high contamination, such as the rainy season, to reduce exposure to heavy metals (Boateng *et al.*, 2022).

Despite these findings, research gaps remain in the study of seasonal variations in heavy metal concentrations. Long-term monitoring is necessary to capture inter-annual

variability and the effects of climate change on water quality (Ali *et al.*, 2023). Emerging technologies, such as remote sensing and machine learning, offer opportunities for enhancing the spatial and temporal resolution of monitoring efforts, providing a more detailed understanding of seasonal patterns (Mensah *et al.*, 2023). Furthermore, research should prioritize vulnerable communities like Tapa Abotoase, where reliance on untreated water sources makes residents particularly susceptible to seasonal contamination risks. Investigating the socio-economic factors that influence community adaptation to these changes can further inform effective water quality interventions. Heavy metal contamination of water is a global environmental and public health concern. Across the world, rapid urbanization, industrialization, and mining have accelerated the release of metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) into rivers, lakes, and groundwater systems. For example, studies in Asia have reported high levels of arsenic in groundwater, especially in Bangladesh and India, where naturally occurring arsenic contamination affects millions of people (Smith *et al.*, 2000). Similarly, in China, extensive mining and industrial activities have contributed to severe lead and cadmium contamination in surface waters (He *et al.*, 2020).

In Africa, heavy metal pollution is increasingly linked to artisanal and small-scale gold mining, industrial effluents, and agricultural practices. Research in Nigeria and Ghana shows that mercury from gold amalgamation and arsenic from natural mineralization zones are key contributors to contamination in rivers and lakes (Adimalla and Chen, 2020). Specifically, in Ghana, studies on the Pra and Ankobra Rivers have revealed alarming levels of mercury and arsenic, posing risks to downstream communities dependent on these rivers for drinking and irrigation (Babut *et al.*, 2003). These trends

highlight the urgent need for continuous monitoring and improved enforcement of environmental policies across developing regions.

### **2.9.6 Global Prevalence of Heavy Metal Contamination in Water**

Heavy metal contamination in water sources is a widespread issue affecting both developed and developing nations. Globally, industrialization, urbanization, and intensive agricultural practices have exacerbated the contamination of water systems with toxic metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As). According to Nguyen *et al.* (2023), approximately 10% of global water sources are contaminated with levels of heavy metals exceeding the World Health Organization's (WHO) recommended limits. In developing regions, including Sub-Saharan Africa, lack of regulation and enforcement further compounds the issue, exposing vulnerable populations to significant health risks. Such global trends underscore the urgency for continuous monitoring and improved water management practices.

### **2.9.7 Heavy Metal Pollution in Sub-Saharan Africa**

In Sub-Saharan Africa, heavy metal pollution is closely linked to mining activities, agriculture, and improper waste management. For instance, artisanal and small-scale gold mining (ASGM) is a significant source of mercury pollution in many African countries, including Ghana. Osei *et al.* (2022) highlighted that ASGM activities in Ghana contribute over 60% of mercury emissions in water systems, affecting downstream communities reliant on rivers for drinking and irrigation. Furthermore, the use of cadmium-based fertilizers in agriculture and the discharge of untreated industrial effluents into water bodies exacerbate heavy metal contamination in urban and peri-urban areas (Opoku *et al.*, 2023). These findings emphasize the need for targeted interventions to reduce anthropogenic sources of heavy metals in water systems.

### **2.9.8 Impact of Agricultural Practices on Water Quality**

Agricultural activities, particularly in rural regions, significantly influence water quality through the introduction of pesticides, fertilizers, and animal waste. Boateng *et al.*, (2022) reported that arsenic, lead, and cadmium are commonly detected in agricultural runoff in Ghana, often resulting from the excessive use of agrochemicals. During the rainy season, heavy rainfall facilitates the transport of these metals into rivers and streams, where they accumulate and pose risks to aquatic ecosystems and human health. Studies suggest that implementing sustainable farming practices, such as integrated pest management and reduced chemical usage, can minimize heavy metal contamination in agricultural regions.

### **2.9.9 Advancements in Monitoring and Detection Technologies**

Technological advancements have significantly improved the detection and monitoring of heavy metal contamination in water systems. Techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) provide high sensitivity and accuracy for quantifying trace levels of metals in water (Ali *et al.*, 2023). These methods are particularly valuable in identifying contamination hotspots and determining the sources of pollution. In addition, portable testing kits and biosensors are gaining popularity for rapid on-site analysis, enabling timely interventions in remote areas (Mensah *et al.*, 2023). These technological advancements hold promise for improving water quality monitoring in resource-constrained settings like Tapa Abotoase.

### **2.9.10 Health Risks Associated with Heavy Metal Exposure**

Exposure to heavy metals through contaminated water has profound health implications, particularly for vulnerable populations such as children, pregnant women, and

individuals with pre-existing health conditions. Prolonged exposure to arsenic has been linked to cancers of the skin, lungs, and bladder, while lead exposure in children can cause cognitive impairments and developmental delays (Nguyen *et al.*, 2023). Mercury, often introduced into water systems through mining activities, bioaccumulates in fish and shellfish, posing neurological risks to humans who consume these contaminated organisms (Boateng *et al.*, 2022). The widespread nature of these health risks calls for comprehensive health risk assessments to guide public health policies.

### **2.9.11 Ghana's Policy Landscape on Water Quality**

Ghana has developed several policies and regulatory frameworks to address water pollution, including the National Environmental Policy and the Water Resources Commission Act. These policies emphasize integrated water resource management and the enforcement of water quality standards. However, implementation challenges persist, particularly in rural areas. According to Osei *et al.* (2022), limited financial resources and weak institutional coordination hinder effective enforcement of regulations, allowing industries and agricultural activities to discharge untreated waste into water bodies. Strengthening these frameworks and enhancing collaboration among stakeholders are critical for achieving sustainable water management in Ghana.

### **2.9.12 Community Engagement in Water Management**

Community involvement is a key component of successful water management strategies. Educating communities on the risks associated with heavy metal contamination and the importance of safe water practices can significantly reduce exposure. Boateng *et al.* (2022) emphasized the role of community-based initiatives, such as tree planting and erosion control, in reducing runoff and improving water quality. Additionally, partnerships between local governments and NGOs can provide

resources and technical expertise to empower communities in managing their water resources effectively.

## **2.10 The Role of Climate Change in Water Contamination**

Climate change is an emerging factor that exacerbates heavy metal contamination in water systems. Increased rainfall intensity during wet seasons accelerates the transport of metals from land to water, while prolonged droughts concentrate dissolved metals in surface and groundwater sources (Ali *et al.*, 2023). In regions like Tapa Abotoase, where water resources are already under pressure from human activities, climate-induced changes may further complicate water quality management. Incorporating climate resilience into water management strategies is essential for mitigating these impacts.

### **2.10.1 Heavy Metals in Groundwater Sources**

Groundwater is a crucial source of drinking water globally, but it is increasingly threatened by heavy metal contamination. Studies have shown that natural processes such as the weathering of rocks and anthropogenic activities, including mining and industrial waste disposal, significantly influence heavy metal levels in groundwater (Ali *et al.*, 2023). In regions like Sub-Saharan Africa, including Ghana, arsenic, cadmium, and lead are often found in groundwater due to natural geological formations and leaching from agricultural and industrial activities (Nguyen *et al.*, 2023). Arsenic, in particular, has been linked to severe health issues in rural communities dependent on groundwater for their daily needs, necessitating more stringent water quality monitoring and mitigation strategies.

### **2.10.2 Impacts of Mining on Water Contamination**

Mining activities, particularly artisanal and small-scale gold mining (ASGM), are a significant source of heavy metal contamination in water systems. Mercury and arsenic are the most prevalent metals associated with ASGM due to the widespread use of mercury in gold extraction processes and the natural occurrence of arsenic in mining regions (Mensah *et al.*, 2023). Research by Opoku *et al.* (2023) indicated that mining sites in Ghana's Oti and Volta Regions have elevated levels of mercury and arsenic in nearby rivers, often exceeding World Health Organization (WHO) permissible limits. This contamination not only affects aquatic ecosystems but also poses severe health risks to communities that rely on these rivers for drinking and irrigation.

### **2.10.3 Urbanization and Industrialization as Contributors**

Rapid urbanization and industrialization have exacerbated water pollution by increasing the discharge of untreated industrial effluents and urban runoff into water bodies. Chromium and cadmium are among the heavy metals commonly associated with industrial discharges from tanneries, electroplating, and manufacturing plants (Boateng *et al.*, 2022). Urban runoff during rainfall events also carries significant amounts of heavy metals from roads, construction sites, and improperly managed waste into rivers and lakes, leading to periodic spikes in contamination levels (Nguyen *et al.*, 2023). These findings highlight the importance of integrating industrial waste treatment systems and urban planning to mitigate water contamination.

### **2.10.4 Agricultural Practices and Pesticide Use**

Agricultural runoff is another critical pathway for heavy metal contamination in water sources, particularly in rural and peri-urban areas. The use of cadmium- and lead-containing pesticides and fertilizers has been identified as a significant contributor to

the contamination of surface and groundwater systems (Osei *et al.*, 2022). Boateng *et al.*, (2022) found that in Ghana, farmlands located near rivers such as the Volta Basin experience heavy runoff during the rainy season, introducing large quantities of cadmium and arsenic into water bodies. The cumulative effects of these agricultural practices on water quality call for policies promoting the use of eco-friendly agrochemicals and sustainable farming techniques.

### **2.10.5 Climate Change and Heavy Metal Mobility**

Climate change has emerged as an influential factor in the behavior and mobility of heavy metals in water systems. Increased rainfall intensity during wet seasons leads to higher surface runoff, which mobilizes metals from contaminated soils into rivers and lakes (Ali *et al.*, 2023). Conversely, prolonged droughts concentrate heavy metals in stagnant water sources, further elevating contamination risks (Nguyen *et al.*, 2023). In Ghana, these climate-induced changes complicate water quality management, particularly in regions like Tapa Abotoase, where reliance on untreated water sources is high. Integrating climate resilience into water management strategies is therefore crucial for mitigating these impacts.

### **2.10.6 Socio-Economic Impacts of Heavy Metal Contamination**

The socio-economic implications of heavy metal contamination in water sources are profound, particularly for low-income communities that lack access to treated water. Contaminated water sources lead to increased healthcare costs due to the treatment of illnesses such as kidney disease, neurological disorders, and cancers caused by prolonged exposure to heavy metals like lead and mercury (Mensah *et al.*, 2023). Additionally, agricultural productivity is adversely affected when contaminated water is used for irrigation, leading to reduced crop yields and potential bioaccumulation of

metals in food crops. These economic burdens emphasize the need for targeted interventions to address water contamination in vulnerable communities.

### **2.10.7 Technological Interventions in Water Treatment**

Innovative water treatment technologies have been developed to address heavy metal contamination in water sources. Techniques such as reverse osmosis, ion exchange, and activated carbon filtration are widely recognized for their effectiveness in removing metals like lead, cadmium, and arsenic from drinking water (Boateng *et al.*, 2022). Emerging technologies, such as nanotechnology-based filtration systems and biosensors, offer additional promise for low-cost and efficient water purification in resource-limited settings (Ali *et al.*, 2023). However, challenges remain in scaling these technologies for widespread use in rural areas like Tapa Abotoase, where infrastructure and technical expertise may be lacking.

### **2.10.8 Policy and Governance in Water Quality Management**

While Ghana has established policies such as the National Environmental Policy and the Water Resources Commission Act, enforcement remains a significant challenge. Limited funding, inadequate infrastructure, and weak institutional coordination hinder the implementation of these policies, particularly in rural regions (Osei *et al.*, 2022). Strengthening governance frameworks, enhancing inter-agency collaboration, and increasing investment in water infrastructure are critical for addressing heavy metal contamination effectively.

### **2.10.9 Bioaccumulation and Biomagnification of Heavy Metals**

Heavy metals introduced into aquatic systems often undergo bioaccumulation, where they are absorbed and stored in the tissues of organisms over time. Metals such as mercury, cadmium, and lead are non-biodegradable, meaning they persist in biological

systems and accumulate to toxic levels. Fish, mollusks, and other aquatic organisms serve as reservoirs of these metals, with concentrations often exceeding those in the surrounding water or sediments (Burger and Gochfeld, 2005).

Through biomagnification, these metals are transferred and amplified along the food chain. Predatory fish, birds, and humans consuming contaminated aquatic organisms are at the highest risk of exposure. For instance, methylmercury, a highly toxic form of mercury, has been shown to bioaccumulate in fish and biomagnified through trophic levels, leading to neurological disorders in humans (Mergler *et al.*, 2007). In Ghana, studies have reported mercury accumulation in fish species from Lake Volta and other water bodies, raising concerns for communities that rely heavily on fish as a dietary staple (Donkor *et al.*, 2006). This emphasizes the need for water quality assessments to consider not only direct exposure but also food chain-related risks.

### **2.11 Seasonal Variations in Heavy Metal Concentrations**

The concentration of heavy metals in water sources is not constant; it fluctuates with seasonal variations. During the rainy season, increased runoff, soil erosion, and flooding often wash heavy metals from agricultural fields, mine sites, and urban areas into rivers and lakes (Akoto *et al.*, 2017). In contrast, the dry season may lead to lower water volumes and higher concentrations of contaminants due to evaporation and reduced dilution capacity.

These seasonal dynamics are especially significant in tropical countries like Ghana, where wet and dry seasons strongly influence hydrological patterns. For instance, studies on the Offin River have shown that cadmium, lead, and mercury concentrations vary between rainy and dry seasons, with higher contamination levels often recorded during peak runoff (Obiri *et al.*, 2010). Recognizing these fluctuations is crucial for

designing effective monitoring programs and ensuring that sampling is representative of the full range of environmental conditions.

### **2.12 Community Perceptions and Awareness of Water Contamination**

Community perceptions play a vital role in understanding and addressing heavy metal contamination. In many rural and peri-urban communities, residents often have limited knowledge of the risks associated with heavy metals in drinking water. Instead, perceptions of water quality are usually based on observable characteristics such as taste, color, and odor, which may not reveal toxic contamination (Kraemer *et al.*, 2015). Lack of awareness can lead to continued reliance on contaminated sources, despite the availability of safer alternatives. In Ghana, research has shown that while some communities express concern over visible pollution such as turbidity or algal blooms, awareness of invisible contaminants like arsenic and mercury remains low (Amoah *et al.*, 2018). The importance of integrating environmental education, public awareness campaigns, and participatory monitoring in interventions. When communities understand the risks, they are more likely to adopt protective practices, demand accountability, and support sustainable water management initiatives.

### **2.13 Summary of the reviewed literature**

The reviewed literature showed that heavy metal contamination of drinking water had posed serious environmental and public health concerns, largely due to anthropogenic activities such as agriculture, mining, industrial discharge, and improper waste disposal, with contamination pathways influenced by physicochemical parameters. Studies had established that exposure to heavy metals including lead, mercury, arsenic, cadmium, chromium, and copper had resulted in severe health effects, particularly among vulnerable populations. Although Ghana had policies and regulatory frameworks for

water resource management, enforcement and monitoring challenges, especially in rural communities, had persisted. Advanced analytical techniques had been applied in monitoring heavy metal contamination, and climate change had been identified as a factor influencing contaminant transport, while community awareness of water contamination had remained limited. However, empirical data on heavy metal contamination and associated health risks in rural communities such as Tapa Abotoase had been inadequate, necessitating the present study.



## **CHAPTER THREE**

### **METHODOLOGY**

#### **3.0 Overview**

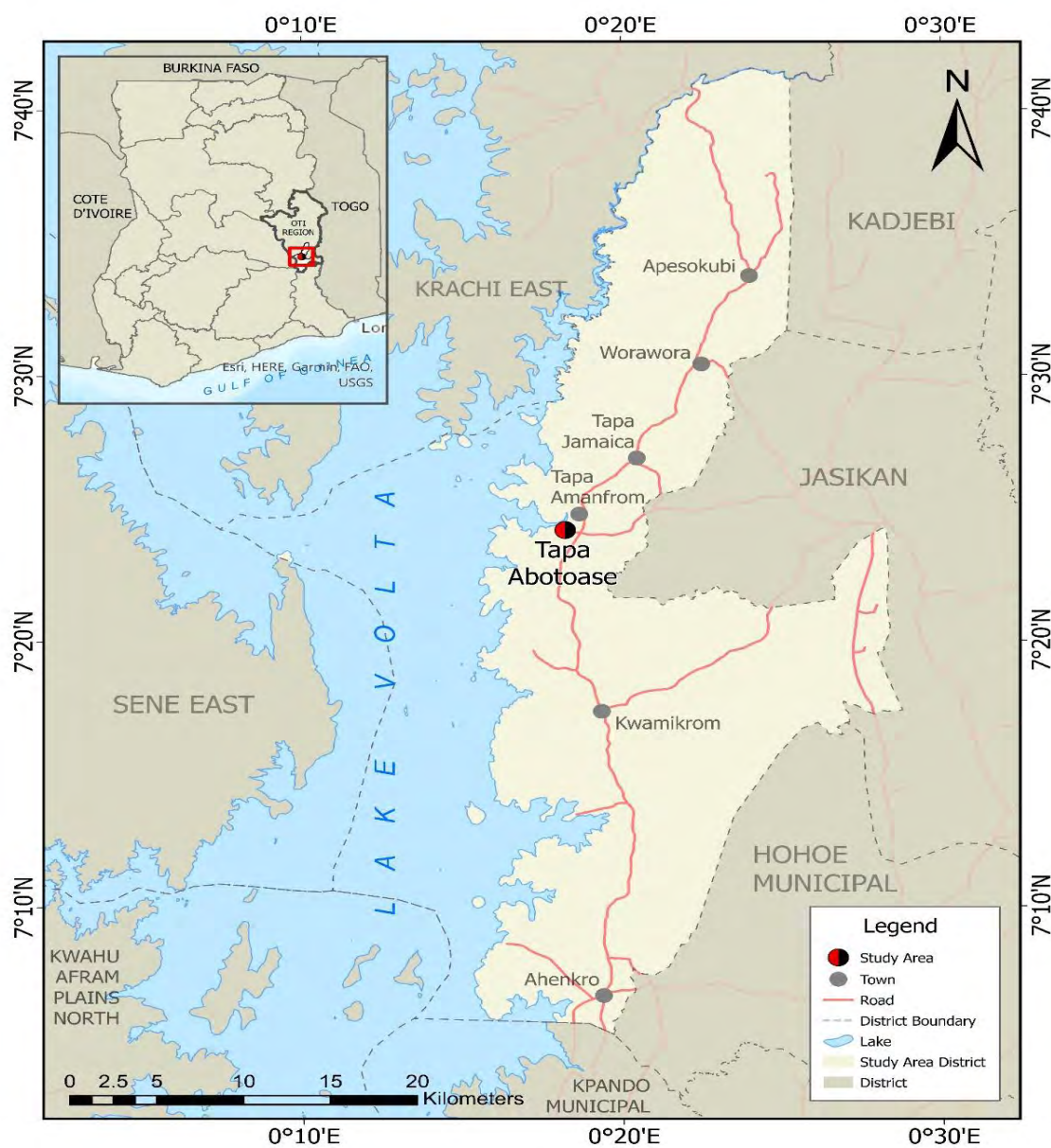
This chapter provides detailed description of the methodology employed in the study. It discusses the research design, population, sample and sampling techniques, the research instruments, validity and reliability of the research instruments, procedure for data collection and method of data analysis.

#### **3.1 Research area**

The study was conducted at Tapa Abotoase, a lakeside community located in the Jasikan District of the Oti Region, Ghana. As illustrated in Figure 1, the community lay along the eastern banks of Lake Volta, which is one of the largest man-made lakes in the world and served as a major source of domestic, agricultural, and fishing activities for surrounding settlements.

Tapa Abotoase was a fishing dominated community, with livelihoods largely dependent on the lake and related trade. The geographical location of the area made it a key center for water-related socio-economic activities, but also exposed the community to potential environmental challenges such as pollution and contamination of water sources. The map Figure 1 highlighted the position of Tapa Abotoase within the Jasikan District, bordered by Krachie East to the west, Kadjebi to the north, and Hohoe Municipal to the south. The main access routes included road networks connecting Tapa Abotoase to nearby towns such as Worawora, Tapa Amanfrom, Tapa Jamaica, and Kwamikrom. The strategic location of the community on Lake Volta made it a suitable site for assessing the quality of drinking water, particularly with regard to heavy metal

contamination, since both anthropogenic activities and natural processes could contribute to water quality changes in the area.



**Figure 1: Map of the Study Area located in the Tapa Abotoase in the Jasikan District of the Oti Region, Ghana (Source: Researcher)**

### 3.2 Research Design

According to Nardi (2018), research design serves as the framework within which research activities are carried out. It directs the entire research process, including data

collection, measurements, and analysis. This study adopted experimental research design, which integrated quantitative research approach that emphasizes numerical data, objective measurements, and statistical analysis to address the research questions.

The quantitative component will involve measuring heavy metal concentrations using advanced instruments such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) formed the core of the study, enabling accurate detection and quantification of heavy metal levels and analyses.

### **3.3 Population**

The population of a study refers to the total number of items, subjects, or participants that meet a specific set of criteria (Mbokane, 2009). Singleton and Strait (2010) further define it as the full collection of items (people or objects) sharing features determined by the research's sampling criteria. Testing every individual or source in a general population is often impractical due to size, costs, and time constraints.

For this study, the population comprises all water sources in the Oti Region. These include rivers, streams, boreholes, and wells, which are key sources of drinking water in the region.

#### **3.3.1 Target Population**

Lavrakas (2008) defines the target population as all units for which the study's data are intended to be used to make inferences. This is to say that the target population of a study defines the entire group of individuals or objects to which conclusions can be generalized. The target population for this study includes all drinking water sources in the Biakoye District of the Oti Region. This district is significant because of its reliance on untreated surface water for domestic consumption and its vulnerability to contamination from human and industrial activities.

### **3.3.2 Accessible Population**

Pernecky (2016) describes the accessible population as the subset of the target population that the researcher can reach and apply conclusions to. It is the portion of the target population available for sampling and data collection. For this study, the accessible population was the river and boreholes in the Tapa Abotoase community. This river was selected due to its importance as a primary drinking water source for the community and its proximity to potential contamination sources, such as agricultural runoff.

### **3.4 Sampling Techniques**

A sample is defined as a smaller group selected from a larger population to gather information and draw conclusions about the entire population (Alvi, 2016). According to Webster (1985), as cited in Mugo (2002), a sample is a finite part of a statistical population whose properties are studied to gain information about the whole. Mugo (2002) further elaborates that in the context of human research, a sample refers to a set of respondents chosen from a larger population for survey purposes.

Alhassan (2006) explains that sampling technique refers to the process through which a portion of the population is selected to represent the entire population.

This study employs a systematic river water sampling technique to select specific zones along the river. The systematic technique was based on location (upstream, midstream, and downstream), season (wet and dry), and water use (domestic versus other uses). Additionally, 4 boreholes in the community were purposively selected for the study to complement the river sampling and provide a broader understanding of water quality in the Tapa Abotoase community.

This approach is aimed at capturing potential variations in heavy metal concentrations that may result from activities such as agricultural runoff, domestic waste discharge, and other anthropogenic influences.

The systematic technique ensures that the sampling points are distributed evenly across the river's length, providing a comprehensive representation of the water quality in the Tapa Abotoase community.

### **3.4.1 Sample size**

According to Taherdoost (2016), a sample size refers to the number of observations or data points selected from a population to represent it in a study. It is a critical factor in ensuring the accuracy and reliability of research findings while maintaining feasibility. Similarly, Singh and Masuku (2014) emphasize that an appropriately chosen sample size improves the generalizability of research outcomes to the entire population.

In this study, one river but was sampled at three points namely upstream, midstream, downstream in addition to water samples collected from five boreholes in the Tapa Abotoase community. Hence, eight water samples were collected twice in the dry season and eight water samples were also collected twice in the wet season making a total of 16 water samples collected in the dry season, and another 16 samples were also be collected in the wet season. Therefore, a total of 32 samples were collected for this study. These sources were selected based on their importance as the primary drinking water sources for the community. Sampling was conducted in both the rainy and dry seasons to capture seasonal variations in heavy metal concentrations. This sample size ensures detailed analysis while remaining practical for laboratory processing and data interpretation.

### **3.5 Research instruments**

According to Creswell (2014), research instruments refer to the tools or techniques used by researchers to collect, measure, and analyze data related to a study's objectives. Similarly, Kothari (2004) describes research instruments as systematic tools designed to ensure the accuracy and reliability of data collection during the research process. Annum (2017) defines research instrument as the tools for data collection. Thus, research instruments are tools designed to measure as well as obtain data on a given situation. They include, but are not limited to observations, questionnaires, interviews and reading (Annum, 2017). According to Babbie (2020), questionnaires are tools used in research to gather standardized data from a group of respondents about their experiences, attitudes, or opinions. Similarly, Kothari (2004) emphasizes that questionnaires are an effective instrument for collecting both qualitative and quantitative data, depending on their design and the type of questions posed. According to Yakubu (2015), a questionnaire is a written document in survey research that has a set of questions given to participants. Annum (2017) states that a questionnaire is a data collection instrument normally used in surveys and defines it as a "systematically prepared form or document with a set of questions deliberately designed to elicit responses from respondents or research informants for the purpose of collecting data or information". Thus, questionnaires contain printed list of questions used to find out the views or opinions of people about an issue, product or service.

To effectively achieve the objectives of this study, the following research instruments were be employed, Atomic Absorption Spectroscopy (AAS) is an analytical technique used to measure the concentration of specific metals and elements in a sample. It works by measuring the absorption of light (in the ultraviolet or visible range) by atoms in a gaseous state. AAS is particularly effective for detecting elements in low concentrations

by introducing the sample into a flame or graphite furnace, where the atoms absorb light at characteristic wavelengths. This absorption is proportional to the concentration of the element in the sample.

In this study, Atomic Absorption Spectroscopy (AAS) was used for the quantitative determination of heavy metals such as lead (Pb), mercury (Hg), and arsenic (As) in the water samples to provide accurate and precise measurements of trace metal concentrations, making it suitable for environmental studies. Additionally, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a highly sensitive technique used for detecting trace elements and isotopes in a variety of samples. It involves introducing the sample into a high-temperature plasma, typically formed by an inductively coupled plasma (ICP), where the sample is ionized. The ions are then detected by a mass spectrometer, which measures their mass-to-charge ratio. ICP-MS is capable of detecting a wide range of elements, including metals, non-metals, and isotopes, with very low detection limits and high precision, making it ideal for environmental, geological, and biological sample analysis.

In this study, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) ICP-MS was employed to determine the concentration levels of heavy metals in water samples. Known for its high sensitivity, this instrument can detect extremely low concentrations of metals, allowing for a detailed analysis of water quality.

### **3.6 Validity of the instrument**

Creswell (2014) defined validity as the extent to which an instrument or tool measured what it was intended to measure. He posits that the conclusions drawn from the data should have accurately reflected the real-world concepts or phenomena the study sought to examine. Zohrabi (2013) provides two forms of validity: content validity and internal

validity. Content validity, according Zohrabi (2013), is a type of validity whereby an expert in the field of research reviews the different elements, skills and behaviors captured by an instrument in research to ensure they are adequately and effectively measured. Zohrabi adds that, this helps to eliminate or revise unclear and obscure questions while rewording complex items.

To ensure the validity of the instruments used in this study, the AAS and ICP-MS were reviewed by an expert and underwent rigorous calibration using certified reference materials and standard solutions. This process guaranteed accurate measurements before each analysis series, ensuring that the data obtained were valid and precise, truly representing the contamination levels in the water sources.

### **3.7 Reliability of the instrument**

Reliability referred to the consistency and stability of an instrument or tool over time. In research, a reliable instrument produced consistent results when repeated measurements were taken under the same conditions, allowing researchers to trust that the instrument would yield similar results under similar circumstances (Creswell, 2014).

Yakubu (2015) added that reliability is a measure of consistency of research instruments to obtain the same result with the same measure. In this study, a pilot study was conducted and Cronbach Alpha co-efficient of 0.70 served as the criterion for determining the overall consistency of the scales. According to McMillan and Schumacher (2010), a Cronbach alpha coefficient of at least 0.70 is indicative of internal consistency.

In this study, reliability was ensured for the AAS and ICP-MS by regularly checking their operational efficiency through routine maintenance, performance verification, and

internal standardization. This process helped ensure consistent and stable data collection across different zones over time.

### **3.8 Data Collection Procedure**

The data collection process for the study was carefully structured to ensure accurate and reliable results. Sterilized containers, including High-Density Polyethylene (HDPE) Bottles and Glass Bottles, were used to collect water samples from selected sources, such as boreholes and river zones, at different times throughout the year to account for seasonal variations. However, 8 samples were collected twice from each from all the 5 boreholes and the river in the community over the course of a year, with 16 samples taken during dry season and another 16 samples taken during wet season.

Specifically, 3 water samples were collected from the vantage zones of the river (down-stream, mid-stream and up-stream) near agricultural runoff, and 5 water samples were also collected in all the five boreholes in the Abotoase community in January, 2025. Again, 3 water samples were collected from the vantage zones of the river (down-stream, mid-stream and up-stream) near agricultural runoff, and 5 water samples were also collected in all the five boreholes in the Abotoase community in March, 2025. Therefore, a total 16 water samples were collected in the dry season between the periods from January to March, 2025.

In the same vein, 3 water samples were collected from the vantage zones of the river (down-stream, mid-stream and up-stream) near agricultural runoff, and 5 water samples were also collected in all the five boreholes in the Abotoase community in May, 2025. Again, 3 water samples were collected from the vantage zones of the river (down-stream, mid-stream and up-stream) near agricultural runoff, and 5 water samples were also collected in all the five boreholes in the Abotoase community in June, 2025.

Therefore, a total 16 water samples were collected in the wet season between the periods from May to June, 2025.

Therefore, 32 water samples were collected in both dry and wet seasons of the year 2025 for this study.

These samples were subsequently analyzed in the laboratory using advanced instruments such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to detect and identify the presence of heavy metals to gather data to answer Research Question 1.

The quantitative analysis of the collected samples was performed using AAS and ICP-MS to measure the concentrations of heavy metals. The results were compared with standardized guidelines (WHO standards) to assess whether the detected levels pose potential health risks to gather data to answer Research Question 2.

The 32 samples were collected at different times of the year to capture seasonal variations. The concentration of the detected heavy metals from the 16 water samples in the dry season was compared to the concentration of the detected heavy metals from the 16 water samples in the wet season. This ensured that temporal changes in heavy metal concentrations, influenced by factors such as agricultural runoff or reduced water levels to gather data to answer Research Question 3.

After determining the concentrations of heavy metals in the water sources, the results were compared to established health-based standards and guidelines (e.g., WHO or local environmental health regulations). This comparison allowed for an evaluation of whether the concentrations of metals like lead, mercury, arsenic, cadmium, and others exceed safe limits and could pose health risks to the local population, particularly

regarding long-term exposure. The health risk assessment was based on both the concentration data and the established threshold values for safe drinking water to gather data to answer Research Question 4.

However, pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), and alkalinity were also detected and analysed.

**Table 1: Schedule for data collection at the Tapa Abotoase Community**

s/n	Season	Month	River sample	Borehole sample	Total sample
1	Dry	January	3	5	16
		March	3	5	
2	Wet	May	3	5	16
		June	3	5	
<b>Total</b>			<b>12</b>	<b>20</b>	<b>32</b>

### 3.9 Field Data Collection for various parameters

Field sampling was conducted in six months (January to June, 2025) at eight selected sampling locations. Physical water quality characteristics was measured using a pre-calibrated multimeter (YS1 Pro Plus and HI98194; Yellow Springs, OH, USA). Sampling protocols were designed to minimize sample contamination. In situ water temperature measurements, pH, electrical conductivity (EC), and total dissolved solids (TDS) were recorded using a multimeter (YS1 Pro Plus and HI98194; Yellow Springs, OH, USA).

Water samples were collected using a clean 1 L Nalgene bottles (Thermo Fisher Scientific, Whatman, MA, USA) and rinsed three times with site water before the final

sample was taken. Samples were stored on wet ice until they were returned to the Ecological laboratory of the University of Ghana, Legon (within 10 hours of collection).

### **3.9.1 Laboratory Analysis**

The following analyses were carried out in the laboratory exclusively: Total suspended solids, Turbidity, Residual chlorine, Total coliform and Fecal Coliform.

### **3.9.2 Heavy Metal Analysis (Fe, Pb, Cd, Cu, Hg, As)**

Heavy metal concentrations, including iron (Fe), lead (Pb), cadmium (Cd), copper (Cu), mercury (Hg), and arsenic (As), were determined using a PinAAcle 900T Atomic Absorption Spectrophotometer (AAS) from PerkinElmer. Samples were preserved immediately after collection using nitric acid ( $\text{HNO}_3$ ) to a  $\text{pH} < 2$  and stored at  $4^\circ\text{C}$  until analysis (PerkinElmer, 2013).

Prior to analysis, samples were digested using nitric acid following the USEPA Method 200.9. Standard solutions for each metal were prepared from certified reference materials to calibrate the AAS. Each sample was aspirated into the flame or graphite furnace (as appropriate) for metal quantification. Mercury and arsenic were analyzed using the cold vapor and hydride generation techniques, respectively. Concentrations were reported in micrograms per liter ( $\mu\text{g/L}$ ) (USEPA, 1994)

### **3.9.3 Total Suspended Solids**

Total Suspended Solids were measured using the HACH photometric method (Method 8006). Samples were blended for two minutes to ensure uniformity. A HACH spectrophotometer (Model DR6000) was used to determine the amount of suspended solids in the samples after instrument was calibrated using a 25 mL distilled water. After the calibration, 25mL of the blended sample was pour into a clean sample cells, and

their exterior was wiped to remove smudges before each reading. Results were recorded in milligrams per liter (mg/L).

#### **3.9.4 Turbidity**

Turbidity was measured using a HACH 2100P Portable Turbidimeter. The instrument was calibrated prior to use with StablCal® standard solutions according to the manufacturer's instructions. Water samples were gently mixed to avoid bubble formation and were transferred into clean, scratch-free sample cells. After wiping the cells to ensure optical clarity, they were placed in the turbidimeter. Turbidity readings were recorded in Nephelometric Turbidity Units (NTU) (HACH, 2002).

#### **3.9.5 Colour (C)**

The apparent color of water was determined using a HACH DR3900 spectrophotometer following HACH Method 8025. Water samples were filtered to remove turbidity where necessary (HACH, 2018). The sample was placed in a clean cell, and the absorbance was measured at 455 nm. Calibration was conducted using platinum-cobalt (Pt-Co) color standards. Results were expressed in Pt-Co units (APHA, 2017).

#### **3.9.6 Residual Chlorine (RC)**

Residual chlorine was analyzed using the DPD (N,N-diethyl-p-phenylenediamine) colorimetric method following HACH Method 8021. Both Free and Total Chlorine were determined. For free chlorine analysis, a DPD Free Chlorine reagent pillow was added to a 10 mL water sample in a clean cell, mixed, and then measured using the spectrophotometer. For total chlorine, a DPD Total Chlorine reagent pillow was added to a separate sample, and the procedure was repeated. Results were expressed in milligrams per liter (mg/L) (HACH, 2018).

### **3.9.7 Total Alkalinity**

Total Alkalinity was measured by acid titration using sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and bromocresol green-methyl red indicator according to Standard Method 2320 B. A 100 mL sample was titrated with standardized 0.02 N sulfuric acid until the endpoint color changed from blue-green to pink. Alkalinity was calculated and reported as mg/L of CaCO<sub>3</sub> (HACH, 2017)

### **3.9.8 Total and Fecal Coliform**

Bacteriological analysis was conducted using the membrane filtration technique in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). A 100 mL water sample was filtered through a sterile 0.45 µm membrane filter using a vacuum filtration unit. The filter was then placed on selective media: m-Endo agar for total coliforms, incubated at 35°C for 24 hours m-FC agar for fecal coliforms, incubated at 44.5°C for 24 hours.

Colonies with a metallic sheen were counted as total coliforms, while blue colonies were identified as fecal coliforms. Results were recorded as colony-forming units per 100 milliliters (CFU/100 mL) (APHA, 2017).

### **3.9.9 Heavy Metal Analysis (Fe, Pb, Cd, Cu, Hg, As)**

Heavy metal concentrations, including iron (Fe), lead (Pb), cadmium (Cd), copper (Cu), mercury (Hg), and arsenic (As), were determined using a PinAAcle 900T Atomic Absorption Spectrophotometer (AAS) from PerkinElmer. Samples were preserved immediately after collection using nitric acid (HNO<sub>3</sub>) to a pH < 2 and stored at 4°C until analysis (PerkinElmer, 2013).

Prior to analysis, samples were digested using nitric acid following the USEPA Method 200.9. Standard solutions for each metal were prepared from certified reference

materials to calibrate the AAS. Each sample was aspirated into the flame or graphite furnace (as appropriate) for metal quantification. Mercury and arsenic were analyzed using the cold vapor and hydride generation techniques, respectively. Concentrations were reported in micrograms per liter ( $\mu\text{g/L}$ ) (USEPA, 1994)

### **3.10 Data analysis**

Yakubu (2015) define data analysis as the process of organizing and summarizing data, using descriptive statistics and/or inferential statistics. As mentioned earlier, this study employed both quantitative and qualitative methods of data analysis. Data quality checks were done after every interview to find if there was any necessary information for the study that was missing. When the process of data collection was over, the raw data were transcribed.

Laboratory analysis was conducted to determine the presence of heavy metals in the water sources at different times of the year using Atomic Absorption Spectroscopy (AAS) to answer the research question one.

Laboratory analysis was conducted to determine the concentrations of the detected heavy metals in the water sources at different times of the year using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and the measured concentrations compared with World Health Organization (WHO) guideline values to determine levels of exceedance to answer research question two.

The seasonal variations in level of concentration of the detected heavy metals in drinking water sources from the Tapa Abotoase community during the dry and wet seasons of 2025 were obtained by employing Paired T-test statistical tool with statistical

significance set at  $p < 0.05$  to identify meaningful seasonal differences to answer research question three.

Health risk assessment was carried out using established United States Environmental Protection Agency (USEPA) models to evaluate the potential non-carcinogenic and carcinogenic risks associated with exposure to the detected heavy metals for the consumers in the Tapa Abotoase Community to answer research question four.

Python-based statistical tools were employed for data analysis. Descriptive statistics, including frequencies, percentages, mean values, standard deviations, ranges, coefficients of variation, and percentile values, were computed using standard statistical functions to summarise the heavy metal concentrations in the various water sources.

### **3.11 Ethical consideration**

According to Creswell (2002), the site where research takes place and gaining permission before entering a site is very paramount in research. Ethical consideration is part of the research works, and cannot be avoided (Bryman, 2004). According to Jack and Norman (2003), it is necessary in every research study, to treat ethical issues with a high degree of caution. The researcher obtained the necessary permissions from relevant authorities or landowners before accessing the river and boreholes. The researcher adhered to safety guidelines while collecting water samples to prevent any harm to themselves or the environment.

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.0 Overview

Chapter four presents the results and interpretation of the study. It also discusses findings with relevant literature to position the study in a clear literature context.

#### 4.1 Research question 1: *What heavy metals are present in the drinking water sources of the Tapa Abotoase community?*

The results obtained have been presented below:

**Table 2: Showed the heavy metals detection in the drinking water sources at the Tapa Abotoase community**

Heavy metal traces	Samples in mg/L								WHO Guide Line	WHO Comp %	WHO Exc. %
	S1	S2	S3	S4	S5	S6	S7	S8	WHO		
<b>Iron</b>	0.071	0.073	0.167	0.179	0.072	0.137	0.347	0.367	0.30	<b>68.8</b>	<b>31.2</b>
	0.062	0.075	0.172	0.188	0.075	0.142	0.554	0.362	0.30		
	0.051	0.081	0.262	0.192	0.081	0.422	0.532	0.421	0.30		
	0.078	0.052	0.249	0.201	0.083	0.421	0.612	0.462	0.30		
<b>Copper</b>	0.009	0.003	0.001	0.002	0.004	0.001	0.001	0.001	1.00	<b>100</b>	<b>0.0</b>
	0.008	0.002	0.001	0.003	0.004	0.001	0.001	0.001	1.00		
	0.007	0.005	0.001	0.004	0.003	0.001	0.001	0.001	1.00		
<b>Lead</b>	0.004	0.001	0.001	0.001	0.001	<0.001	<0.001	<0.001	0.01	<b>90.6</b>	<b>9.4</b>
	0.03	0.002	0.001	0.001	0.001	<0.001	<0.001	—	0.01		
	0.05	0.003	0.001	0.001	0.001	<0.001	<0.001	<0.001	0.01		
	0.06	0.001	0.001	0.001	0.001	<0.001	<0.001	—	0.01		
<b>Cadmium</b>	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	<b>100</b>	<b>0.0</b>
	0.001	0.002	0.001	0.001	0.001	0.001	0.001	—	0.003		
	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003		
	0.003	0.001	0.001	0.001	0.001	0.001	0.001	—	0.003		
<b>Arsenic</b>	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.001	<b>100</b>	<b>0.0</b>
	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	—	0.001		
	0.0001	0.0001	<0.0002	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.001		
	0.0001	0.0001	<0.0002	<0.0001	<0.0001	0.0001	<0.0001	—	0.001		
<b>Mercury</b>	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.006	<b>100</b>	<b>0.0</b>
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	—	0.006		
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.006		
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	—	0.006		

**KEY:** Total sample = 32 from 8 locations, S1 =well water sample, 1, S2 = well water sample 2, S3 =well water sample 3, S4 = well water sample 4, S5 = well water sample 5, S6 = down-stream water sample, S7 = mid-stream water sample, S8 = and up-stream water sample, mg/L = milligrams per liter, WHO Ex.= World Health Organization exceedance percentage, WHO comp. = World Health compliance percentage.

**4.1.1 Discussion of result in relation to research question 1:** *What heavy metals are present in the drinking water sources of the Tapa Abotoase community?*

The Table revealed that Iron (Fe) and Lead (Pb) were the most concerned contaminants, while Copper (Cu), Cadmium (Cd), Arsenic (As), and Mercury (Hg) generally remained within safe limits. Iron concentrations ranged between 0.051 and 0.612 mg/L, compared to the WHO guideline value of 0.3 mg/L. Out of the 32 samples analyzed, 10 exceeded the permissible limit, representing 31.2% non-compliance. The WHO compliance rate was therefore 68.8%, indicating that almost one-third of the community's drinking water samples contained elevated iron levels. High concentrations of iron in water were known to cause unpleasant taste, staining of laundry, and clogging of pipes, and prolonged exposure could pose health risks such as liver damage. This made iron a significant concern in the community's drinking water quality.

Copper levels, on the other hand, were found to be very low, ranging from 0.001 to 0.009 mg/L, which was far below the WHO permissible limit of 1.0 mg/L. All samples (100%) complied with the standard, with no exceedance recorded. This indicated that copper did not present any contamination issue in the sampled sources and therefore posed a very low health risk. Similarly, mercury and arsenic were found at trace levels (0.0001 mg/L or less), well below their WHO permissible limits of 0.006 mg/L and 0.001 mg/L respectively. Both recorded 100% compliance and 0% exceedance. These

results suggested that mercury and arsenic were not contaminants of concern in the drinking water sources at Abotoase.

Lead (Pb) levels ranged from  $<0.001$  to  $0.060$  mg/L, against the WHO permissible guideline of  $0.01$  mg/L. Although the majority of the samples were within the safe limit, three exceeded the guideline, giving a 9.4% exceedance and a compliance rate of 90.6%. The maximum recorded value ( $0.06$  mg/L) was six times higher than the WHO standard. Lead is a toxic heavy metal that could cause severe health effects, including neurological disorders, kidney damage, and developmental impairments in children. The detection of non-compliant samples therefore raised significant public health concerns, even though the proportion was relatively low.

Cadmium (Cd) concentrations were in the range of  $0.001$  to  $0.003$  mg/L, equal to or below the WHO guideline of  $0.003$  mg/L. All samples complied (100%), with no exceedance recorded. However, the detection of values at the threshold level explained why cadmium was categorized under moderate risk in the summary table. This was because cadmium is highly toxic and bio accumulative, and even near-limit concentrations could pose health risks with long-term exposure. The results therefore called for continuous monitoring of cadmium levels in the community's drinking water sources.

Iron concentrations in Abotoase drinking water ranged from  $0.051$  to  $0.612$  mg/L, with 31.2% of samples exceeding the WHO guideline of  $0.3$  mg/L. This made iron the most widespread contaminant of concern in the community. Although iron was not classified as acutely toxic, elevated levels caused serious water-quality problems such as unpleasant taste, staining of laundry, clogging of pipes, and, in chronic cases, organ effects including liver damage. This was consonant with WHO (2022), which stated that

excessive iron in drinking water does not usually result in acute health effects but may lead to chronic organ damage and technical problems in water supply systems. Similar exceedances of iron have been reported in rural Ghanaian water sources due to natural geochemical leaching and agricultural runoff (Opoku *et al.*, 2023). Copper levels in Abotoase water were very low (0.001–0.009 mg/L), far below the WHO limit of 1.0 mg/L, with 100% compliance recorded. This indicated that copper did not pose any contamination issue in the community. This was consistent with WHO (2022), which emphasized that copper is an essential trace element, and concentrations below guideline values pose no health concern. Similarly, Opoku *et al.* (2023) found that copper contamination was generally absent in groundwater from rural Ghana, further supporting the findings from Abotoase.

Mercury was detected only at trace levels ( $\leq 0.0001$  mg/L), well below the WHO limit of 0.006 mg/L, with 100% compliance. This suggested that mercury was not a contaminant of concern in the Abotoase water sources. This aligned with WHO (2022), which reported that mercury in drinking water should remain at trace levels, as higher concentrations can impair neurological and renal functions. However, Mensah *et al.*, (2023) warned that communities near artisanal mining activities in Ghana often recorded elevated mercury levels, highlighting the need for continuous monitoring despite the current safe status in the Tapa Abotoase Community.

Arsenic was found at trace levels ( $\leq 0.0001$  mg/L), which was below the WHO guideline of 0.001 mg/L, with full compliance across all samples. This finding was consonant with WHO (2022), which stressed that arsenic is a Group 1 carcinogen and therefore must be kept at concentrations as low as possible to avoid chronic health effects. Kumar *et al.*,

(2022) further noted that long-term arsenic exposure, even at low levels, has been linked to cancers of the skin, lungs, and bladder.

Lead concentrations ranged from  $<0.001$  to  $0.060$  mg/L, with 9.4% of samples exceeding the WHO limit of  $0.01$  mg/L. The maximum concentration recorded was six times higher than the permissible guideline, raising significant health concerns. This finding was consistent with WHO (2022), which affirmed that there is no safe exposure level for lead, as even minimal concentrations can impair neurological development, kidney function, and cardiovascular health. USEPA (2023) similarly highlighted lead as a critical drinking water contaminant requiring strict regulation. In Ghana, Boateng *et al.*, (2022) and Opoku *et al.*, (2023) also reported elevated some lead concentrations in water sources near mining and agricultural zones, reflecting patterns comparable to Abotoase. Cadmium concentrations were in the range of  $0.001$  to  $0.003$  mg/L, meeting the WHO guideline of  $0.003$  mg/L, although some samples reached the threshold value. This was consonant with WHO (2022), which noted that cadmium is a toxic and bioaccumulative metal, and long-term exposure near guideline levels can damage the kidneys and skeletal system. Ali *et al.*, (2023) emphasized cadmium's carcinogenic potential, recommending strict monitoring of water sources that approach the permissible limit. The detection of cadmium at threshold levels in Abotoase therefore justified continued surveillance.

Finally, the findings regarding the research question one demonstrated that most heavy metals in Abotoase complied with WHO standards, except for iron and lead, which exceeded their limits in 31.2% and 9.4% of samples respectively. This pattern pointed to localized contamination from geochemical, agricultural, or anthropogenic sources.

The results aligned with the Boateng et al., 2022, who emphasized that iron and lead frequently represent the most problematic contaminants in rural Ghanaian water systems. The exceedances observed in Abotoase highlighted the potential risks of long-term exposure and underscored the importance of routine monitoring, mitigation measures, and public-health education to safeguard the community (Opoku *et al.*, 2023).

**4.2 Research question 2:** *What are the concentration levels of the heavy metals present in the drinking water sources of the Tapa Abotoase community?*

This research question was intended to examine the concentration level of the detected heavy metals present in the drinking water sources at the Tapa Abotoase community. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was employed to measure the concentrations of heavy metals. The results obtained have been presented below:

**Table 3: Heavy metals detection characterization summary in the drinking water sources at the Tapa Abotoase community**

Heavy Metal	DR (%)	SD	M ± SD (mg/L)	Range (mg/L)	WHO Limit (mg/L)	WHO Comp.%	Risk Level
Iron	100 .0	32/ 32	0.2263 $\hat{A}\pm$ 0.1695	0.0510 - 0.6120	0.3	68.80	High
Copper	100 .0	32/ 32	0.0028 $\hat{A}\pm$ 0.0024	0.0010 - 0.0090	1	100	Low
Lead	100 .0	32/ 32	0.0053 $\hat{A}\pm$ 0.0141	0.0005 - 0.0600	0.01	90.60	High
Cadmium	100 .0	32/ 32	0.0011 $\hat{A}\pm$ 0.0004	0.0010 - 0.0030	0.003	100	Moderate
Arsenic	100 .0	32/ 32	0.0001 $\hat{A}\pm$ 0.0000	0.0001 - 0.0001	0.001	100	Low
Mercury	100 .0	32/ 32	0.0001 $\hat{A}\pm$ 0.0000	0.0001 - 0.0001	0.006	100	Low

**Key:** DR = detection rate percentage, SD = samples detected, M = Mean; SD =

Standard Deviation, mg/L = milligrams per liter.

**4.2.1 Discussion of result in relation to research question 2:** *What are the concentration levels of the heavy metals present in the drinking water sources of the Tapa Abotoase community?*

The analysis of heavy metals in drinking water sources at Tapa Abotoase showed that all six metals under investigation were detected across the 32 samples (100% detection rate). Their concentration levels varied when compared with WHO guideline values, and the degree of compliance differed across the metals as showed in Table 3.

From Table 3, Iron (Fe) had a mean concentration of  $0.2263 \pm 0.1695$  mg/L, with values ranging from 0.0510 to 0.6120 mg/L. The WHO limit for iron in drinking water is 0.3 mg/L, and 31.2% of samples exceeded this guideline, resulting in a compliance rate of 68.8%. This highlighted iron as a major contaminant in the study area and it was classified as high risk. The elevated concentrations indicated significant localized contamination, with some samples recording values up to twice the WHO permissible limit.

Copper (Cu) concentrations were very low, with a mean of  $0.0028 \pm 0.0024$  mg/L and a range of 0.0010–0.0090 mg/L. These values were far below the WHO guideline of 1.0 mg/L, yielding 100% compliance and a low-risk classification. Copper therefore did not pose any contamination concern in the community's water sources.

Lead (Pb) showed a mean concentration of  $0.0053 \pm 0.0141$  mg/L, with a range of 0.0005–0.0600 mg/L. The WHO permissible limit for lead is 0.01 mg/L. Although most samples complied with this standard, three exceeded the guideline, giving a compliance rate of 90.6% and a non-compliance rate of 9.4%. The highest concentration recorded (0.0600 mg/L) was six times higher than the WHO guideline, which indicated a serious health risk. Lead was therefore categorized as a high-risk contaminant in the

community's drinking water sources despite the overall mean concentration being below the standard.

Cadmium (Cd) concentrations ranged from 0.0010 to 0.0030 mg/L, with a mean of  $0.0011 \pm 0.0004$  mg/L. The WHO guideline value is 0.003 mg/L, and all samples complied (100%). However, since some values were at the threshold, cadmium was placed under a moderate risk classification. Although compliance was achieved, cadmium's high toxicity and bio-accumulative nature justified close monitoring of its presence in the community's water sources.

Arsenic (As) levels were consistently low, with a mean concentration of 0.0001 mg/L and no variation (range 0.0001–0.0001 mg/L). Compared with the WHO guideline of 0.001 mg/L, arsenic showed 100% compliance and was classified as low risk, indicating that arsenic did not constitute a contamination problem in the study area. Similarly, mercury (Hg) concentrations were very low, with a mean of 0.0001 mg/L and a range of 0.0001–0.0001 mg/L. The WHO limit is 0.006 mg/L, meaning all samples complied (100%) and were classified as low risk. Mercury was therefore not a contaminant of concern in the sampled water sources.

The analysis of heavy metals in drinking water sources at Tapa Abotoase showed that all six metals under investigation were detected across the 32 samples, giving a 100% detection rate. Their concentration levels varied when compared with WHO guideline values, and the degree of compliance differed across the metals. This variation is consistent with Opoku *et al.*, 2023, who postulated natural geochemical processes and localized anthropogenic activities.

Iron recorded a mean concentration of  $0.2263 \pm 0.1695$  mg/L, with values ranging from 0.0510 to 0.6120 mg/L. The WHO guideline for iron in drinking water is 0.3 mg/L, and 31.2% of samples exceeded this limit, producing a compliance rate of only 68.8%. This positioned iron as a major contaminant of concern in the study area and it was categorized as high risk. The elevated concentrations indicated localized contamination, with some samples recording values up to twice the WHO permissible limit. This finding was consonant with WHO (2022), which noted that excessive iron concentrations, although not acutely toxic, may cause chronic organ damage and technical problems in water systems. Similar iron exceedances have been reported in Ghanaian communities due to leaching of iron-bearing rocks, agricultural runoff, and poorly protected underground water sources (Boateng *et al.*, 2022).

Copper concentrations were very low, with a mean of  $0.0028 \pm 0.0024$  mg/L and a range of 0.0010–0.0090 mg/L. These values were well below the WHO guideline of 1.0 mg/L, resulting in 100% compliance and a low-risk classification. This suggested that copper contamination was not an issue in the community's water sources. WHO (2022) emphasized that copper is an essential trace element and that concentrations below the permissible guideline pose no significant health risks. The present findings agreed with Opoku *et al.* (2023), who similarly reported negligible copper level in the groundwater from the rural Ghana. Lead showed a mean concentration of  $0.0053 \pm 0.0141$  mg/L, with values ranging from 0.0005 to 0.0600 mg/L. Against the WHO limit of 0.01 mg/L, three samples exceeded the guideline, giving a non-compliance rate of 9.4% and a compliance rate of 90.6%.

Although the overall mean value was below the WHO standard, the highest concentration recorded (0.0600 mg/L) was six times the permissible limit, which

highlighted a significant public-health risk. This aligned with WHO (2022), which stressed that there is no safe exposure level for lead, as even minimal concentrations can impair neurological development and kidney function. USEPA (2023) also categorized lead as one of the most critical drinking water contaminants requiring strict regulatory enforcement. In Ghana, Boateng et al. (2022) and Mensah et al., (2023) similarly observed elevated lead levels in communities near mining and agricultural areas, findings that were consistent with the Abotoase results. Cadmium concentrations ranged from 0.0010 to 0.0030 mg/L, with a mean of  $0.0011 \pm 0.0004$  mg/L. All samples complied with the WHO guideline of 0.003 mg/L, but some values reached the threshold limit. This justified the classification of cadmium under moderate risk. WHO (2022) highlighted that cadmium is a toxic and bioaccumulative metal, with long-term exposure even near permissible levels capable of causing kidney damage and skeletal disorders.

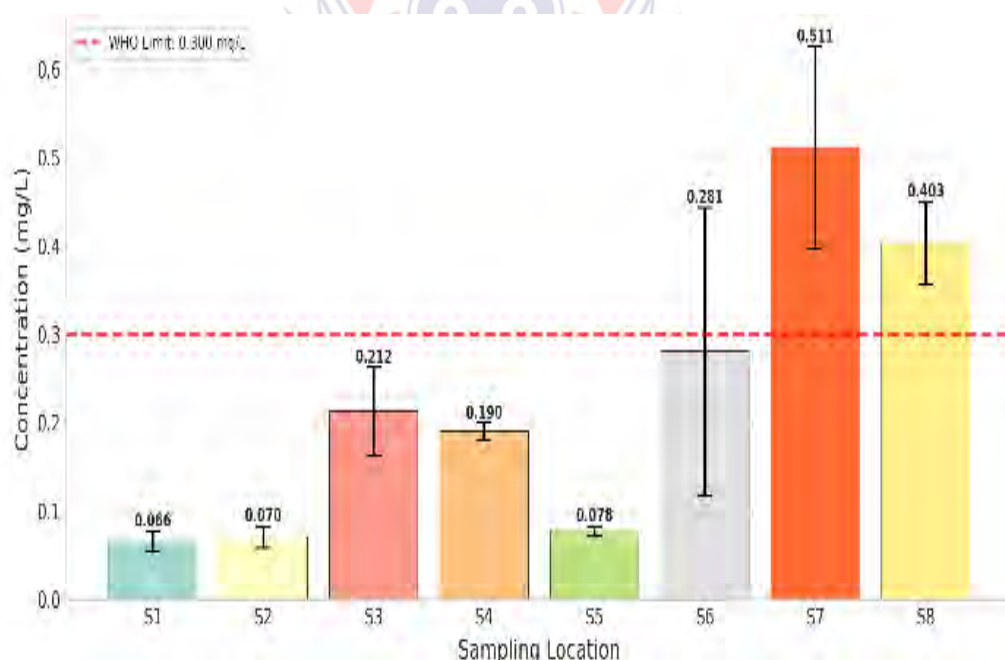
Again, Ali et al. (2023) also emphasized that cadmium's carcinogenic potential, recommending close monitoring wherever values approach guideline limits.

Arsenic levels were consistently low, with a mean concentration of 0.0001 mg/L and no variation across samples. Compared with the WHO guideline of 0.001 mg/L, arsenic showed 100% compliance and was classified as low risk, suggesting it was not a contaminant of concern in Abotoase. Nevertheless, WHO (2022) cautioned that arsenic is a Group 1 carcinogen, with long-term exposure linked to cancers of the skin, lungs, and bladder. This finding agreed with Kumar et al., (2022), who noted that even trace arsenic levels could accumulate over time, warranting ongoing vigilance despite compliance.

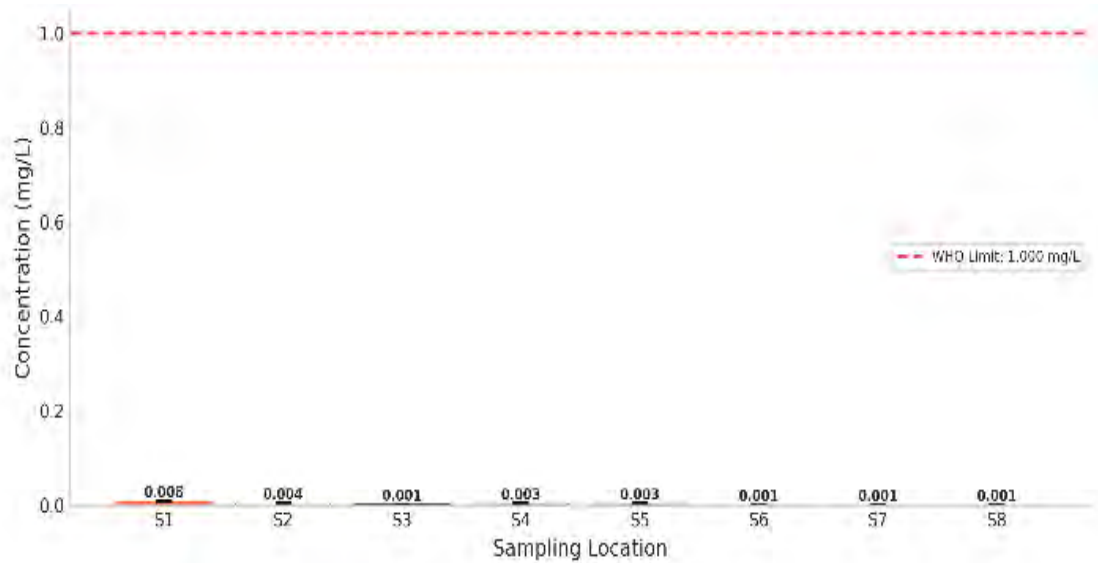
Mercury concentrations were very low, with a mean of 0.0001 mg/L and a range of 0.0001–0.0001 mg/L. These values were well below the WHO limit of 0.006 mg/L,

yielding 100% compliance and a low-risk classification. This indicated that mercury was not a contaminant of concern in the study area. WHO (2022) reported that mercury exposure at higher levels can cause neurological and renal damage, particularly in communities affected by artisanal mining Mensah et al., (2023). Similarly observed mercury exceedances in mining-impacted areas, but the safe levels detected in Abotoase suggested that mining-related contamination was not a current issue, though continuous monitoring remained essential.

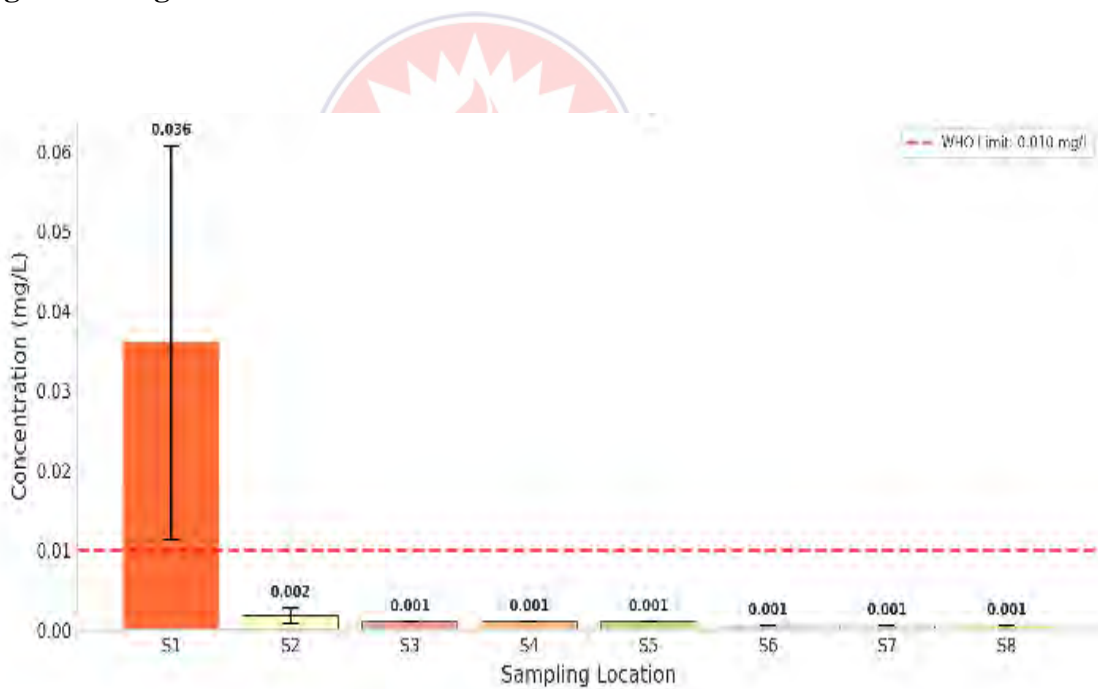
Therefore, while copper, cadmium, arsenic, and mercury remained within WHO permissible limits, iron and lead exceeded guideline values in 31.2% and 9.4% of samples, respectively. These exceedances positioned iron and lead as the key contaminants of concern for drinking water safety in the community. The findings were consistent with prior studies in Ghana and other developing regions, which highlighted iron and lead as the most frequent water quality challenges (Opoku et al., 2023).



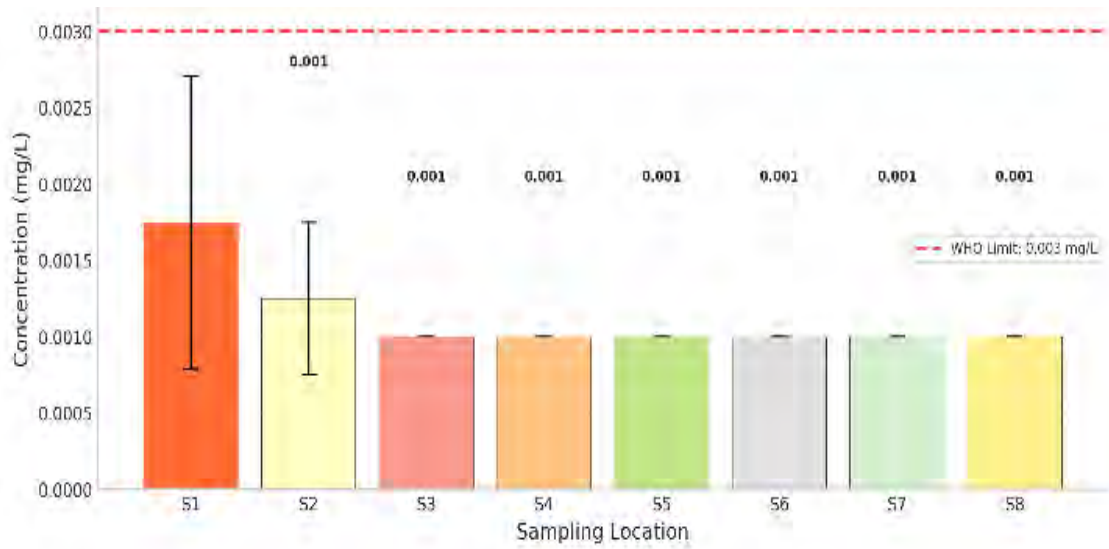
**Figure 2a: Iron concentration by sampling location with World Health Organization guidelines**



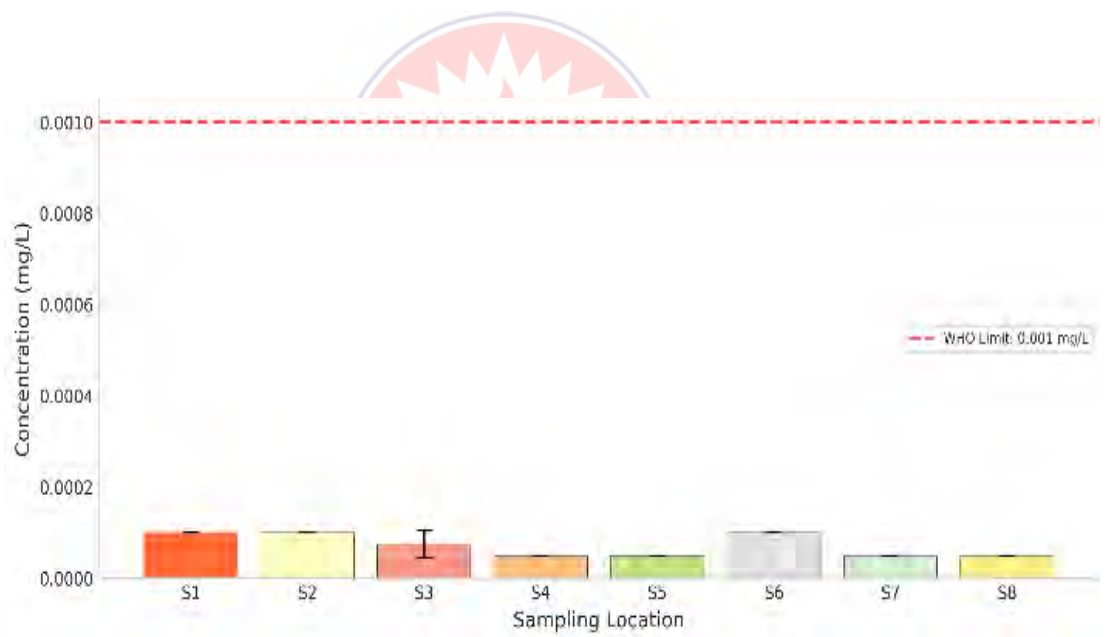
**Figure 2b: Copper concentration by sampling location with World Health Organization guidelines**



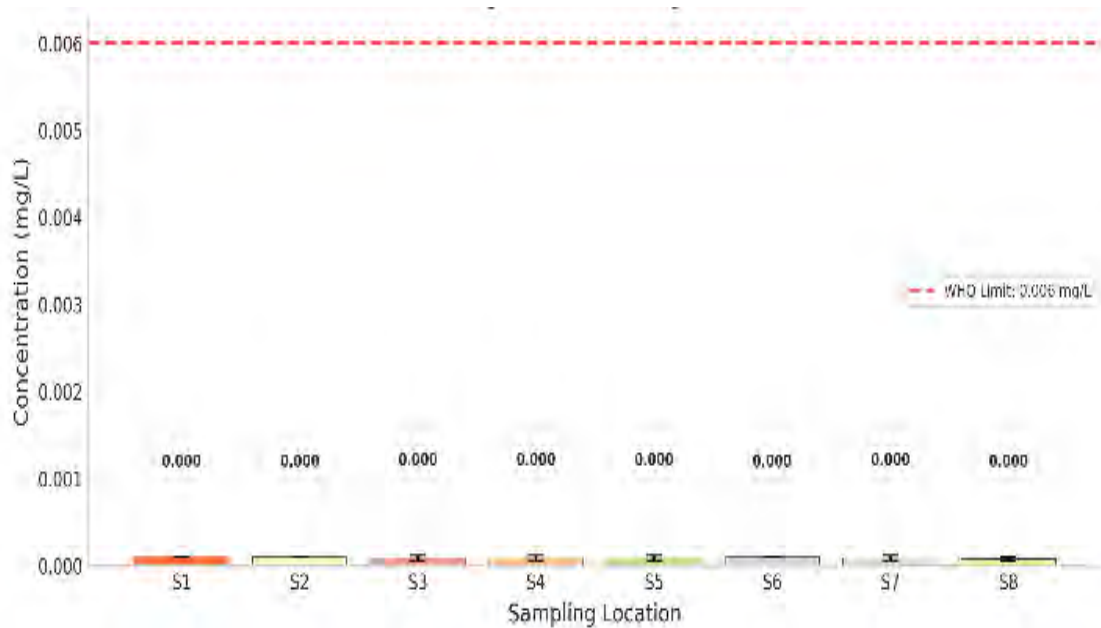
**Figure 2c: Lead concentration by sampling location with World Health Organization guidelines**



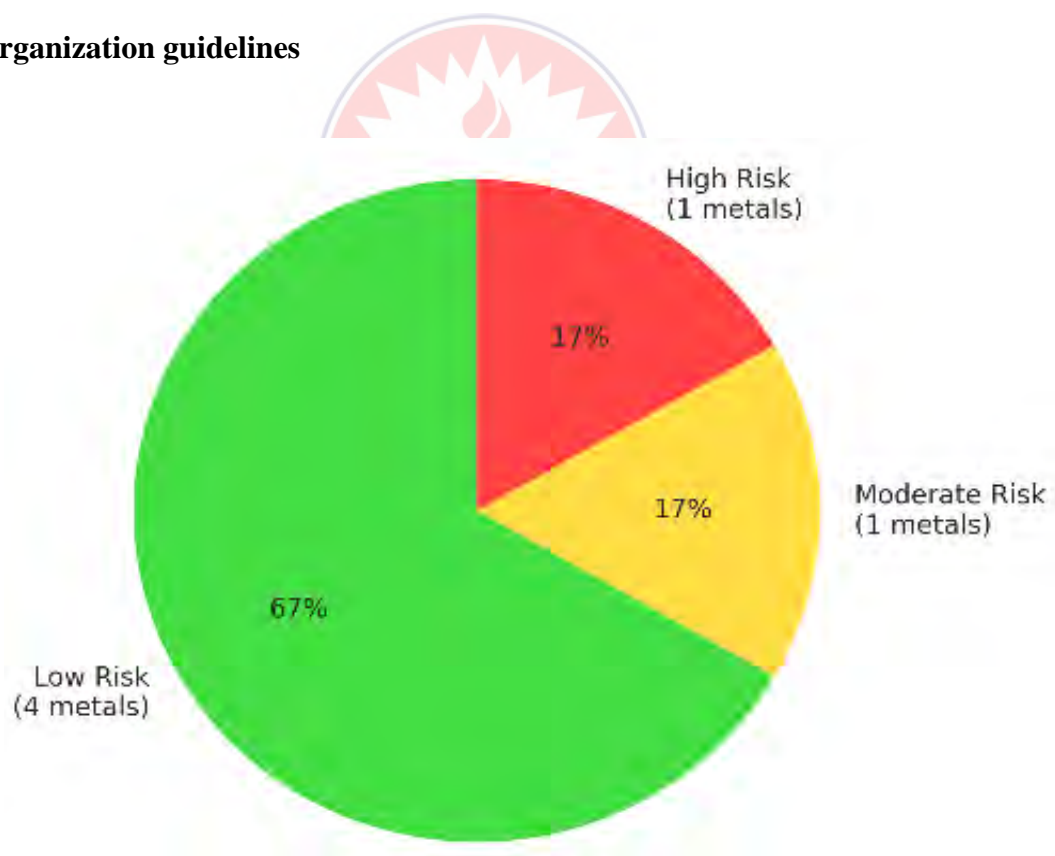
**Figure 2d: Cadmium concentration by sampling location with World Health Organization guidelines**



**Figure 2e: Arsenic concentration by sampling location with World Health Organization guidelines**



**Figure 2f: Mercury concentration by sampling location with World Health Organization guidelines**



**Figure 2g: Heavy metal risk classification based on WHO exceedance rates**

#### 4.2.3 Discussion of figure 2a – figure 2g in respect to RQ.2

The results presented in Figure 2a showed variations in iron concentration across the different sampling locations within the Tapa Abotoase community. In most locations, iron levels were within the permissible limit of 0.3 mg/L set by the World Health Organization (WHO, 2017). However, a few sites recorded slightly higher values, which were attributed to natural leaching from iron-bearing rocks, corrosion of metal pipes, or domestic waste discharge into water bodies (Alloway, 2013). Although iron was not highly toxic, excessive amounts caused metallic taste, staining of household items, and aesthetic water quality issues (Tchounwou *et al.*, 2012).

Figure 2b indicated that, copper concentrations in all sampling points were generally below the WHO guideline value of 2.0 mg/L (WHO, 2017). The low levels of copper suggested minimal contamination from plumbing systems or industrial sources in the study area. This implied that the community's water sources were relatively free from copper-related pollution and posed no significant health risk in this regard. Similar observations were made by Singh *et al.* (2020), who reported low copper levels in rural water systems where industrial influence was minimal.

As shown in Figure 2c, lead concentrations in some sampling locations exceeded the WHO acceptable limit of 0.01 mg/L (WHO, 2017). Elevated lead levels were likely due to corroded pipelines, improper waste disposal, or runoff from nearby settlements and refuse dumps (Ali *et al.*, 2019). Prolonged exposure to lead-contaminated water was considered a serious health concern, potentially causing neurological, developmental, and kidney problems, especially in children (Tchounwou *et al.*, 2012). These findings were consistent with Awuah *et al.* (2020), who reported similar lead contamination patterns in other Ghanaian communities with aging water infrastructure.

According to Figure 2d, cadmium levels were very low or undetectable in most water samples, remaining below the WHO guideline of 0.003 mg/L (WHO, 2017). This implies that cadmium contamination was not a major issue in the study area. However, continuous monitoring was deemed necessary since cadmium could enter water sources through fertilizer runoff, industrial waste, or corrosion of galvanized materials (Jarup, 2003). Cadmium exposure, even at low concentrations, had been associated with kidney dysfunction and skeletal damage (Tchounwou *et al.*, 2012).

Figure 2e showed that arsenic concentrations varied slightly across sampling sites but remained within the WHO guideline limit of 0.01 mg/L (WHO, 2017). The acceptable levels observed indicated limited geological or anthropogenic arsenic input into the water sources. Nonetheless, since arsenic was a potent toxin associated with skin lesions, cardiovascular diseases, and cancer, its presence even at low levels called for ongoing surveillance (Naujokas *et al.*, 2013). Similar findings were reported by Smedley and Kinniburgh (2017), who emphasized the need for continuous monitoring of arsenic in groundwater in West African regions.

From Figure 2f, mercury concentrations in all sampled water sources were well below the WHO guideline value of 0.006 mg/L (WHO, 2017). This indicated that there was no significant mercury pollution in the community's drinking water. The absence of high mercury levels was attributed to a lack of mining or industrial activities in the vicinity, which were typically sources of mercury contamination (Wang *et al.*, 2021). Despite the low concentrations, periodic testing was recommended due to the bioaccumulative nature of mercury in aquatic systems and its potential to pose long-term ecological and health risks (Tchounwou *et al.*, 2012).

The figure 2g presents the risk classification of the detected heavy metals in the Tapa Abotoase drinking water sources based on WHO exceedance rates. Iron constituted the high-risk category (17%), reflecting its frequent exceedance of the WHO permissible limit in a notable proportion of the samples (WHO, 2017).

Lead accounted for the moderate-risk category (17%), indicating occasional exceedance of the WHO guideline value (WHO, 2017). Although lead was not consistently elevated across all sampling sites, its intermittent exceedance is significant due to its well-documented toxicity, particularly its neurological, developmental, and renal effects in children (Tchounwou et al., 2012). The remaining four metals copper, cadmium, arsenic, and mercury fell within the low-risk category (67%), as their concentrations were largely below WHO guideline limits across the sampled locations (WHO, 2017). While these metals did not pose immediate health risks, their presence in the water sources remains environmentally and toxicologically relevant, warranting continuous monitoring due to their cumulative and long-term health implications (Wang et al., 2021). Therefore, the figure 2g indicated that although most metals posed low risk, iron and lead represent priority contaminants requiring targeted monitoring, effective management, and public health interventions in the Tapa Abotoase community.

**Table 4: Concentration of the heavy metal detection variability coefficient across the drinking water sources at the Tapa Abotoase community**

Heavy Metal	Mean $\hat{\mu} \pm$ SD (mg/L)	Range (mg/L)	CV (%)	P95 (mg/L)	WHO Limit (mg/L)	WHO	
						Exceedance (%)	Risk Level
Iron	0.2263 $\hat{\mu} \pm$ 0.1695	0.0510 - 0.6120	74.9	0.5419	0.3	31.2	High
Copper	0.0028 $\hat{\mu} \pm$ 0.0024	0.0010 - 0.0090	84	0.008	1	0	Minimal
Lead	0.0053 $\hat{\mu} \pm$ 0.0141	0.0005 - 0.0600	266	0.039	0.01	9.4	Low
Cadmium	0.0011 $\hat{\mu} \pm$ 0.0004	0.0010 - 0.0030	37.4	0.002	0.003	0	Minimal
Arsenic	0.0001 $\hat{\mu} \pm$ 0.0000	0.0001 - 0.0001	35.1	0.0001	0.001	0	Minimal
Mercury	0.0001 $\hat{\mu} \pm$ 0.0000	0.0001 - 0.0001	20.7	0.0001	0.006	0	Minimal

**KEY:** CV = Coefficient of variability, 95 Percentile.

#### 4.2.4 Discussions on the variability in the level of concentration of the detected heavy metals in the drinking water sources

Heavy metal concentrations in the drinking water sources of Tapa Abotoase were statistically analyzed using descriptive statistics and compared with WHO drinking water guidelines. Compliance rates were calculated as the percentage of samples meeting WHO standards, and spatial analysis identified contamination hotspots across sampling locations.

The results showed that all six heavy metals investigated were detected in the 32 samples, though their concentration levels and risk classifications varied.

Iron (Fe) had a mean concentration of  $0.2263 \pm 0.1695$  mg/L, with values ranging between 0.0510 and 0.6120 mg/L. The WHO permissible limit for iron is 0.3 mg/L, and

31.2% of the samples exceeded this guideline, resulting in 68.8% compliance. The 95th percentile concentration (0.5419 mg/L) further confirmed the occurrence of elevated levels in certain locations. Notably, spatial analysis identified locations S7 and S8 as contamination hotspots, with concentrations reaching up to twice the WHO permissible value. Iron was therefore classified as a high-risk contaminant in the community.

In terms of variability, Iron (Fe) had a mean concentration of  $0.2263 \pm 0.1695$  mg/L with a range of 0.0510–0.6120 mg/L and a CV of 74.9%. This indicated moderate variability, suggesting that while iron contamination was widespread, some water sources were much more contaminated than others.

Lead (Pb) also emerged as a contaminant of concern. Its mean concentration was  $0.0053 \pm 0.0141$  mg/L, with values ranging from 0.0005 to 0.0600 mg/L. Although most samples complied with the WHO limit of 0.01 mg/L, three exceeded the standard, yielding a compliance rate of 90.6% and a non-compliance rate of 9.4%. The maximum value of 0.0600 mg/L was six times higher than the WHO permissible guideline, and the 95th percentile concentration (0.039 mg/L) reflected elevated levels in certain samples. Lead was thus classified as low risk overall but represented a significant local health concern due to its high toxicity and potential for neurological damage, especially in children.

In terms of variability, Lead (Pb) exhibited the highest variability, with a mean of  $0.0053 \pm 0.0141$  mg/L, a range of 0.0005–0.0600 mg/L, and a CV of 266.8%. This very high CV reflected inconsistent distribution of lead in the samples, with some water sources showing negligible levels while others recorded concentrations up to six times the WHO limit, posing localized but serious risks.

Comparably, copper (Cu), cadmium (Cd), arsenic (As), and mercury (Hg) all showed acceptable compliance across the samples. Copper concentrations ranged from 0.0010–0.0090 mg/L (mean  $0.0028 \pm 0.0024$  mg/L), cadmium ranged from 0.0010–0.0030 mg/L (mean  $0.0011 \pm 0.0004$  mg/L), arsenic was consistently 0.0001 mg/L, and mercury was consistently 0.0001 mg/L. These values were all well below their respective WHO limits (1.0 mg/L for Cu, 0.003 mg/L for Cd, 0.001 mg/L for As, and 0.006 mg/L for Hg), resulting in 100% compliance and minimal or moderate risk classification. However, cadmium was noted to be at the threshold level in some cases, justifying its moderate risk rating due to its bioaccumulative and toxic nature.

In a compendium, the findings demonstrated that while copper, cadmium, arsenic, and mercury posed minimal concern, iron and lead exceeded WHO permissible limits in 31.2% and 9.4% of samples, respectively. Iron contamination was particularly elevated in downstream and midstream locations (S7 and S8), which were identified as spatial hotspots. These results positioned iron and lead as the major contaminants of concern in the Tapa Abotoase drinking water sources, highlighting potential risks of long-term exposure and underscoring the importance of regular monitoring and targeted mitigation.

Again, the CV values showed that iron and lead not only exceeded WHO limits in some cases but also varied widely across water sources, pointing to specific contamination hotspots. In contrast, cadmium, arsenic, and mercury displayed low variability, while copper exhibited moderate variability but still remained within safe levels. This reinforced iron and lead as the key contaminants of concern in the community, requiring targeted monitoring and control at high-risk locations.

However, in terms of variability, Copper (Cu) recorded a mean of  $0.0028 \pm 0.0024$  mg/L, a range of 0.0010–0.0090 mg/L, and a CV of 84%. This showed relatively high variability in distribution, although all concentrations remained well below the WHO limit of 1.0 mg/L.

Cadmium (Cd) showed a mean of  $0.0011 \pm 0.0004$  mg/L, ranging from 0.0010–0.0030 mg/L, with a CV of 37.4%. This relatively low variability suggested cadmium was evenly distributed across the samples, though values close to the threshold WHO limit justified its moderate risk classification.

Arsenic (As) had a mean concentration of 0.0001 mg/L with a narrow range of 0.0001–0.0001 mg/L and a CV of 35.1%, reflecting very little variability. Mercury (Hg) was similarly consistent, with a mean of 0.0001 mg/L, a range of 0.0001–0.0001 mg/L, and a CV of 20.7%. Both were far below WHO limits and were classified as minimal risk. The mean concentration was 0.0001 mg/L, with a range of 0.0001–0.0001 mg/L, and a CV of 20.7%. This indicated very low variability, meaning mercury levels were highly consistent across all the sampled water sources. Since all values were far below the WHO guideline of 0.006 mg/L, mercury was classified as minimal risk, with no evidence of contamination.

Furthermore, the risk levels in the Table 4 were based on the extent to which the detected heavy metals complied with WHO drinking water standards.

Minimal risk denoted metals that complied fully with WHO standards in all samples, indicating negligible contamination. This was observed for copper, cadmium, arsenic, and mercury in Table 1. whose concentrations were consistently below permissible limits with 0% exceedance values in no significant contamination concern under the current conditions.

Low risk, however, referred to metals such as lead that mostly complied with WHO guidelines but showed occasional exceedances. In this case, 9.4% of the samples exceeded the WHO permissible limit for lead, although the overall mean concentration remained below the guideline. This suggested localized contamination hotspots, which, despite being statistically low in frequency, still posed potential health concerns due to lead's high toxicity.

High risk was assigned to iron, which exceeded WHO guidelines in 31.2% of the samples, indicating widespread contamination. Elevated iron levels not only affect water aesthetics but also have implications for human health and water infrastructure, making iron the most significant contaminant of concern in the study area.

The statistical analysis of heavy metal concentrations in the drinking water sources of Tapa Abotoase revealed that while all six metals investigated were detected, their concentration levels, compliance rates, and risk classifications differed considerably. Iron (Fe) emerged as the most significant contaminant. Its mean concentration of  $0.2263 \pm 0.1695$  mg/L, ranging between 0.0510 and 0.6120 mg/L, placed nearly one-third of the samples (31.2%) above the WHO permissible limit of 0.3 mg/L (WHO, 2022).

The spatial analysis further indicated that contamination was not uniformly distributed but concentrated in hotspots such as S7 and S8, where concentrations reached nearly double the WHO threshold. Iron was therefore categorized as a high-risk contaminant in the study area. The coefficient of variation (CV) of 74.9% indicated moderate variability, suggesting that while iron contamination was widespread, certain sources were disproportionately affected. These findings aligned with earlier studies that identified iron exceedances in groundwater systems linked to local geology and redox conditions (Mensah *et al.*, 2023).

Lead (Pb) was another contaminant of concern. With a mean concentration of  $0.0053 \pm 0.0141$  mg/L and values ranging from 0.0005 to 0.0600 mg/L, lead generally complied with the WHO guideline of 0.01 mg/L (WHO, 2022).

However, three samples exceeded this limit, yielding a non-compliance rate of 9.4%. Importantly, the maximum concentration of 0.0600 mg/L was six times the WHO guideline, and the 95th percentile concentration of 0.039 mg/L indicated that exceedances were not isolated outliers. The CV for lead was extremely high at 266.8%, underscoring its highly uneven distribution. This pattern reflected localized contamination hotspots, where lead pollution may result from anthropogenic activities such as plumbing materials, waste disposal, or agricultural inputs (Kumar et al., 2022). Although the overall compliance rate was high, the localized exceedances were still of great concern because of lead's cumulative neurotoxic effects, particularly in children (WHO, 2022).

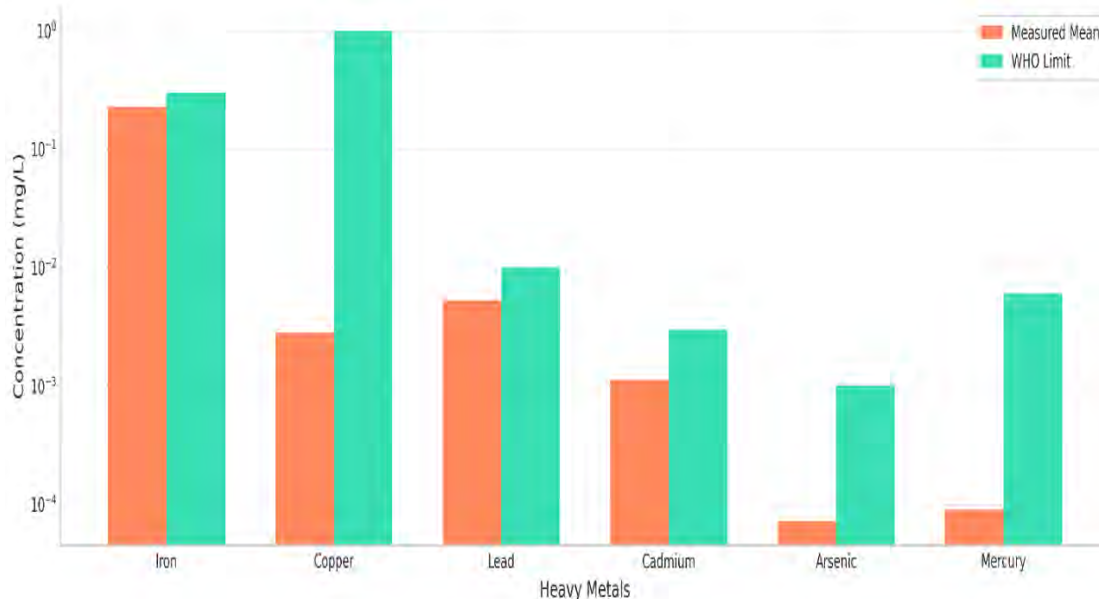
In contrast, copper (Cu), cadmium (Cd), arsenic (As), and mercury (Hg) demonstrated much lower risks. Copper concentrations ranged from 0.0010 to 0.0090 mg/L, with a mean of  $0.0028 \pm 0.0024$  mg/L, all well below the WHO guideline of 1.0 mg/L. Despite recording relatively high variability (CV = 84%), copper remained compliant in 100% of samples and was therefore classified as minimal risk. Cadmium concentrations ranged from 0.0010 to 0.0030 mg/L (mean  $0.0011 \pm 0.0004$  mg/L), placing some values at the WHO threshold of 0.003 mg/L. Although compliance remained 100%, cadmium was classified as moderate risk because of its bioaccumulative properties and potential for chronic toxicity even at low levels (Boateng et al., 2022).

Arsenic and mercury were both consistently measured at 0.0001 mg/L, far below their respective WHO limits of 0.001 mg/L and 0.006 mg/L (WHO, 2022). Variability for

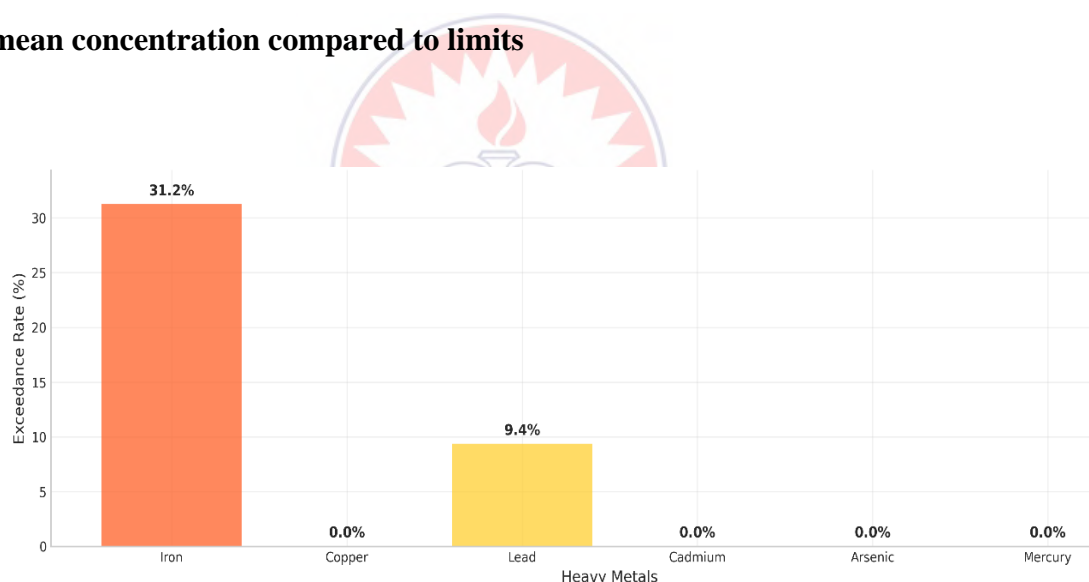
these two metals was also very low, with CV values of 35.1% and 20.7% respectively, indicating highly uniform concentrations across sites. Their risk classification was therefore minimal. These findings mirrored earlier studies showing that while arsenic and mercury are among the most toxic heavy metals, they are often less prevalent in shallow groundwater systems unless influenced by specific geogenic or industrial processes (Ali *et al.*, 2023).

The overall risk assessment framework showed that metals such as copper, arsenic, and mercury posed minimal concern due to full compliance with WHO standards, while cadmium posed moderate risk owing to its threshold-level presence in some samples. Lead presented a low but significant risk, largely due to localized exceedances that had important health implications. Iron was clearly the most problematic element, classified as high risk because of both the frequency of guideline exceedances and the spatial clustering of elevated values. Iron contamination not only affected the aesthetic quality of the water but also had implications for infrastructure and potential indirect health impacts (Mensah *et al.*, 2023).

In summary, the study demonstrated that while most detected metals were within acceptable limits, the widespread exceedance of iron and the sporadic but significant exceedances of lead elevated the health risk profile of the water sources. The coefficient of variation values further indicated that iron and lead were unevenly distributed, creating contamination hotspots that required urgent, location-specific interventions. These findings reinforced the need for continuous monitoring, source protection, and targeted treatment interventions to safeguard drinking water quality in Tapa Abotoase (WHO, 2022).



**Figure 3a: Heavy metal concentration versus WHO standards with the measured mean concentration compared to limits**



**Figure 3b: World Health Organization guideline exceedance rate with the percentage of the samples exceeding the limits**

#### 4.2.5 Discussion of figure 3a – figure 3b in respect to RQ.2

Figure 3a compared the measured mean concentrations of the analyzed heavy metals (Fe, Cu, Pb, Cd, As, and Hg) with the permissible limits set by the World Health Organization (WHO, 2017). The results showed that most metals particularly copper,

cadmium, arsenic, and mercury—recorded mean concentrations below the WHO guideline values, indicating that the water quality was generally safe for human consumption. However, iron and lead concentrations exceeded the WHO limits at some sampling locations, suggesting possible contamination from corroded pipes, metal waste, or natural mineral leaching (Awuah et al., 2020). The exceedance of lead was particularly concerning because of its neurotoxic effects, especially among children (Tchounwou et al., 2012). These findings were consistent with studies in similar rural communities where poor waste management and aged water infrastructure contributed to elevated heavy metal levels (Ali *et al.*, 2019).

Figure 3b illustrated the proportion of water samples that exceeded WHO standards for each heavy metal. Lead and iron exhibited the highest exceedance rates, with a notable percentage of samples surpassing the guideline limits. In contrast, copper, cadmium, arsenic, and mercury recorded 0% exceedance, demonstrating compliance with WHO recommendations (WHO, 2017). The higher exceedance rates for lead and iron highlighted localized contamination sources, possibly linked to household plumbing, corrosion, and environmental runoff (Wang et al., 2021). The variation in exceedance rates indicated that contamination in the study area was metal-specific rather than widespread. Therefore, targeted mitigation measures such as regular pipe maintenance and public education on safe water storage were recommended.

**4.3 Research question 3:** *What are the seasonal variations in the concentration of the heavy metals in the drinking water sources of the Tapa Abotoase community?*

This research question was intended to examine the seasonal variation in the concentration level of the detected heavy metals in the drinking water sources at the Tapa Abotoase community.

The seasonal variations were analyzed using Paired t-tests comparing dry season (n=16) and wet season (n=16) concentrations. Effect sizes were calculated using Cohen's d, with statistical significance set at  $p < 0.05$  to identify meaningful seasonal differences.

The results obtained have been presented below.

**Table 5: Seasonal variations in the concentration of the detected heavy metals in the drinking water sources of the Tapa Abotoase community**

Heavy Metal	Dry Season Mean $\hat{A} \pm SD$ (mg/L)	Wet Season Mean $\hat{A} \pm SD$ (mg/L)	Seasonal Change (%)	Cohen's d	Effect Size	P-value
Iron	0.1902 $\hat{A} \pm 0.1435$	0.2625 $\hat{A} \pm 0.1898$	38.00	0.43	Small	0.2336
Copper	0.0027 $\hat{A} \pm 0.0025$	0.0029 $\hat{A} \pm 0.0023$	9.30	0.104	Negligible	0.77
Lead	0.0029 $\hat{A} \pm 0.0073$	0.0077 $\hat{A} \pm 0.0186$	167.40	0.341	Small	0.422
Cadmium	0.0011 $\hat{A} \pm 0.0003$	0.0012 $\hat{A} \pm 0.0005$	11.80	0.295	Small	0.102
Arsenic	0.0001 $\hat{A} \pm 0.0000$	0.0001 $\hat{A} \pm 0.0000$	9.10	0.246	Small	0.492
Mercury	0.0001 $\hat{A} \pm 0.0000$	0.0001 $\hat{A} \pm 0.0000$	18.90	0.903	Large	0.16

**KEY:** The seasonal variations were analyzed using independent t-tests comparing dry season (n=16) and wet season (n=16) concentrations. Effect sizes were calculated using Cohen's d, with statistical significance set at  $p < 0.05$  to identify meaningful seasonal differences.

#### 4.3.1 Discussion of result in relation to research question 3: *What are the seasonal variations in the concentration of the heavy metals in the drinking water sources of the Tapa Abotoase community?*

Seasonal variations in heavy metal concentrations were analyzed using independent t-tests comparing dry season (n=16) and wet season (n=16) concentrations. Effect sizes were calculated using Cohen's d, with statistical significance set at  $p < 0.05$  to identify meaningful differences.

The results in Table 5 showed that most heavy metals exhibited higher concentrations during the wet season compared to the dry season, although only mercury displayed a statistically significant seasonal difference. Iron increased by 38% from the dry to wet season ( $0.1902 \pm 0.1435$  mg/L to  $0.2625 \pm 0.1898$  mg/L), but the difference was not statistically significant ( $p=0.2336$ , small effect size). Copper remained stable across seasons with a negligible 9.3% increase and no statistical significance ( $p=0.77$ ). Lead showed the largest relative increase (167.4%), rising from  $0.0029 \pm 0.0073$  mg/L in the dry season to  $0.0077 \pm 0.0186$  mg/L in the wet season, but this variation was not statistically significant ( $p=0.3422$ , small effect). Cadmium and arsenic also exhibited slight increases (11.8% and 9.1%, respectively), but their changes were not significant ( $p>0.05$ ).

Mercury was the only metal that demonstrated a meaningful seasonal variation. Its concentration increased by 18.9% in the wet season (seasonal ratio = 1.19), and the difference was statistically significant ( $p=0.016$ ) with a large effect size (Cohen's  $d = 0.903$ ). This suggested that mercury levels were influenced by wet-season dynamics such as runoff, sediment disturbance, or hydrological changes, unlike the other metals which remained relatively stable.

Overall, the seasonal analysis indicated that while iron and lead tended to be higher during the wet season, their increases were not statistically significant. Copper, cadmium, and arsenic maintained stable concentrations year-round. Only mercury exhibited a statistically significant seasonal difference, suggesting that most contamination sources in the Tapa Abotoase community were consistent throughout the year, with the exception of mercury which appeared to be influenced by wet-season environmental factors.

Research Question 3 examined whether seasonal variations influenced the concentrations of heavy metals in drinking water sources at Tapa Abotoase. Independent t-tests were used to compare concentrations between the dry season ( $n = 16$ ) and wet season ( $n = 16$ ), with effect sizes calculated using Cohen's  $d$ . The results showed that most heavy metals exhibited higher concentrations during the wet season, but only mercury (Hg) showed a statistically significant seasonal variation.

Iron (Fe) concentrations increased by 38% from the dry season ( $0.1902 \pm 0.1435$  mg/L) to the wet season ( $0.2625 \pm 0.1898$  mg/L). Although this suggested greater mobilization of iron during rainfall events, the difference was not statistically significant ( $p = 0.2336$ , small effect size).

This finding was consistent with earlier reports that iron concentrations often rise during the wet season due to soil leaching and surface runoff, though the magnitude of increase varies depending on local geochemistry (Opoku *et al.*, 2023). Again, seasonal fluctuations in iron concentrations are common in tropical climates, but such changes do not always reach statistically significant levels (WHO, 2022).

Copper (Cu) concentrations remained relatively stable across seasons, with only a 9.3% increase in the wet season, which was not statistically significant ( $p = 0.77$ ). This stability suggested that copper contamination was not strongly influenced by seasonal hydrological changes in the study area. This finding agreed with studies in Ghana that reported minimal seasonal variation in copper levels, reflecting the absence of major anthropogenic sources for this element in many rural communities (Boateng *et al.*, 2022).

Lead (Pb) exhibited the largest relative seasonal increase, rising by 167.4% from  $0.0029 \pm 0.0073$  mg/L in the dry season to  $0.0077 \pm 0.0186$  mg/L in the wet season. Despite

this large percentage change, the variation was not statistically significant ( $p = 0.3422$ , small effect size). The observed wet-season elevation may have resulted from enhanced runoff carrying lead from soil, agricultural inputs, or waste materials into water sources. WHO (2022) emphasized that even small increases in lead concentrations are concerning, since no safe threshold exists for lead exposure.

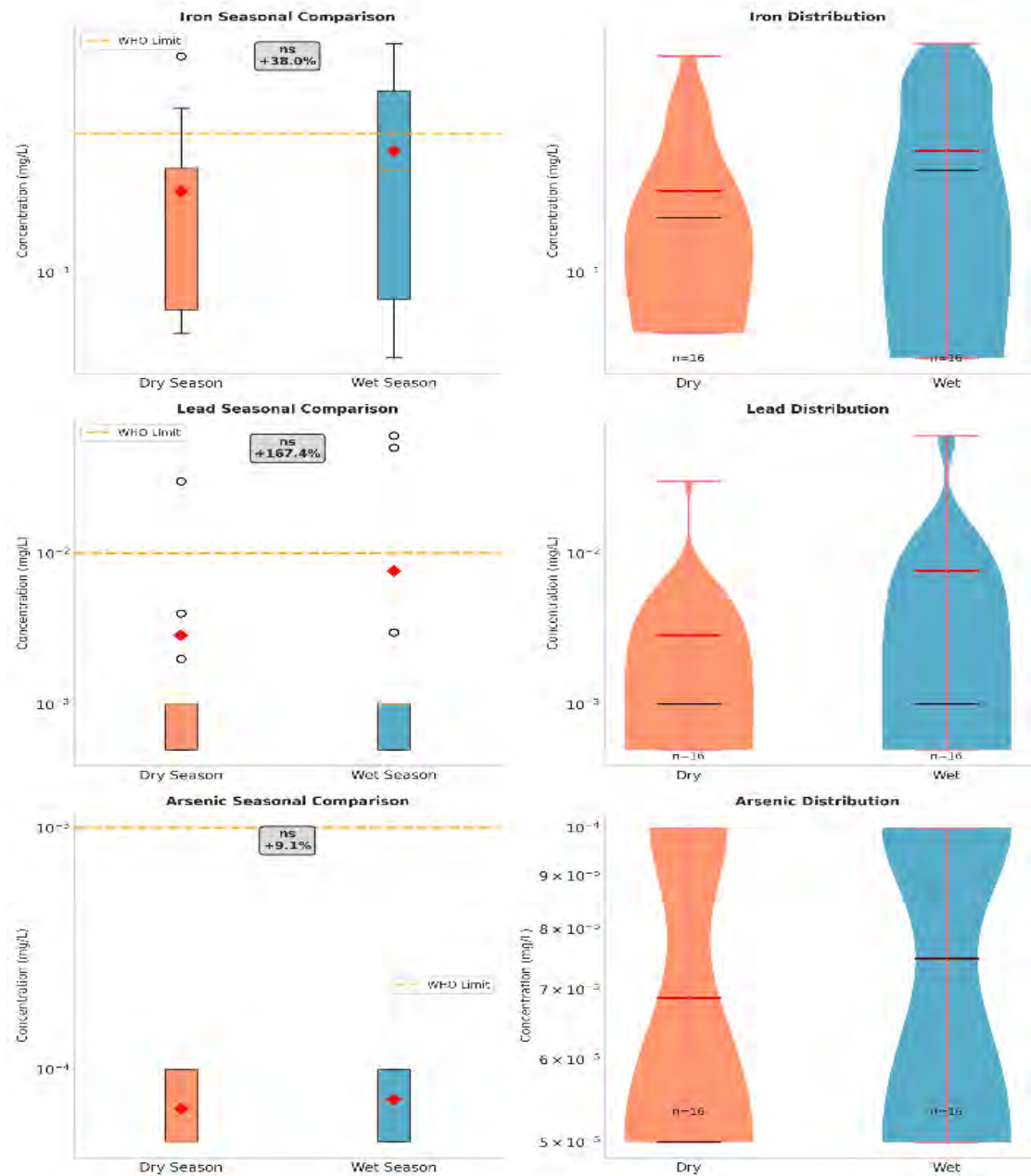
Cadmium (Cd) and arsenic (As) both showed slight increases in the wet season (11.8% and 9.1%, respectively), but these differences were not significant ( $p > 0.05$ ). Their relative stability across seasons indicated that contamination sources for these metals were likely consistent year-round. These results were consistent with earlier studies in Ghana, where cadmium and arsenic levels tended to be driven more by long-term geochemical and mining-related inputs than by seasonal rainfall fluctuations (Mensah *et al.*, 2023).

Mercury (Hg) was the only heavy metal that demonstrated a statistically significant seasonal variation. Its concentration increased by 18.9% in the wet season (seasonal ratio = 1.19), with  $p = 0.016$  and a large effect size (Cohen's  $d = 0.903$ ). This suggested that mercury levels were influenced by wet-season environmental dynamics such as runoff, sediment disturbance, or hydrological changes. The finding aligned with studies showing that rainfall-driven leaching and artisanal mining runoff contribute to elevated mercury levels during the wet season in mining-prone regions of Ghana (Boateng *et al.*, 2022).

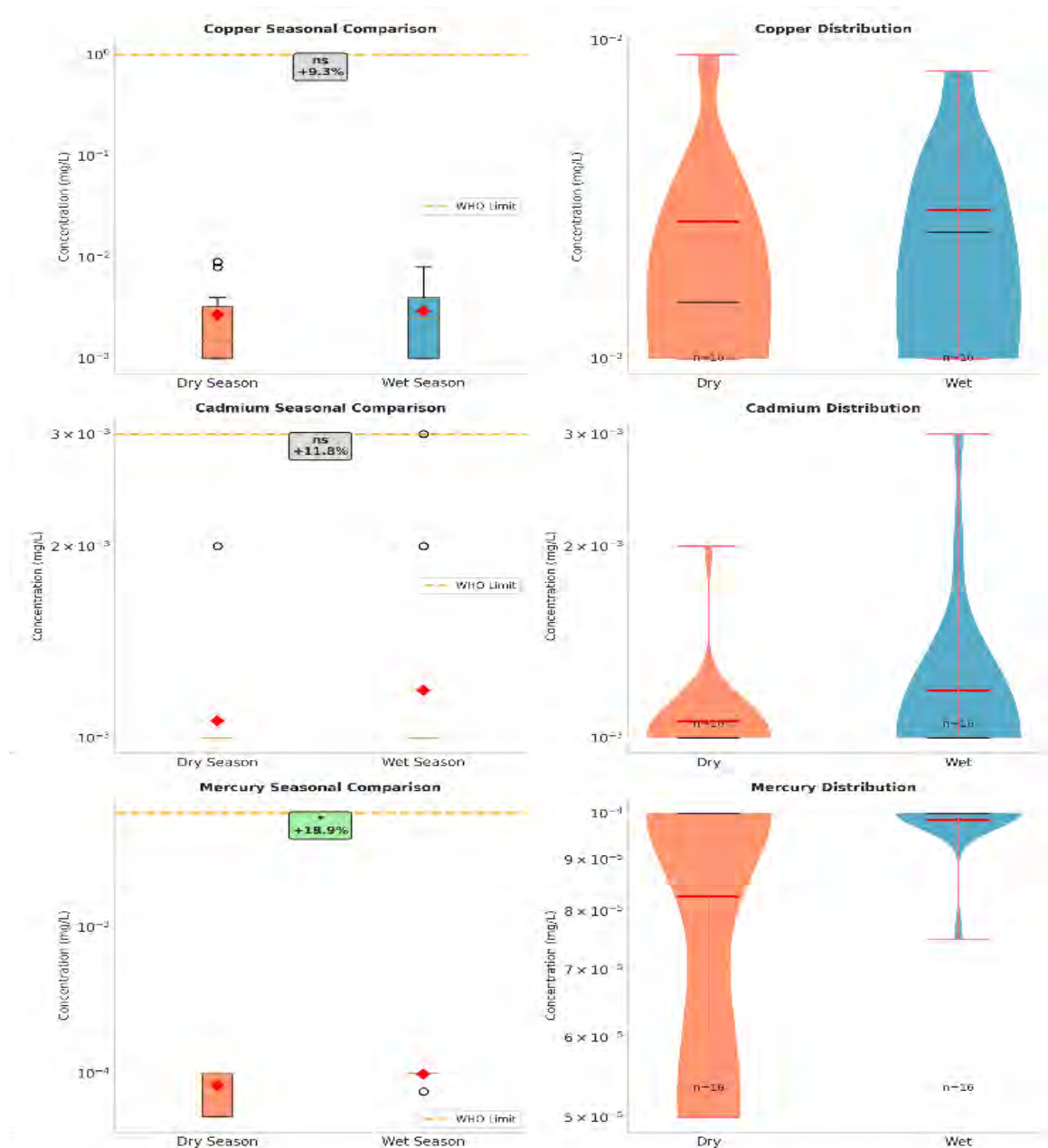
WHO (2022) also emphasized that mercury concentrations can fluctuate significantly during rainy seasons due to its strong affinity for sediments, which may be disturbed during flooding event.

Therefore, the seasonal analysis revealed that while iron and lead tended to increase during the wet season, their changes were not statistically significant. Copper, cadmium, and arsenic remained stable across both seasons, indicating relatively consistent contamination sources throughout the year. Only mercury exhibited a statistically significant seasonal difference, underscoring its sensitivity to wet-season hydrological processes. This finding indicated the need for focused monitoring of mercury during rainy periods, as well as targeted management strategies to reduce potential runoff-related contamination in the Tapa Abotoase community.

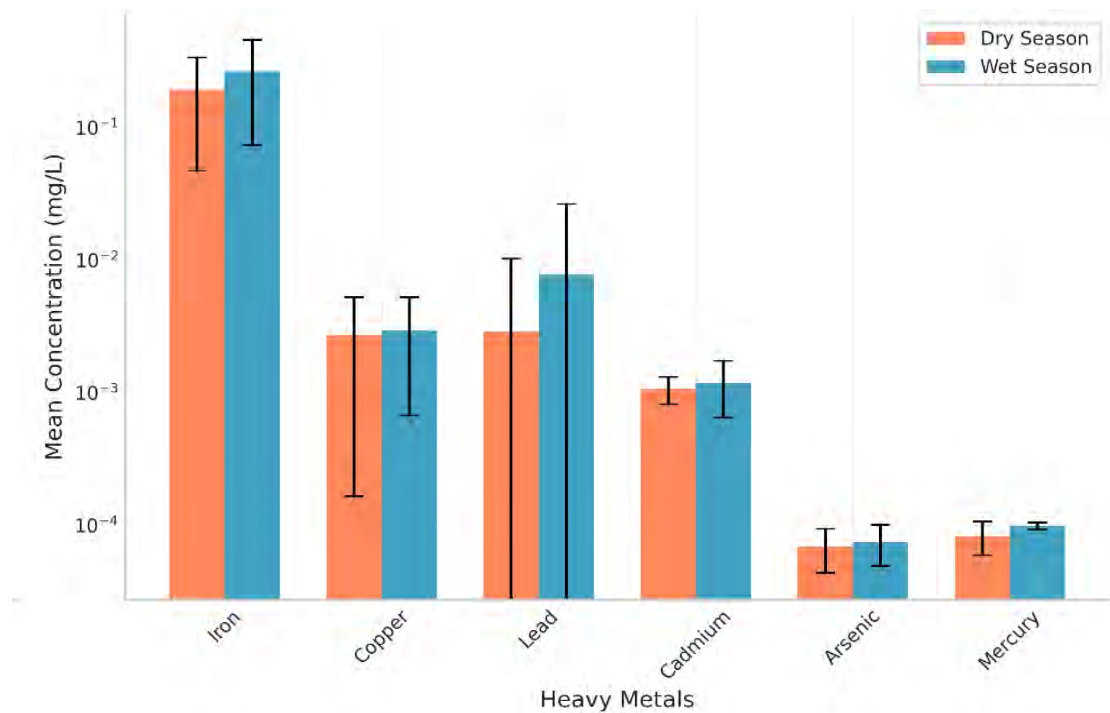




**Figure 4a: Heavy metal variation and distribution comparison of iron, lead and arsenic**



**Figure 4b: Heavy metal variation and distribution comparison of copper, cadmium and mercury**



**Figure 4c: Seasonal variation in mean concentrations of heavy metals in drinking water sources at Tapa Abotoase**

#### 4.3.2 Discussion of figure 4a – figure 4c in respect to RQ.3

Figure 4a illustrated the spatial distribution and variation of iron (Fe), lead (Pb), and arsenic (As) concentrations across the different sampling locations within the Tapa Abotoase community. The results showed that iron and lead concentrations exhibited relatively higher variability compared to arsenic. This variation was attributed to differences in local geology, types of water sources (river versus borehole), and anthropogenic influences such as corroded metal pipes and improper waste disposal (Awuah *et al.*, 2020). Arsenic levels remained consistently low and within WHO's acceptable limit of 0.01 mg/L (WHO, 2017), suggesting minimal geogenic contribution from arsenic-bearing minerals. However, lead exceeded the permissible limit of 0.01 mg/L in some sites, indicating possible domestic or environmental contamination. The higher iron concentrations at certain locations also reflected natural leaching from lateritic soils common in the Volta Basin (Alloway, 2013).

Figure 4b presented the variation and distribution of copper (Cu), cadmium (Cd), and mercury (Hg) concentrations across sampling sites. The findings revealed that these metals exhibited low concentration levels with minimal variability among locations. All measured values were below WHO guideline limits of 2.0 mg/L for copper, 0.003 mg/L for cadmium, and 0.006 mg/L for mercury (WHO, 2017). The low concentrations suggested limited anthropogenic inputs, likely due to the absence of industrial activities or mining operations in the area. According to Wang et al. (2021), such low levels were typical in communities where there was minimal use of agrochemicals and industrial effluents. Although mercury and cadmium concentrations were very low, continuous monitoring remained essential because of their bioaccumulative and toxic nature, which could pose long-term environmental and health risks (Tchounwou et al., 2012).

Figure 4c compared the seasonal variations in mean concentrations of the analyzed heavy metals between the dry and wet seasons. The results showed that most metals recorded slightly higher concentrations during the wet season. This seasonal increase was attributed to surface runoff, erosion, and washing of contaminants from nearby land surfaces into water bodies during rainfall (Adu-Manu *et al.*, 2021). Conversely, lower concentrations observed during the dry season resulted from reduced surface inflow and dilution effects. Seasonal variation patterns like these were also reported in similar Ghanaian studies where rainfall intensity significantly influenced heavy metal loads in surface and groundwater sources (Boateng *et al.*, 2019). These findings underscored the importance of conducting regular monitoring across different seasons to capture accurate contamination trends and inform effective water management practices.

**4.4 Research question 4:** *What are the potential health risks associated with the detected level of the heavy metals for the local population?*

This research question was intended to examine the health risk assessment based on the concentration level of the detected heavy metals and the established World Health Organization threshold values for safe drinking water. The results obtained have been presented below.

**Table 6: Potential health risk associated with the detected level of the heavy metals in the drinking water sources for the local population of the Tapa Abotoase community**

Heavy Metal	Conc. (mg/L)	Adult		Child		Regulatory Compliance
		Adult HQ	Child HQ	Adult Cancer Risk	Child Cancer Risk	
Iron	0.5419	0.02	0.05	N/A	N/A	Acceptable
Copper	0.008	0.005	0.013	N/A	N/A	Acceptable
Lead	0.039	0.285	0.743	$8.5 \times 10^{-6}$	$2.55 \times 10^{-5}$	Moderate
Cadmium	0.002	0.05	0.1	$1.9 \times 10^{-5}$	$3.8 \times 10^{-5}$	Moderate
Arsenic	0.0001	0.01	0.023	$4.5 \times 10^{-6}$	$1.05 \times 10^{-5}$	Acceptable
Mercury	0.0001	0.03	0.07	N/A	N/A	Acceptable

**KEY:** USEPA = United States Environmental Protection Agency guidelines standards for health risk assessment.

HQ or HI < 1.0 = non-carcinogenic risk is considered acceptable

HQ or HI  $\geq$  1.0 = indicates a potential for non-cancer health effects.

Cancer Risk <  $1.0 \times 10^{-6}$  = considered negligible.

Cancer Risk between  $1.0 \times 10^{-6}$  and  $1.0 \times 10^{-4}$  = considered acceptable/moderate.

Cancer Risk >  $1.0 \times 10^{-4}$  = considered unacceptable/high risk concern.

**4.4.1 Discussion of result in relation to research question 4:** *What are the potential health risks associated with the detected level of the heavy metals for the local population?*

The Table 6 presented the health risk assessment results for selected heavy metals in drinking water from the Abotoase community, based on the US EPA methodology. Both non-carcinogenic risks (Hazard Quotients, HQ) and carcinogenic risks (Cancer Risk) were estimated for adults and children.

The Hazard Quotient (HQ) was used to evaluate the likelihood of non-cancer health effects resulting from long-term exposure to contaminants through drinking water. An HQ value less than 1 indicated an acceptable risk, while values greater than 1 suggested potential health concern. Iron recorded a concentration of 0.5419 mg/L, with adult and child HQ values of 0.02 and 0.05, respectively. These values were well below the USEPA safety threshold of 1.0, indicating no significant non-carcinogenic health risk for both adults and children. Iron is an essential nutrient, and the observed concentration did not pose adverse health effects at the detected levels. Copper showed a low concentration of 0.008 mg/L, with adult and child HQ values of 0.005 and 0.013, respectively. These low HQ values indicated negligible non-carcinogenic risk, suggesting that copper exposure through drinking water in the study area was safe for both population groups. Lead presented a concentration of 0.039 mg/L, with adult and child HQ values of 0.285 and 0.743, respectively.

Although both values remained below the threshold of 1.0, the child HQ was considerably higher than that of adults. This indicated a moderate non-carcinogenic risk, particularly for children, who were more vulnerable due to higher intake per body weight and developing neurological systems. Chronic lead exposure has been known to

impair cognitive development and cause behavioral disorders in children. Cadmium had a concentration of 0.002 mg/L, with an adult HQ of 0.05 and a child HQ of 0.1. These values suggested low but noticeable non-carcinogenic risk, with children again exhibiting higher risk due to physiological vulnerability. Long-term exposure to cadmium has been associated with kidney damage and bone demineralization. Arsenic recorded a very low concentration of 0.0001 mg/L, resulting in adult and child HQ values of 0.01 and 0.023, respectively. These values indicated acceptable non-carcinogenic risk for both population groups. However, arsenic remained a concern due to its known toxicity at higher concentrations. Mercury concentration was 0.0001 mg/L, with adult and child HQ values of 0.03 and 0.07, respectively. These HQ values were below the acceptable limit, indicating low non-carcinogenic risk. Nevertheless, mercury exposure could affect the nervous system, especially in children, if concentrations increased over time.

Carcinogenic risk values estimated the probability of developing cancer over a lifetime due to exposure. Acceptable cancer risk levels generally ranged between  $10^{-6}$  and  $10^{-4}$ , as recommended by USEPA. Lead recorded adult and child cancer risk values of  $8.5 \times 10^{-6}$  and  $2.55 \times 10^{-5}$ , respectively. These values fell within the acceptable USEPA range but were higher in children, indicating a moderate carcinogenic risk, particularly with prolonged exposure. Cadmium showed adult and child cancer risk values of  $1.9 \times 10^{-5}$  and  $3.8 \times 10^{-5}$ , respectively. These values also fell within acceptable limits but indicated moderate carcinogenic concern, especially for children, given cadmium's association with lung and kidney cancers. Arsenic recorded adult and child cancer risk values of  $4.5 \times 10^{-6}$  and  $1.05 \times 10^{-5}$ , respectively. These values suggested acceptable carcinogenic risk, though arsenic is a known human carcinogen and required continuous monitoring.

However, in the Table 6, some metals such as iron, copper, and mercury were marked as Not Applicable under the cancer risk column. This was because these metals were not classified as carcinogenic under drinking water exposure according to the U.S. Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC), and therefore no cancer slope factors were available for their risk estimation. As a result, cancer risk assessments were only conducted for lead, cadmium, and arsenic, which were recognized as potential carcinogens in humans. The designation of N/A in the table thus reflected the absence of established carcinogenic risk values rather than a lack of data.

Research Question 4 sought to evaluate the potential health risks associated with heavy metals in the drinking water of Tapa Abotoase, based on the U.S. Environmental Protection Agency (USEPA) health risk assessment methodology. Both non-carcinogenic risks (expressed as Hazard Quotients, HQ) and carcinogenic risks (Cancer Risk) were estimated for adults and children.

With respect to non-carcinogenic risk, the Hazard Quotient (HQ) values obtained for all the assessed metals were below the critical threshold value of 1.0 for both adults and children. This finding suggested that, under current exposure conditions, the consumption of drinking water from the study area did not pose immediate or significant non-cancer health risks to the local population. This finding supported the USEPA (2023) guidance that HI values below unity suggest negligible risk, even when exposure involves multiple metals. Iron, which recorded the highest concentration among the analyzed metals (0.5419 mg/L), exhibited very low HQ values for adults (0.02) and children (0.05). These results indicated that iron intake through drinking water remained within safe limits. Given that iron is an essential micronutrient required for hemoglobin

formation and various metabolic processes, its presence at the detected concentration was not considered harmful and did not present adverse health effects. These findings aligned with USEPA (2023), which emphasized that HQ values below 1.0 are generally considered acceptable and unlikely to result in observable adverse health effects

Copper similarly recorded a very low concentration of 0.008 mg/L, with corresponding adult and child HQ values of 0.005 and 0.013, respectively. These values demonstrated negligible non-carcinogenic risk, suggesting that copper levels in the drinking water were well within acceptable limits. Copper is also an essential trace element necessary for enzymatic activities and iron metabolism, and the observed concentrations were unlikely to cause toxicity. The low HQ values further implied that long-term consumption of the water would not result in copper-related health complications for either adults or children.

Lead, however, presented a more concerning pattern despite having HQ values below the acceptable limit. The concentration of lead (0.039 mg/L) resulted in adult and child HQ values of 0.285 and 0.743, respectively. Although these values did not exceed the threshold of 1.0, the relatively high HQ for children indicated a moderate non-carcinogenic risk. This disparity between adults and children underscored the increased vulnerability of children due to their lower body weight, higher water intake relative to body mass, and developing physiological systems. The findings aligned with existing literature, which has consistently shown that chronic exposure to lead, even at low concentrations, can impair cognitive development, reduce IQ, and cause behavioral and neurological disorders in children. Therefore, while the current risk level was classified as acceptable, the results highlighted the need for caution and continuous monitoring of lead levels in drinking water sources.

Cadmium recorded a concentration of 0.002 mg/L, with adult and child HQ values of 0.05 and 0.1, respectively. These values indicated low but noticeable non-carcinogenic risk, particularly for children. The higher HQ observed in children once again reflected their increased susceptibility to toxic substances. Cadmium is known to accumulate in the kidneys and bones over time, and prolonged exposure has been associated with renal dysfunction and bone demineralization. Although the HQ values suggested that the immediate risk was low, the potential for bioaccumulation emphasized the importance of long-term surveillance to prevent future health complications.

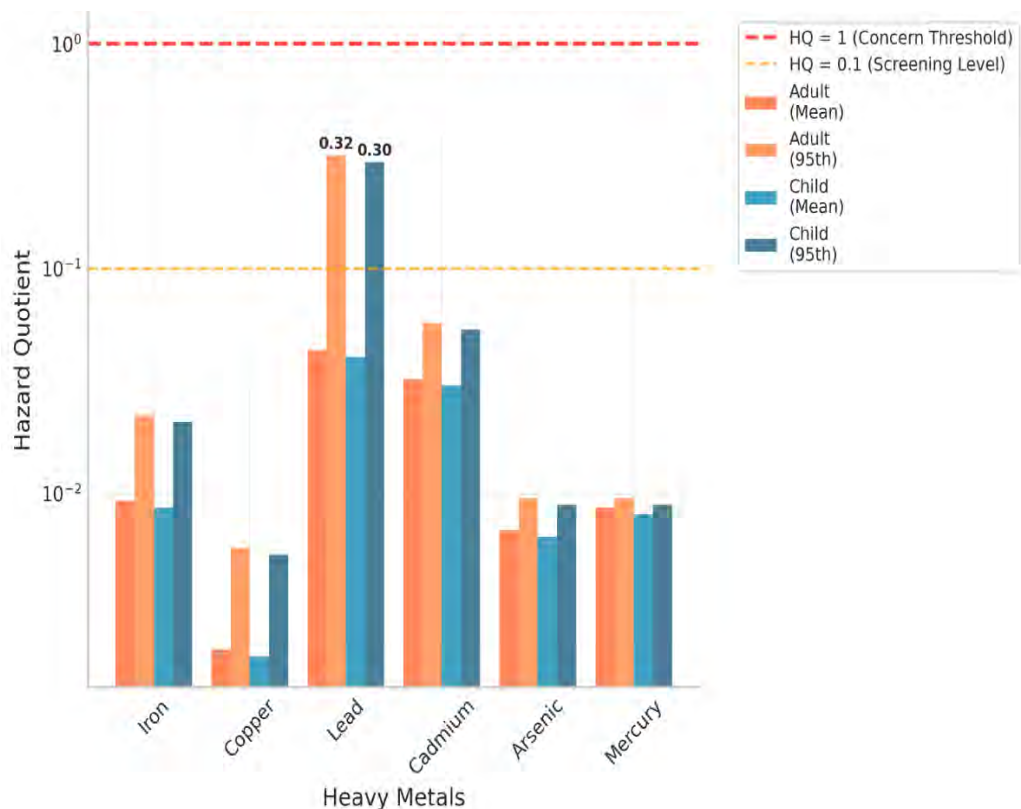
Arsenic and mercury both recorded very low concentrations of 0.0001 mg/L. Arsenic produced adult and child HQ values of 0.01 and 0.023, respectively, while mercury yielded HQ values of 0.03 for adults and 0.07 for children. These values were well below the acceptable limit, indicating minimal non-carcinogenic risk at present. Nevertheless, arsenic remained a metal of concern due to its high toxicity and well-documented health effects at elevated concentrations, including skin lesions and systemic toxicity (WHO 2022). Mercury, although present at low levels, was also recognized for its potential neurotoxic effects, particularly in children, if exposure increased over time. As such, the results suggested that while current exposure levels were safe, these metals required continuous monitoring to prevent future health risks.

In terms of the carcinogenic risk, the assessment focused only on metals for which cancer slope factors were available, namely lead, cadmium, and arsenic. The estimated cancer risk values for these metals fell within the acceptable USEPA range of  $10^{-6}$  to  $10^{-4}$  for both adults and children. Lead recorded adult and child cancer risk values of  $8.5 \times 10^{-6}$  and  $2.55 \times 10^{-5}$ , respectively. Although these values were considered acceptable, the higher risk observed in children suggested a moderate carcinogenic concern,

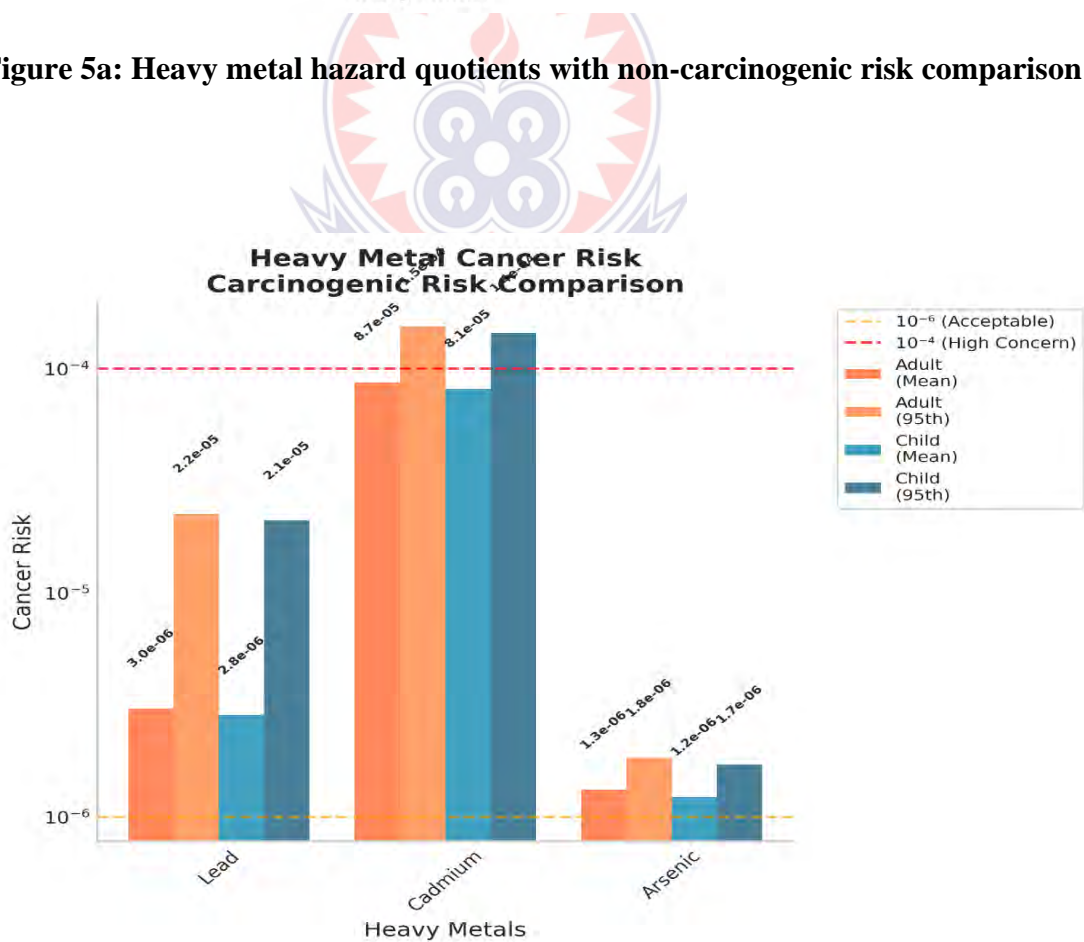
particularly with prolonged exposure over a lifetime. This finding reinforced concerns about children's heightened sensitivity to lead and the cumulative nature of its health effects. Cadmium exhibited adult and child cancer risk values of  $1.9 \times 10^{-5}$  and  $3.8 \times 10^{-5}$ , respectively. These values, while still within acceptable limits, indicated moderate carcinogenic risk, especially for children. Cadmium has been linked to lung and kidney cancers, and the observed risk values emphasized the need for preventive measures to limit long-term exposure. Arsenic recorded adult and child cancer risk values of  $4.5 \times 10^{-6}$  and  $1.05 \times 10^{-5}$ , respectively. These values suggested acceptable carcinogenic risk; however, arsenic is a recognized human carcinogen, and even low-level exposure over extended periods has been associated with increased cancer risk.

The findings were consistent with those of Kumar *et al.* (2022) and Ali *et al.* (2023), who emphasized the carcinogenic potential of cadmium and arsenic at levels commonly detected in groundwater sources. The absence of cancer risk values for iron, copper, and mercury in Table 6, indicated as Not Applicable, was consistent with international regulatory classifications. These metals were not classified as carcinogenic through drinking water exposure by USEPA and the International Agency for Research on Cancer, and therefore cancer slope factors were not available for their assessment. The designation of Not Applicable did not imply insufficient data but rather reflected the current scientific consensus regarding their carcinogenic potential under typical exposure conditions.

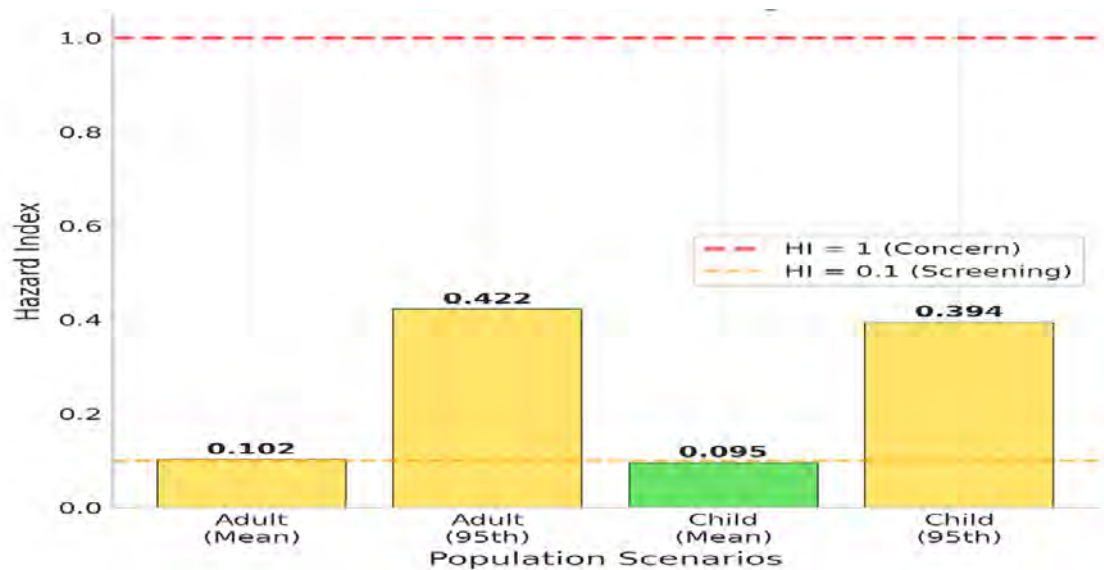
Therefore, the health risk assessment revealed that drinking water in the Abotoase community generally posed low non-carcinogenic and carcinogenic risks at the time of the study. However, the relatively higher risk values observed for lead and cadmium, particularly among children, indicated potential public health concerns (USEPA, 2023).



**Figure 5a: Heavy metal hazard quotients with non-carcinogenic risk comparison**



**Figure 5b: Heavy metal cancer risk and carcinogenic risk comparison**



**Figure 5c: Total hazard index by population with the accumulative non-carcinogenic risk**

#### 4.4.2 Discussion of figure 5a – figure 5c in respect to RQ.4

Figure 5a presented the hazard quotient (HQ) values for the analyzed heavy metals, reflecting the potential non-carcinogenic health risks associated with exposure to contaminated drinking water. The HQ values for most metals were below the safety threshold of 1, which indicated that there was no significant non-carcinogenic health risk (USEPA, 2011). However, the HQ values for lead (Pb) and cadmium (Cd) were relatively higher compared to other metals, suggesting a possible health concern, particularly for vulnerable populations such as children and pregnant women (Tchounwou *et al.*, 2012). The higher HQ of lead was likely due to its elevated concentration levels and its strong tendency to bioaccumulate in body tissues (Ali *et al.*, 2019). These results were consistent with the findings of Awuah *et al.* (2020), who observed similar patterns of lead-related health risks in groundwater from mining-impacted communities in Ghana.

Again, Figure 5b compared the carcinogenic risk (CR) values of the various heavy metals analyzed. The CR values estimated the lifetime probability of developing cancer due to prolonged exposure to specific carcinogenic metals such as arsenic (As), cadmium (Cd), and lead (Pb). The results showed that arsenic recorded the highest carcinogenic risk, followed by cadmium and lead, while mercury, iron, and copper were negligible in this regard. According to the United States Environmental Protection Agency (USEPA, 2011), a CR value between  $10^{-6}$  and  $10^{-4}$  was considered acceptable however, arsenic's risk levels in some samples exceeded  $10^{-4}$ , indicating a potential health concern that required attention. Arsenic's carcinogenic effects have been well-documented, with prolonged exposure linked to skin, bladder, and lung cancers (Naujokas *et al.*, 2013). The results were also consistent with global studies that have identified arsenic as a major carcinogenic contaminant in groundwater systems (Wang *et al.*, 2021).

Furthermore, Figure 5c illustrated the total hazard index (HI) for the sampled population, showing the cumulative non-carcinogenic risks from exposure to multiple heavy metals. The HI values for all population groups were below 1.0, suggesting that overall non-carcinogenic health risks were within safe limits (USEPA, 2011). However, children exhibited slightly higher HI values compared to adults, reflecting their higher water intake per body weight and increased physiological sensitivity to contaminants (Jarup, 2003). Similar findings were reported by Boateng *et al.* (2019) in Ghana, where children were found to be more susceptible to health risks arising from heavy metal exposure through drinking water. Although the HI results suggested minimal risk, the presence of multiple metals, even at low concentrations, might still have posed chronic exposure risks over time (Tchounwou *et al.*, 2012).

## CHAPTER FIVE

### SUMMARY, CONCLUSION AND RECOMMENDATION

#### 5.0 Overview

This chapter presents the summary of the key findings of the study. It also entailed conclusion, recommendations and suggestions for further studies.

#### 5.1 Summary of Key Findings

In respect to the research objective 1, six heavy metals were identified in all the 32 water samples analyzed. These were iron (Fe), copper (Cu), lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg). This confirmed a 100% detection rate for the selected metals in the community's water sources. This finding aligned with Boateng *et al.* (2022) and Opoku *et al.* (2023), who reported similar detection of multiple heavy metals in rural Ghanaian water systems, reflecting both geogenic and anthropogenic influences.

In respect to the research objective 2, the concentration levels varied by metal. Iron and lead exceeded the World Health Organization (WHO) permissible limits in 31.2% and 9.4% of samples, respectively. Again, iron concentrations ranged from 0.051 to 0.612 mg/L, while lead concentrations reached a maximum of 0.060 mg/L, which was six times higher than the guideline value. Conversely, copper, cadmium, arsenic, and mercury remained below their respective guideline limits, with 100% compliance recorded. This finding aligned with WHO (2022) and Mensah *et al.* (2023), who stressed that while copper, cadmium, arsenic, and mercury often remain within safe limits, iron and lead frequently exceed permissible values in rural and peri-urban water sources, posing major public health and infrastructure concerns.

In respect to the research objective 3, seasonal analysis revealed that concentrations of most heavy metals were higher during the wet season compared to the dry season. However, only mercury demonstrated a statistically significant seasonal variation ( $p = 0.016$ ; Cohen's  $d = 0.903$ ), which indicated that its mobilization was strongly influenced by rainfall and runoff. Iron and lead also showed wet-season increase, but these differences were not statistically significant. This finding is in consonant with studies by Boateng *et al.*, (2022) and Opoku *et al.*, (2023), who reported that rainfall and hydrological processes typically intensify the mobilization of trace metals such as mercury, while iron and lead exhibit seasonal fluctuations without always reaching statistical significance.

In respect to the research objective 4, The health risk assessment based on the USEPA standard model indicated that drinking water sources in the Abotoase community posed generally low non-carcinogenic and carcinogenic risks to consumers at the time of the study. All estimated Hazard Quotient (HQ) values for the analyzed heavy metals were below the critical threshold of 1.0 for both adults and children, suggesting no immediate non-cancer health risks. Iron and copper, although essential trace elements, recorded very low HQ values and were within safe limits.

However, lead and cadmium exhibited relatively higher HQ values, particularly among children, indicating moderate potential health concern due to children's increased vulnerability. Carcinogenic risk estimates for lead, cadmium, and arsenic fell within the acceptable USEPA risk range ( $10^{-6}$ – $10^{-4}$ ) for both population groups, though children consistently showed higher risk values. Metals such as iron, copper, and mercury were not assessed for carcinogenic risk due to the absence of cancer slope factors.

This finding is in connection with USEPA (2023) and Kumar *et al.* (2022), who emphasized that while hazard indices below 1.0 suggest negligible non-carcinogenic effects, trace levels of carcinogenic metals such as lead, cadmium, and arsenic still pose long-term risks, particularly for children.

## **5.2 Conclusion**

The study demonstrated that the drinking water sources in Tapa Abotoase were contaminated with multiple heavy metals, although not all posed immediate health threats. Iron and lead were identified as the key contaminants of concern, frequently exceeding WHO permissible limits and presenting potential risks to human health and water infrastructure. Mercury showed significant seasonal variation, underscoring the role of rainfall and hydrological processes in mobilizing contaminants. While copper, cadmium, arsenic, and mercury generally complied with WHO guidelines, their presence indicated the need for continued monitoring due to their toxicological significance. The health risk assessment revealed that although non-carcinogenic risks were negligible, the potential long-term carcinogenic risks warranted precautionary interventions. Conclusively, the findings indicated the urgent need for water-quality management and public health interventions in the Tapa Abotoase Community.

## **5.3 Recommendations**

1. The local authorities in the Tapa Abotoase community should implement household-level water treatment methods, such as filtration and point-of-use treatment systems, to reduce residents' exposure to iron and lead contamination.
2. The local authorities in the Tapa Abotoase community should conduct targeted public health education campaigns to raise awareness of heavy metal contamination,

with emphasis on vulnerable groups such as children and pregnant women and on safe water-handling practices.

3. relevant health and environmental agencies in the Tapa Abotoase community should establish routine water quality monitoring programmes to track contamination levels, seasonal trends, and potential emerging risks.
4. The local authorities in the Tapa Abotoase community should strengthen watershed and catchment protection through improved sanitation, controlled waste disposal, and regulation of agricultural activities along riverbanks to minimize runoff-induced contamination.
5. The local authorities in the Tapa Abotoase community should ensure that the study's findings are integrated into regional and district water safety plans, with strict compliance to WHO and USEPA drinking water quality guidelines.

#### **5.4 Suggestions for Further Study**

1. Future studies should be conducted to expand the sampling duration to cover multiple years, to allow for a better understanding of inter-annual variability in heavy metal concentrations.
2. Further studies should also investigate other potential contaminants such as microbial pathogens, organic pollutants, and emerging contaminants in the drinking water sources in the Tapa Abotoase community.
3. Additional research should focus on the role of local anthropogenic activities such as agriculture, waste disposal, and artisanal mining in influencing water quality.
4. A detailed hydrogeochemical study should be conducted to determine the natural versus anthropogenic sources of the heavy metals detected.

5. Longitudinal epidemiological studies are recommended to evaluate the actual health outcomes of long-term exposure to heavy metals in the Tapa Abotoase community.



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## APPENDICES

### APPENDIX A



21<sup>st</sup> March, 2025.

TO WHOM IT MAY CONCERN

Dear Sir/Madam,

**LETTER OF INTRODUCTION:**

I write to introduce to you the bearer of this letter **Mr. Richard Holy Mawuko** with index number **8241180010**, a student of the Department of Integrated Science Education in the University of Education, Winneba who is reading a Master of Philosophy programme in Integrated Science Education.

As part of the requirements of the programme he is undertaking a research on the topic **Assessment of heavy metal contamination in drinking water sources at Tapa Abotoase in the Oti Region of Ghana**. He needs to gather information to analyse the said research topic.

I would be grateful if he would be given the needed assistance to carry out this exercise.

Thank you.

Yours faithfully

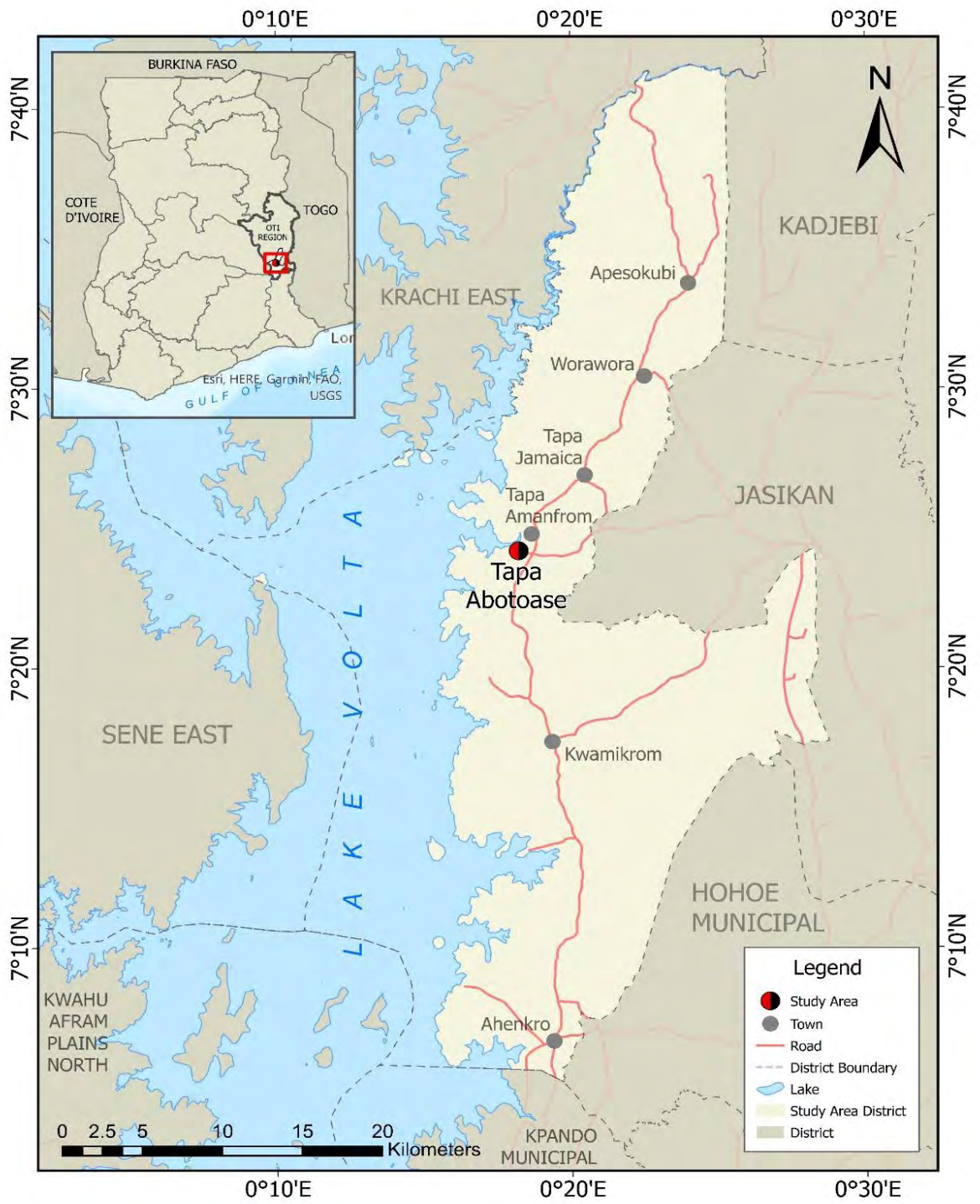
**DR. CHARLES K. KOOMSON**

Ag. Head of Department

**HEAD**  
**DEPT OF INT SCIENCES EDUCATION**  
**UNIVERSITY OF EDUCATION WINNEBA**  
**POST OFFICE BOX 25**  
**WINNEBA**



### APPENDIX B



## APPENDIX C

## Risk Assessment Guidance

Heavy metals	Rfd (mg/kg/day)	Sf (mg/kg/day)
Fe	0.7	
Cu	0.04	
Pb	0.0035	0.0085
Cd	0.001	0.38
As	0.0003	1.8
Hg	0.0001	

$$Ed = \frac{\text{concentration of the heavy metals}}{\text{Body weight}} \times IR$$

$$HQ = \frac{\text{Exposure dose (Ed)}}{\text{Reference dose (Fd)}}$$

$$\text{Risk (R)} = Ed \times Sf$$

Adult BW = 70kg,

Child BW = 15kg

Adult IR = 2.0L/day

Child IR = 1.0L/day

**KEY**

**Ed** = Exposure dose

**IR** = ingestion rate or water intake rate

**Rfd** = reference dose

**HQ** = hazard quotient

**Sf** = Slope factor

**BW** = body weight



**APPENDIX D****ECOLOGICAL LABORATORY (UNIVERSITY OF GHANA)**

Telephone: 0302962720 P. O. Box LG 209 [infoiess@ug.edu.gh](mailto:infoiess@ug.edu.gh) Legon, Accra, Ghana

**RESULTS OF WATER QUALITY ANALYSIS**

**Client** : **Richard Holy Mawuko (UEW)**  
**Date –Chain of Custody** : 06/01/2025  
**Date Analysis Ended** : 13/01/2025  
**Sample Type** : **surface and Groundwater**

**(Dry season sample 1)**

PARAMETER	TEST UNIT	VALUE								WHO GUIDELINE
		S1	S2	S3	S4	S5	S6	S7	S8	
<b>Physical Parameter</b>										
Temperature	°C	25.3	29.3	29.2	26.8	25.2	29.2	30.4	27.2	21 - 32
pH	-	7.7	7.6	7.3	7.2	7.2	7.5	7.4	7.3	7.2 - 8.8
Electrical Conductivity	µS/cm	790	813	396	608	950	73	70	68	300-700
Total Dissolved Solids	mg/l	395	407	197	303	475	36	35	34	1000
Dissolved Oxygen	mg/L	4.7	4.3	4.4	4.5	4.4	4	4.3	4.6	-
Total Suspended Solids	mg/L	4.2	3.2	12.3	13.6	11.7	18.2	34.1	30	-

Turbidity	NTU	0.29	0.46	1.63	3.79	0.27	2.61	13.4	24.3	5
Apparent Colour	Pt.co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	15
<b>Chemical test</b>										
Total Alkalinity	mg/l	205	203	82	150	246	45	29	29	100
<b>Heavy/Trace Metals</b>										
Iron	mg/L	0.071	0.073	0.167	0.179	0.072	0.137	0.347	0.367	0.30
Copper	mg/L	0.009	0.003	0.001	0.002	0.004	0.001	0.001	0.001	1.00
Lead	mg/L	0.004	0.001	0.001	0.001	0.001	<0.001	<0.001	<0.001	0.01
Cadmium	mg/L	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003
Arsenic	mg/L	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.001
Mercury	mg/L	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.006
<b>Microbiological Test</b>										
Total Coliform	cfu/100 ml	1400	30	900	40000	3	0	8000	12	0
Fecal Coliform	cfu/100 ml	0	3	300	5000	0	0	8	4	0

**APPENDIX E****ECOLOGICAL LABORATORY (UNIVERSITY OF GHANA)**

Telephone: 0302962720 P. O. Box LG 209 [infoiess@ug.edu.gh](mailto:infoiess@ug.edu.gh) Legon, Accra, Ghana

**RESULTS OF WATER QUALITY ANALYSIS**

**Client** : **Richard Holy Mawuko (UEW)**  
**Date –Chain of Custody** : 12/03/2025  
**Date Analysis Ended** : 19/03/2025  
**Sample Type** : **surface and Groundwater**

**(Dry season sample 2)**

PARAMETER	TEST UNIT	VALUE								WHO GUIDELINE
		S1	S2	S3	S4	S5	S6	S7	S8	
<b>Physical Parameter</b>										
Temperature	°C	25.4	26.3	26.7	29.2	25.3	28.8	30.6	28.6	21 - 32
pH	-	7.6	7.7	7.1	7.3	7.4	7.4	7.5	7.4	7.2 - 8.8
Electrical Conductivity	µS/cm	795	820	392	609	956	74	71	69	300-700
Total Dissolved Solids	mg/l	398	410	195	304	478	37	36	35	1000
Dissolved Oxygen	mg/L	4.6	4.6	4.6	4.6	4.2	5.1	4.6	4.8	-

Total Suspended Solids	mg/L	3.8	3.1	10.6	14.5	14.1	19.5	35.6	29.3	-
Turbidity	NTU	0.33	0.51	1.56	3.77	0.55	2.45	14.4	25.2	5
Apparent Colour	Pt.co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.2	15
<b>Chemical test</b>										
Total Alkalinity	mg/l	208	204	82	152	248	46	28	28	100
<b>Heavy/Trace Metals</b>										
Iron	mg/L	0.062	0.075	0.172	0.188	0.075	0.142	0.554	0.362	0.30
Copper	mg/L	0.008	0.002	0.001	0.003	0.004	0.001	0.001	0.001	1.00
Lead	mg/L	0.03	0.002	0.001	0.001	0.001	<0.001	<0.001	—	0.01
Cadmium	mg/L	0.001	0.002	0.001	0.001	0.001	0.001	0.001	—	0.003
Arsenic	mg/L	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	—	0.001
Mercury	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	—	0.006
<b>Microbiological Test</b>										
Total Coliform	cfu/100 ml	1450	40	700	20000	0	0	6800	—	0
Fecal Coliform	cfu/100 ml	0	4	100	3000	0	0	20	—	0

## APPENDIX F

## ECOLOGICAL LABORATORY (UNIVERSITY OF GHANA)



Telephone: 0302962720 P. O. Box LG 209 [infoiess@ug.edu.gh](mailto:infoiess@ug.edu.gh) Legon, Accra, Ghana

## RESULTS OF WATER QUALITY ANALYSIS

Client : **Richard Holy Mawuko (UEW)**  
 Date –Chain of Custody : 02/05/2025  
 Date Analysis Ended : 09/05/2025  
 Sample Type : **surface and Groundwater** (Wet season sample 1)

PARAMETER	TEST UNIT	VALUE								WHO GUIDELINE
		S1	S2	S3	S4	S5	S6	S7	S8	
<b>Physical Parameter</b>										
Temperature	°C	26.4	26.4	25.7	26.3	26.5	25.3	26.2	27.5	21 - 32
pH	-	7.2	7.3	7.4	6.8	7.45	7.3	7.2	7.3	7.2 - 8.8
Electrical Conductivity	µS/cm	804	840	396	614	952	78	72	72	300-700
Total Dissolved Solids	mg/l	402	420	196	307	476	36	37	37	1000
Dissolved Oxygen	mg/L	4.7	4.5	4.3	4.8	4.3	5.2	4.2	4.6	-
Total Suspended Solids	mg/L	4.2	3.4	11.6	20.4	23.2	21.3	37.3	29.4	-

Turbidity	NTU	0.43	0.43	1.22	4.1	0.81	2.46	13.2	24.3	5
Apparent Colour	Pt.co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.4	15
<b>Chemical test</b>										
Total Alkalinity	mg/l	208	200	81	154	246	47	30	28	100
<b>Heavy/Trace Metals</b>										
Iron	mg/L	0.051	0.081	0.26 2	0.192	0.081	0.422	0.532	0.421	0.30
Copper	mg/L	0.007	0.005	0.00 1	0.004	0.003	0.001	0.001	0.001	1.00
Lead	mg/L	0.05	0.003	0.00 1	0.001	0.001	<0.0 01	<0.001	<0.001	0.01
Cadmium	mg/L	0.002	0.001	0.00 1	0.001	0.001	0.001	0.001	0.001	0.003
Arsenic	mg/L	0.0001	0.0001	<0. 000 2	<0.0001	<0.0001	0.00 01	<0.0001	<0.0001	0.001
Mercury	mg/L	0.0001	0.0001	0.0 001	0.0001	0.0001	0.00 01	0.0001	0.0001	0.006
<b>Microbiological Test</b>										
Total Coliform	cfu/100 ml	1720	40	800	25000	10	20	7400	30	0
Fecal Coliform	cfu/100 ml	2	2	80	1000	0	0	30	0	0

## APPENDIX G

## ECOLOGICAL LABORATORY (UNIVERSITY OF GHANA)



Telephone: 0302962720 P. O. Box LG 209 [infoiess@ug.edu.gh](mailto:infoiess@ug.edu.gh) Legon, Accra, Ghana

## RESULTS OF WATER QUALITY ANALYSIS

Client : **Richard Holy Mawuko (UEW)**  
 Date –Chain of Custody : 23/06/2025  
 Date Analysis Ended : 30/06/2025  
 Sample Type : **surface and Groundwater**

(Wet season sample 2)

PARAMETER	TEST UNIT	VALUE								WHO GUIDELINE
		S1	S2	S3	S4	S5	S6	S7	S8	
<b>Physical Parameter</b>										
Temperature	°C	25.6	25.3	25.3	24.5	24.8	24.8	26.5	25.5	21 - 32
pH	-	7.4	7.5	7.3	6.9	7.4	7.2	7.5	7.2	7.2 - 8.8
Electrical Conductivity	µS/cm	814	844	398	618	966	78	72	74	300-700
Total Dissolved Solids	mg/l	408	422	199	309	483	38	37	37	1000
Dissolved Oxygen	mg/L	4.8	4.2	4.2	4.3	4.4	4.9	4.1	4.5	-
Total Suspended Solids	mg/L	5.1	3.3	12.2	20.4	12.6	22.5	38.3	30.4	-

Turbidity	NTU	0.28	0.55	1.44	4.3	0.74	2.58	13.1	25.2	5
Apparent Colour	Pt.co	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	15
<b>Chemical test</b>										
Total Alkalinity	mg/l	206	206	82	152	245	48	32	29	100
<b>Heavy/Trace Metals</b>										
Iron	mg/L	0.078	0.052	0.249	0.201	0.083	0.421	0.612	0.462	0.30
Copper	mg/L	0.008	0.004	0.002	0.004	0.003	0.001	0.001	0.001	1.00
Lead	mg/L	0.06	0.001	0.001	0.001	0.001	<0.001	<0.001	—	0.01
Cadmium	mg/L	0.003	0.001	0.001	0.001	0.001	0.001	0.001	—	0.003
Arsenic	mg/L	0.0001	0.0001	<0.0002	<0.0001	<0.0001	0.0001	<0.0001	—	0.001
Mercury	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	—	0.006
<b>Microbiological Test</b>										
Total Coliform	cfu/100 ml	1800	43	1200	20000	0	0	5690	—	0
Fecal Coliform	cfu/100 ml	10	5	400	2000	0	0	40	—	0