ASSESSMENT OF NATURAL RADIOACTIVITY LEVELS IN SURFACE WATERS WITHIN PROXIMITY TO A PROPOSED NEW MINE SITE AT AHAFO NORTH, GHANA.

BY

ODUMANYE MARY QUEENETTE

(11007392)

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DECLARATION

I, **Odumanye Mary Queenette**, affirm that this thesis is the result of my independent research conducted during my Master of Philosophy studies in Health Physics and Radiation Protection. It has not been submitted for any degree at this or any other institution.

Sign  Sign 

Odumanye Mary Queenette **Prof David Okoh Kpeglo**

(Student) (Principal Supervisor)

Date …31-05-2025…… Date: …09-06-2025…….

Sign  Sign 

Prof Augustine Faanu **Dr. Eric Tetteh Glover**

(Co-Supervisor) (Co-Supervisor)

Date: …09-06-2025…….. Date: ……09-06-2025….


INTEGRI PROCEDAMUS

DEDICATION

I dedicate this work to the Almighty God, for the grace and countless blessings in my life. I also dedicate it to my family, whose unwavering support has been my strength. In particular, my cousin, Raymond Gogo, and my grandmother, Mary Kai Mensah-Fio, whose love, support, and guidance have been instrumental in shaping the person I am today.

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ABSTRACT

This study investigates the natural radioactivity levels, in surface waters close to a proposed mining area in Ahafo North of Ghana by analyzing the presence of uranium 238 and thorium 232 among elements in 16 water samples through gamma and alpha spectrometry methods. It was found that uranium 238 levels varied from < 0.01 to 22.3 Bq/L, with an average concentration of 5.24 ± 0.26 Bq/L and the highest levels were observed in sample CSw26. Thorium 232 levels peaked at 56.5 Bq/L in the sample; meanwhile potassium-40 levels fluctuated between 0.1 to 189 Bq/L on average of 44.8 ± 2.98 Bq/L.

Polonium 210 showed variation, in its levels from < 0.01 to 65.5 Bq/kg, with an average of 17.5 ± 0.8 Bq/kg. The higher end of this spectrum correlates with discoveries in areas abundant in phosphates but surpasses the usual concentrations observed in non-mined regions globally indicating geological factors affecting polonium levels in these water bodies Analysis of gross alpha and beta activity revealed alpha values ranging from 0.00358 and 0.0053 Bq/L and beta activity ranging from 0.0345 to 0.0488 Bq/L. Even though the levels detected were lower, than the standards set by the WHO (with 0.5 Bq/L for alpha and 1 Bq/l for beta) 23% of the samples surpassed the recommended threshold for thorium content, in water sources that people rely on – emphasizing the importance of monitoring to ensure radiation protection and safety.

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LIST OF ACRONYMS AND ABBREVIATION

EPA	Environmental Protection Agency
NEQ	Natural Exposure Quotient
WHO	World Health Organization
USEPA	United States Environmental Protection Agency
SPSS	Statistical Package for Social Sciences
ANOVA	Analysis Using one – way analysis of Variance
IAEA	International Atomic Energy Agency
NORM	Natural Occurring Radioactivity Material
IDC	The Individual dose Criterion
MAC	Maximum Activity Concentration
DC	Dose Coefficient
TDS	Total dissolved Solid
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
ICRP	International Commission on Radiological Protection
AED	Annual effective dose

NGGL	Newmont Ghana Gold Limited
GWCL	Ghana Water Company Limited
MCA	Multi – Channel Analyzer
HPGe	High Purity Germanium detector
PIPS	Passivated Implanted planer Silicon
SD	Standard deviation
APHA	American Public Health Association
TSS	Total Suspended Solids

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Research conducted by Faanu et al. (2011) highlights how various human activities—such as agriculture, fossil fuel consumption, urban development, and mining—can elevate naturally occurring radioactivity levels in the environment. Unlike radioactivity generated from nuclear power plants and industrial processes, natural radioactivity arises from the extraction of minerals like uranium and thorium. The processing of these minerals can enhance levels of Naturally Occurring Radioactive Materials (NORM) in affected areas.

Processes such as rock weathering and soil formation can lead to the movement of radioactive materials into surface water bodies, potentially increasing health risks due to elevated radioactivity levels. This concern underscores the importance of monitoring radionuclide levels in aquatic environments. Long-lived radionuclides present in radioactive waste necessitate careful management and long-term oversight.

Jobson (1997) noted that uranium-bearing rocks prevalent in mining regions can release radionuclides into water systems, contributing to freshwater ecosystems' contamination. Given that many rural communities depend on surface water for daily needs, the introduction of radionuclides into these sources may pose significant health risks. The primary sources of radioactivity in surface waters include decay chains from uranium-

238, thorium-232, and potassium-40 found in soils, alongside runoff from industrial activities (Grabow, 2000).

Research into the natural radioactivity of these elements provides vital insights into environmental pollutants in water bodies. Furthermore, aquatic organisms can bioaccumulate radionuclides, leading to increased radiation exposure for humans through the food chain (IAEA, 2011). Continuous monitoring of radioactivity levels is thus critical for protecting public health.

A research project carried out in a mining region found that the average activity concentration values for 238U, 232Th, and 40^{K} in the soil were 15.2, 26.9, and 157.1 Bq kg-1, respectively. The estimated total annual effective dose from soil, water, airborne radon, and dust samples in this research was 0.69 mSv (Faanu et al., 2011). Currently, the Radiation Protection Institute of Ghana is working on a national initiative to create baseline radioactivity measurements for all mines across the country, aiming to develop a national reference database. The main goal of this study is to evaluate the levels of natural radioactivity in surface waters near a proposed new mine site at Ahafo North to establish baseline data.

1.2 Problem Statement

Mining industries often operate without fully understanding the radiological implications of their activities, leading to elevated levels of NORM that can affect surrounding

communities. Many residents near mining sites rely on surface water for their livelihoods; however, there is currently insufficient data regarding radioactivity levels in these waters near the Ahafo North concession. This lack of information hampers regulatory decision-making.

The evaluation of baseline radioactivity levels is essential before mining operations commence in Ahafo North. Some NORM substances are water-soluble and have the potential to seep into adjacent water bodies and farmland posing health risks due to prolonged exposure to elevated radiation levels. Exceeding international limits for radionuclides can lead to serious health issues (IAEA, 2005).

Conducting this study will provide reliable data necessary for developing effective radiation protection strategies and regulatory measures aimed at mitigating potential harm from ionizing radiation.

1.3 Objectives

1.3.1. Main objectives

The main objective was to assess radiological risk associated with natural radioactivity in surface water sources within selected communities close to a proposed mine site.

1.3.2 Specific objectives

The specific objectives of the study were:

i. To determine the activity concentration of K-40, U-238, and Th – 232 (decay series).

ii. To determine the gross alpha and beta activity in the water samples.

iii. To Determine U -238 and U-234, Th-230 and Th-232 and Po-210 Using Alpha Spectrometry

iv. To estimate the committed effective dose due to radionuclides in the water

1.4 Relevance and Justification of the Study

This research investigates potential radiological hazards posed by naturally occurring radioactive materials in surface waters within Ahafo North district, Ghana. The current knowledge gap regarding radionuclide levels in raw materials and waste products limits understanding among policymakers and industry operators. By establishing baseline measurements of radioactivity levels around the Ahafo North Mine, this study aims to contribute crucial data that will inform the development of comprehensive regulations regarding NORM in Ghana. Specifically, it focuses on measuring concentrations and distribution patterns of natural radionuclides from uranium/thorium decay chains and potassium-40 in local water sources.

1.5 Organization of the Thesis

This thesis is organized into five main chapters. Chapter One introduces the study by presenting the background, problem statement, objectives, and the relevance and importance of the research. Chapter Two reviews relevant literature on naturally occurring radioactive materials, health effects of radiation exposure, exposure through drinking water, and guidance levels set by international bodies. Chapter Three outlines the materials and methods employed in the study, including details on the study area, sampling procedures, laboratory techniques, instrumentation, and methods used for calculating activity concentrations and effective doses. Chapter Four presents and discusses the results of the physicochemical analyses and radioactivity measurements, comparing them with national and international standards. Finally, Chapter Five concludes the study by summarizing the key findings and offering recommendations for future research and policy considerations.

CHAPTER TWO

2.0 LITERATURE REVIEW

This chapter presents a review of pertinent literature regarding similar research conducted on naturally occurring radioactive materials, including their presence and concentration levels.

2.1 Naturally occurring radioactive materials

Natural radiation emerges from two main sources: terrestrial radiation from radioactive elements in soil and rock, and cosmic radiation originating from space penetrating through Earth's atmosphere. This environmental radiation occurs naturally when unstable radioactive isotopes decay, releasing various forms of ionizing radiation including cosmic rays, gamma rays, and alpha and beta particles. This decay process can result in either stable elements or additional radioactive daughter products.

While perhaps unexpected, radioactive elements are present in various water sources, including surface water, groundwater, and precipitation. This presence raises health concerns due to the toxic and carcinogenic properties of certain radionuclides. However, some radioactive elements serve valuable scientific purposes, helping researchers understand groundwater dynamics, water residence time, decay rates, water quality parameters, contamination patterns, sediment age in reservoir dead zones, and aquifer characteristics.

The health implications of prolonged exposure to elevated background radiation levels can be significant. Consuming water, food, or environmental materials containing radionuclide concentrations above internationally established reference level may lead to cardiovascular problems and other radiation-related health issues over time. This concern is particularly relevant to the study area, where previous research has documented water quality issues and revealed that local residents rely on potentially unsafe water sources without adequate safety assurances.

2.2 Sources and Health Effects of Radiation Exposure

Environmental radiation includes both natural and human-made sources, with naturally occurring radioactive materials (NORM) being prevalent throughout our surroundings. Key examples include primordial radionuclides such as uranium, thorium, and potassium-40. Certain industrial activities, especially those involving extraction like mining, can amplify these naturally occurring radioactive substances, potentially raising their concentrations above typical background levels. The radiological importance of these substances lies in their potential biological effects through internal and external exposure routes. Internal exposure happens when radionuclides are absorbed into biological systems, causing direct radiation to tissues. In contrast, external exposure occurs when radiation sources, although situated outside the organism, are close enough to interact with tissues through emitted radiation. Comprehending the environmental transport and biokinetic behavior of radionuclides is essential for ensuring effective radiation

protection. This understanding aids in designing and applying suitable intervention measures to disrupt or reduce exposure pathways. The main routes of human exposure to radionuclides involve inhalation through the respiratory system, gastrointestinal absorption from consuming contaminated food and water, and dermal uptake through direct contact with the skin.

2.3 Radiation Exposure through Drinking-Water

Environmental radiation comprises both natural and artificial sources, with naturally occurring radioactive materials (NORM) widely distributed in our surroundings. Typical examples include primordial radionuclides like uranium, thorium, and potassium-40. Specific industrial processes, particularly those related to extraction like mining, can increase the concentration of these natural radioactive substances, elevating them beyond normal background levels. The health implications of these materials stem from their potential biological impact through both internal and external exposure. Internal exposure takes place when radionuclides enter biological systems, directly irradiating tissues, whereas external exposure occurs when nearby radiation sources emit radiation that interacts with tissues from outside the body.

For effective radiation protection, it is crucial to grasp how radionuclides behave both in the environment and within biological systems. This knowledge aids in devising strategies to interrupt or minimize exposure pathways. The main routes of human exposure include

inhaling airborne radionuclides, ingesting contaminated food and water, and skin contact with radioactive materials.

2.4 Radiation-Induced Health Effects through Drinking-Water

The principles of radiation protection rest on the understanding that any level of radiation exposure carries a certain amount of risk. Studies suggest that long-term exposure, such as the continuous intake of drinking water containing radionuclides, can increase cancer risk in humans if doses exceed 100 mSv (WHO, 2011). On the other hand, epidemiological research indicates no significant risk increase for exposures below this level. The current risk assessment model is based on a linear correlation between exposure and risk, implying that even minimal exposure is not entirely risk-free. An individual dose limit of 0.1 mSv annually is regarded as a minimal risk threshold, which is unlikely to produce any observable negative health outcomes. Research conducted on both humans and animals indicates that exposure to radiation, even at low to moderate exposure levels, long-term cancer risk may increase. Research in animals also suggests a possible rise in genetic abnormalities linked to radiation exposure. However, when radionuclide concentrations in drinking water are within established limits—ensuring an annual effective dose below 0.1 mSv—no significant health effects from radiation are expected. Acute effects, such as reduced blood cell counts or fatal outcomes, only occur with very high doses affecting large areas or the whole body. Given the typically low radionuclide levels in drinking water, these acute risks are not a concern (WHO, 2011).2.5 Strategy for Assessing Drinking-Water. When water screening thresholds are surpassed, it is

important to assess the specific contribution of each radionuclide to the Individual Dose Criterion (IDC). If the following formula is met, no further actions are necessary.

$$\sum_{GLi}^{Ci} \leq 1 \qquad (1)$$

- Ci: Represents the detected activity concentration of radionuclide i.
- GLi: Refers to the recommended threshold for radionuclide i. This limit is determined such that consuming 2 liters of water daily over a year would lead to a cumulative effective dose not exceeding 0.1 mSv annually.

This guideline ensures the combined exposure from multiple radionuclides remains within safe limits, protecting public health from radiological risks.

If there were more than one for each sample, then only an RDL of 0.1mSv would be exceeded if exposure at the measured levels lasted one year. Thus, if there is only one occasion when it crossed this line, it does not necessarily mean that the water is bad to drink, it just means we need to look further, get more tests. Gross alpha and beta activity should first be rechecked, and radionuclide-specific analysis performed only when the gross levels exceed the screening limits of 1 Bq/l for beta activity and 0.5 Bq/l for alpha activity (WHO, 2011).

The gross beta measurement encompasses potassium-40 (K-40), a naturally occurring beta emitter that exists in a stable proportion with regular potassium, an essential nutrient

primarily obtained through food. K-40 does not build up in the body, as its levels remain steady regardless of intake. To adjust for K-40's impact on beta activity, its specific beta activity (27.6 Bq/g of stable potassium) should be subtracted after measuring the total potassium content.

To determine the Maximum Activity Concentration (MAC) of a specific radionuclide in drinking water and assess its particular contribution to the Individual Dose Criterion (IDC) of 0.1 mSv per year involves the following calculations

$$MAC\ (Bq/L) = \frac{0.1\,\frac{mSv}{year}}{730\,L/year \times DC\ \left(\frac{Sv}{Bq}\right) \times 1000\,\frac{mSv}{Sv}} \quad (2)$$

Where;

- 0.1 mSv/year: This represents the maximum allowable radiation dose a person can safely receive annually through water consumption.
- 730 L/year: The yearly water consumption estimate is based on an average intake of 2 litres of water per day.
- DC (Sv/Bq): Known as the dose coefficient, this value represents the radiation dose (in Sieverts) absorbed for every unit of radioactive material ingested (in Becquerels). It is specific to the type of radionuclide being measured.

- 1000 mSv/Sv: This conversion factor changes the dose from Sieverts to millisieverts, which is a smaller unit.

The adult dose coefficient is considered protective for both adults and children because:

MAC values are based on a low dose (0.1 mSv/year), which is minimal compared to natural background radiation, and

Higher dose coefficients calculated for children do not result in significantly higher doses due to lower drinking water intake by infants and children and their faster metabolic rates (Health Canada, 2011).

2.6 Guidance Levels for Radionuclides in Drinking-Water

Guidance levels for radionuclides in drinking water encompass both naturally occurring and artificial radionuclides typically present in water sources, including those related to existing exposure scenarios from past activities. These levels are designed for regular operational conditions in both existing and newly developed water systems. They are not intended for emergency scenarios where radionuclides are suddenly released into the environment. However, these guidelines become applicable again once authorities have formally declared the conclusion of the emergency (WHO, 2011). The calculations are based on the following equation:

$$GL = \frac{IDC}{hing \times q} \qquad (3)$$

Where;

GL = represents the recommended concentration limit for a radionuclide in drinking water, expressed in Bq/L.

IDC = refers to the individual dose criterion, which is set at 0.1 mSv per year for these assessments.

"hing" = corresponds to the ingestion dose coefficient for adults, measured in mSv/Bq.

"q" = denotes the total amount of water consumed annually, estimated at 730 liters per year, which aligns with the World Health Organization's standard of 2 liters per day (WHO, 2011).

Although dose coefficients for children are adjusted for their higher absorption and metabolic rates, they do not result in significantly higher radiation doses since infants and children typically consume less water overall (WHO, 1993). Thus, the recommended guidance levels are derived using adult dose coefficients. However, in cases where water contamination persists, it may be advisable to evaluate doses specifically for infants and children (WHO, 2011).

2.7 Assessing Drinking Water if Guidance Levels are Exceeded

The World Health Organization (WHO) has set guidance levels for various radionuclides commonly found in drinking water, both natural and artificial, based on the Individual Dose Criterion (IDC). When multiple radionuclides are present, their individual doses

must be combined to determine if the IDC is exceeded. WHO clarifies that these guidance levels are conservative and should not be treated as strict limits. Exceeding a guidance level warrants further investigation but does not automatically mean the water is unsafe to drink.

Additionally, if an action level is exceeded in a single sample, it does not indicate a significantly high IDC unless exposure continues over an extended period. The IDC would only be surpassed if the measured concentration remains steady for a full year. Consequently, further sampling is required to confirm whether the initial measurement represents typical conditions over time (IAEA, 2016). If guidance levels are consistently exceeded, the National Authority may decide to take measures to reduce the radionuclide concentration in the water supply or restrict its use for drinking. This decision may align with guidelines such as those in GSR Part 3, which recommend setting a reference level for drinking water that typically does not exceed 1 mSv per year (IAEA, 2014). This reference is not meant to represent an "acceptable" dose or a fixed limit; instead, it suggests that all reasonable efforts should be made to minimize exposure as much as possible. Additionally, non-radiological factors such as remediation costs and the availability of alternative water sources should be considered when making a final decision (IAEA, 2016).

2.8 Analytical Methods

2.8.1 Measurement of Gross Alpha and Gross Beta Activity Concentrations

A commonly used method, aside from radon analysis, involves evaporating a specific volume of the water sample until it is completely dry, then measuring the activity of the residual solids. However, the effectiveness of this method for detecting alpha particles can decrease in samples with high total dissolved solids (TDS), as alpha radiation can be absorbed by a thin layer of solid material. Additionally, when measuring gross beta activity through evaporation, the presence of potassium-40 contributes to the detected activity.

Therefore, if the gross beta activity exceeds the screening threshold, further analysis to measure total potassium is necessary. In contrast, the co-precipitation technique eliminates the influence of potassium-40, removing the need for potassium measurement. However, this technique is unsuitable for water samples containing specific fission products, such as cesium-137. Standardized methods are essential for accurately determining gross alpha and gross beta activity concentrations (WHO, 1993).

2.8.2 Measuring Specific Radionuclides

If screening is higher than gross alpha or gross beta activity, they need to know what radionuclides they are detecting and calculate their activity levels individually (WHO, 2011).

2.9 Radon

Radon exists in three naturally occurring isotopes: Actinon (^{219}Rn), produced by the decay of uranium-^{235}; Thoron (^{220}Rn), derived from Thorium^{232} decay; and Radon (^{222}Rn), resulting from uranium^{238} decay (UNSCEAR, 1993). Human radiation exposure from ^{219}Rn is negligible due to the low activity concentration of uranium^{235} and its very short half-life of 3.96 seconds. In comparison, Radon^{220}, with a half-life of 55.6 seconds, becomes significant primarily in environments with elevated thorium^{232} levels.

The isotope that most affects human radiation doses is ^{222}Rn, with a half-life of 3.82 days. It's a noble gas that can't get very much stuffy in the lab, and it weighs 9.73 g/L at 0 °C. It is 510 cm³/L in water at 0 °C, then 220 cm³/L at 25 °C, and 130 cm³/L at 50 °C. Soil and rock release ^{220}Rn and ^{222}Rn, respectively, depending on activity levels of radium^{228} (^{228}Ra) and radium^{226} (^{226}Ra), the two alpha emitters. Humans get the most natural radiation exposure from radon, inhaling its short-lived decay products, particularly lead-^{210} (^{210}Pb) and polonium^{210} (^{210}Po) (UNSCEAR, 1993; 1996; 2000). Radon dissolved in water can escape into indoor air during activities such as showering or washing, with the extent of this release depending on the concentration of radon in the water. Generally,

radon levels are highest in well water, moderate in groundwater, and lowest in surface water (UNSCEAR, 2000). Enhancements in ventilation systems may reduce indoor radon levels by less than 50%. Outdoor radon concentrations can fluctuate significantly throughout the day, sometimes varying by a factor of ten due to solar heating that encourages upward movement during daylight hours. Conversely, atmospheric inversion conditions at night can trap radon close to the ground (UNSCEAR, 2000).

Globally, indoor radon concentrations have arithmetic and geometric averages of approximately 40 Bq/m³ and 30 Bq/m³, respectively (UNSCEAR, 2000). In surface air, typical time-averaged concentrations range from 2 to 30 Bq/m³ (UNSCEAR, 1996). Radon levels in groundwater vary widely depending on the soil and bedrock composition in the area. For plants, decay products of ^{222}Rn, such as ^{210}Pb and ^{210}Po, are significant sources of radiation exposure. Plants can absorb ^{210}Pb through their roots and leaves, with average concentrations of about 10 Bq/kg in leaves and 5 Bq/kg in needles (UNSCEAR, 1996).

Radon poses risks not only in mines but also in various workplaces. It is essential to implement targeted measures to reduce radon concentrations in both air and water to prevent hazardous levels, even in areas with low uranium and radium concentrations (UNSCEAR, 2000). If radon levels in drinking water exceed 2000 Bq/L, it is advised to take action to minimize its release into indoor air (Health Canada, 2011).

2.10 Guidance on Radon in Drinking Water Supplies

Screening thresholds for radon in water should be set based on the national reference level for indoor radon concentrations and the distribution of radon levels in residential buildings across the country. The World Health Organization (WHO) advises a reference level of 100 Bq/m³ for indoor radon. If this target cannot be met due to national circumstances, the level should not exceed 300 Bq/m³, which equates to an annual radiation dose of approximately 10 mSv (WHO, 2011).

In cases where drinking water is suspected to contain high levels of radon, it is advisable to conduct measurements. If significant levels are found, it may be necessary to assess whether mitigation measures should be implemented (WHO, 2011). Consequently, when elevated radon levels are confirmed or suspected, increasing the frequency of gross alpha and gross beta activity measurements may be required. These screening tests are important for capturing contributions from radon decay products, particularly polonium-210, which significantly increases the radiation dose from consuming radon-contaminated drinking water.

A commonly used and effective technique for monitoring radon levels in water is liquid scintillation counting (WHO, 1993).

2.11 Total Annual Committed Effective Doses from Daily Intakes of ^{238}U and ^{232}Th from water

The annual effective dose from natural sources for humans should be taken into account in calculations of the total effective dose (at year-round exposure) to long-lived natural radionuclides. This dose is rounded out by radionuclides like uranium-238 (238U), thorium-232 (232Th), and potassium-40 (40K), which are directly detectable in all kinds of water sources, because the human body indirectly consumes these isotopes. Let's assume that the average adult male gulps 1 litre of water each day (WHO, 2011), and the annual effective dose is computed using the dose of each radionuclide taken in addition to the dose coefficients of ingestion (SvBq–1) established by the International Commission on Radiological Protection (ICRP) (2007). This is the calculation for annual effective dose per person (Pascal et al, 2011).

$$AED = \sum_i I_i \times 365 \times D \qquad (4)$$

Where;

I_i: Represents the daily intake of the radionuclide i, measured in Bq/day.

D_i: Denotes the ingestion dose coefficient for radionuclide i, expressed in Sv/Bq.

Averaging the total annual committed effective doses of the individual alpha or beta emitters in the 238U and 232Th families can then be used to calculate the annual average alpha or beta committed effective dose for any given sample, as shown.

$$E_{avg}(\alpha/\beta) = \frac{Idw}{V_{sam}} \sum^{R(\alpha/\beta)} N^{R(\alpha/\beta)} A(\alpha/\beta) \times DCF_{ing}(\alpha/\beta) \quad (5)$$

Where;

E_{avg} (α/β): Represents the average annual effective dose from alpha or beta radiation in the water sample.

A(α/β): Denotes the activity concentration of alpha or beta radiation in the sample.

I_{dw}: Refers to the daily water consumption rate, assumed to be 2 liters per day.

V_{sam}: Indicates the volume of the water sample.

NR(α/β): Represents the number of radionuclides that are significant contributors to alpha or beta activity, typically those in the uranium-238 (^{238}U) and thorium-232 (^{232}Th) decay series.

DCFing(α/β): Stands for the ingestion dose coefficient, which quantifies the dose per unit intake of radionuclides. This coefficient is based on standards from the ICRP (International Commission on Radiological Protection) Report (2007).

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter outlines the procedures employed in conducting the study, including the description of the study area, sampling strategy, analytical methods, and instruments used for measuring radionuclide concentrations and physicochemical parameters. It also details the quality control measures and dose estimation techniques applied during data analysis.

3.1 Study Area

The study was carried out in the Ahafo North District, specifically within the Tano North area in Ghana's Bono Region. This area has been designated as a mining concession for Newmont Ghana Gold Limited (NGGL) and is located near several towns, including Susuanso, Tekyere, Yamfo, Afresepakrom, Adrobraa, and Tanoso, as shown in Figure 3.1. Significant gold deposits are found in the mountain ranges extending across Tekyere, Yamfo, Bomaa, Adrobraa, and Tanoso (Dickson and Benneh, 1970). As a result, NGGL is moving forward with plans to begin mining operations as part of the second phase of the Ahafo North Gold Mining Project. Currently, NGGL is actively extracting gold at various locations within the district, particularly in Kenyase No. 1 and 2, Ntotroso, Gyedu-Wamahinso, and several smaller communities (Wright et al., 1985).

The Tano River runs through Ghana, then into Ivory Coast, before rushing into the Atlantic Ocean. It starts near Techiman and goes some 400 kilometers through the places we know as Ehy Lagoon and Tendo Lagoon to Aby Lagoon in Ivory Coast. The river is

flowable 60 miles (95 km) upstream, and then Sutre Falls prevents travel towards Tanoso. Both the Tano River and its twin, the Ankobra River, flow into a shallow basin southwest of the Kwahu Plateau, a watershed for Ghana.

The Ankobra-Tano Basin is important for industries such as gold and bauxite extraction, timber production, copra farming, palm oil extraction and rubber production. Furthermore, the lower section of the Tano River is a natural boundary between Ghana and Ivory Coast (Water Resource Commission, 2012). In the Ahafo North District, water is mainly provided by the Tano River, but there are several streams running through the Ahafo Mines project area. Arid streams and rivers break this land into three basins, Subika, Amoma and Awonsu, that dries out from November to late April. Tano River is an important surface water source for the project zone to supply water for residential and agricultural use. Water from the Tano River is treated at Akyerensua by the Ghana Water Company Limited (GWCL), which subsequently flows into nearby villages like Hwidiem, Kenyase No. 1 and 2, New Dormaa, etc. around the development.

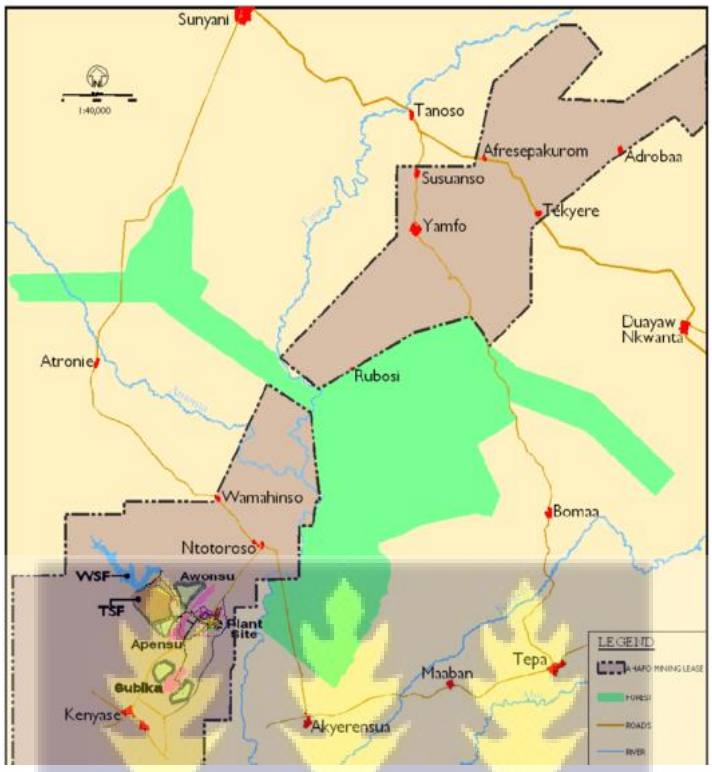

Figure 3.1: Map of Study Area Source: Author, 2024.

3.2 Geological Study of the Area

3.2.1 Climate

This study region is in the wet semi-equatorial climate zone of Ghana, where there is a double peak rainfall. The wettest period is from May to July, and again from September to mid-November. It has average monthly temperatures of 23.9°C to 28.4°C with March normally being the hottest month and August the coolest (Walker, 1962).

3.2.2 Hydrogeology

The geological formations in the study area are primarily composed of metasediments and granitoids. There is a lack of primary porosity, meaning that groundwater availability relies entirely on fractured and weathered zones. The typical aquifer system consists of low-permeability weathered layers that are drained by underlying fractures (NGGL, 2005). Several seasonal streams and perennial rivers traverse the region, flowing into the upper basin of the Tano River and dividing the project area into smaller sub-basins, including Awonsu, Subika, Ntotroso, and Amoma (NGGL, 2005).

The Tano River is a vital source of drinking water for the Brong Ahafo Region, supplying residents in Sunyani and surrounding towns. The Ghana Water Company Limited (GWCL) extracts and treats water from this river at small to medium-sized treatment facilities. The study area features numerous mining pits and proposed infrastructure scattered across various sub-basins. Notably, two proposed mining pits Subika and Awonsu are located within the Subri Sub-basin, with portions extending into the Awonsu Sub-basin (NGGL, 2005).

3.2.3 Soil, vegetation and land use

Human activities, especially agriculture, have a substantial impact on soil quality in the study area, causing problems like nutrient loss, soil erosion, pan formation, and general land degradation (NGGL, 2005). This area falls within Ghana's semi-deciduous agro-

ecological zone and is part of the Celtis-Triplochiton Association. The forest reserves in this region protect remnants of the Eastern Guinean Forest, which historically covered significant parts of central Ghana.

Forests are typically triangular canopy systems with emergent trees of 50 metres or more. Its upper canopy has both evergreen and deciduous species. It has species such as *Nesogordonia papaverifera, Celtis mildbraedii, Argomuerella macrophylla, Sterculia rhinopetala, Aframomum stanfieldii, Ricinodendron heudelotii and Masonia altissima* (NGGL, 2005).

3.3 Sampling and sample preparation for Gamma spectrometry analysis

All the water samples were carefully homogenized and added straight to 1L Marinelli beakers, with no pre-treatment.

To bring the samples to radioactive equilibrium with ^{226}Ra and its stowaway decay products, the homogenised extracts were sealed in the 1000 ml Marinelli beakers, weighted, and preserved for a month. Then each was examined by a high-purity germanium detector. Figure 3.2: Map showing the water sampling locations. Not all of the mentioned sites were sampled (as we emphasise); they were selected according to a calculation of the risk of human exposure.

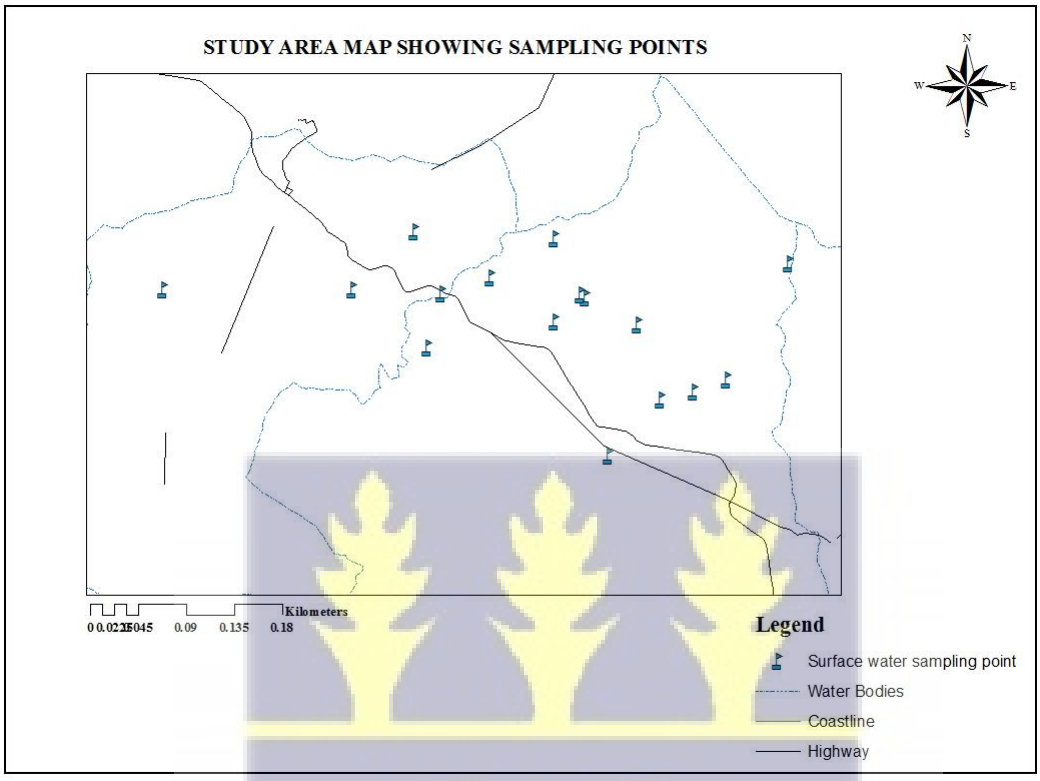

Figure 3. 1: Surface water sampling points. Source: Author, 2024

3.4 **Sampling of the Study**

The sampling method used was purposive sampling, also known as judgmental sampling. This non-probability technique was selected to ensure that the sites chosen for data collection were directly relevant to the study's objectives. Sampling locations were deliberately selected based on three primary criteria: their proximity to the proposed

mining concession, their role in community water use (such as drinking, domestic activities, and irrigation), and their hydrogeological and geological characteristics, which influence the potential presence of naturally occurring radioactive materials (NORM). This targeted approach ensured that the water samples collected would likely reflect areas of highest potential radiological exposure, both from natural sources and from anticipated mining activities.

Regarding sample size determination, the study adopted a practical and context-specific approach rather than relying on a statistical formula. A total of sixteen surface water samples were collected across the study area. This number was determined based on the need for adequate geographic coverage, ensuring that the spatial distribution of surface water bodies in the region was well represented. The sample size also reflected logistical considerations, including the capacity for laboratory processing and analysis, particularly given the intensive procedures required for gross alpha and beta measurement, such as evaporation and extended counting times.

Furthermore, the selected sample size aligned with common regulatory and scientific practice. International guidelines, including those from the IAEA and WHO, typically recommend between 10 and 20 sampling points for baseline environmental radiological assessments in similar settings. Therefore, the chosen number of samples was considered sufficient to provide a reliable baseline for the assessment of radioactivity in surface waters in the Ahafo North region, while also accommodating constraints related to

resource availability and methodological rigor. Although no formal statistical sample size formula was applied, the strategy ensured that the data collected were both scientifically robust and operationally feasible.

3.5 Sample measurement, instrumentation, and analysis for Gamma Spectrometry Analysis

Figure 3.2: Spectrum Analyzer Software setup.

The gamma radiation from the water samples was analyzed directly, non-destructively with a High Purity Germanium (HPGe) detector. The gamma energies were measured using high-resolution gamma spectroscopy using a p-type Extended Range Germanium coaxial detector (Model GX4018) with carbon-epoxy window, relative efficiency of 40% and an energy resolution of 2.0 keV for ^{60}Co at 1332 keV. This was attached to a multi-channel analyzer (MCA) and a desktop computer for data collection.

The semiconductor detector's cylinder had a 5 cm thick lead shield, its diameter was 24 cm and its length 60 cm. This lead shielding was topped with copper, and cadmium and Plexiglas layers of 3 mm each lined its insides. The chemistry of the radionuclides was calculated by their gamma-ray energies, and measured with Genie 2000 gamma acquisition and analysis software. Background spectra were obtained for each radionuclide detected and converted into net spectra so that net peak area of the gamma rays could be corrected. These background spectra also made it possible to estimate minimum activity levels detectable at 95% confidence for ^{232}Th (0.34 Bq), ^{40}K (1.62 Bq) and ^{238}U (0.35 Bq).

Gamma-ray emission from ^{238}U, and the measured gamma yields of ^{214}Pb (351.98%) and 214Bi (609.3 V) (448.88%). Activities for ^{232}Th were calculated from gamma emission for 228Ac at 911 keV (26.6%), ^{212}Pb at 238.6 keV (43.3%) and 208Tl at 583 keV (30.1%) and 2614.7 keV (35.3%), with a branching ratio of 33.7% between 212Bi and 208Tl. ^{40}K's

activity level was calculated right at its emission line at 1460.8 keV (10.7%). All intensities and energies came from a known data library.

A multi-gamma certified cocktail standard containing ^{241}Am, ^{109}Cd,^{57}Co,1^{39}Ce, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{60}Co, and ^{88}Y) was prepared in a 1L Marinelli beaker. After allowing for a four-week period to achieve secular equilibrium, each water sample was placed into the shielded HPGe detector for counting, with individual samples counted for durations ranging from 10 to 24 hours to ensure adequate spectral data collection.

3.6 Calculation of activity concentration and estimation of doses

The analytical formula used to calculate the activity concentrations in Bq/L for water samples is provided in Equation (6).

$$A_{sp} = \frac{N_D e^{\lambda \rho t_d}}{p.T_{c \cdot \eta(E).m}} \qquad (6)$$

ND: Refers to the net counts of the radionuclide detected in the sample.

td: Denotes the time delay between when the sample is collected and when it is measured.

P: Represents the probability of gamma-ray emission, also known as the gamma-ray yield.

η(E): Indicates the absolute efficiency of the detector system for a specific energy (E).

Tc: Refers to the duration for which the sample is counted.

m: Represents the mass of the sample, expressed either in kilograms (kg) for solids or in liters (L) for liquids.

eλptd: Is the decay correction factor that accounts for the time elapsed between sampling and counting.

λp: Refers to the decay constant of the parent radionuclide.

The committed effective doses for the water samples were determined based on the activity concentrations of each radionuclide and the adult rate of water use of 730 litres a year (WHO, 2011). Conversion factors for ^{238}U, ^{232}Th, and ^{40}K were calculated from the Basic Safety Standards (BSS) (IAEA, 1996). These calculations were made with Equation (7).

$$S_{ing}\,(\mathrm{w}) = I_w \sum_{j=1}^{3} DCF_{ing}\,(U, Th, K)\ \mathrm{A_{sp}}(w) \qquad (7)$$

Where;

Asp(w): Refers to the activity concentration of radionuclides in the water sample, expressed in Bq/L.

Iw: Denotes the rate of water consumption.

DCF_{ing}: Represents the ingestion dose coefficient for the radionuclides, expressed in Sv/Bq. This coefficient accounts for uranium (U), thorium (Th), and potassium (K).

For each location, the γ dose rate from the surrounding area was measured at a height of 1 meter above ground level and recorded in μGy/h. The annual effective dose (Eγ, ext)

was subsequently calculated using the measured average outdoor external gamma dose rate (Dγ, ext), as described in Equation (8).

$$E_{\gamma,ext} = D_{\gamma.ext} T_{exp} DCF_{ext} \qquad (8)$$

Where;

Dγ, ext: Represents the average external gamma dose rate outdoors, measured in μGy/h.

T_{exp}: Denotes the annual exposure duration, assumed to be 8,760 hours (one full year).

Outdoor occupancy factor: A factor of 0.2 is used to account for the time spent outdoors relative to the total exposure.

DCF_{ext}: Refers to the dose conversion factor, which converts the absorbed dose to an effective dose. This is set at 0.7 Sv/Gy for environmental gamma radiation, based on the UNSCEAR (2008) guidelines.

3.7 Determination of natural radioactivity in water samples using gross alpha and gross beta counter

Radioactivity gross alpha and gross beta were measured in sixteen (16) surface water samples from various streams and rivers. 1 ml of concentrated HNO3 was added per 500 ml sample, and evaporated almost to 100% by means of a hot plate in a fume hood. The solution was then filtered out of the beaker with 1M HNO3 and evaporated again to about

dryness. After that, the residue was dissolved in a few drops of 1M HNO3 and poured on to a pre-weighed 25 mm stainless steel planchet.

Figure 3.4 Planchet with the sample removed from oven to get rid of any moisture. Then it was placed in a desiccator to dry and soak up water. The alpha and beta activity of the prepared samples was quantified by a low background, gas-free Automatic Alpha/Beta counting device (Canberra iMaticTM) with beta standard. It uses a solid-state PIPS (Passivated Implanted Planar Silicon) detector to measure alpha and beta radiation. The detection efficiencies came out as 36.39 ±2.1% for alpha particles and 36.61± 2.2% for beta particles. The baseline activity was 0.40 ± 0.01 counts per minute (cpm) of alpha radiation, and 0.22 ± 0.03 cpm of beta radiation.

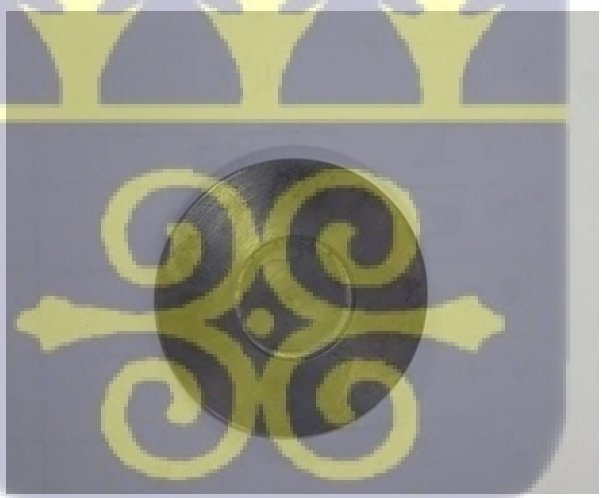

Figure 3.3: Stainless Steel Planchet

3.8 Determination of natural radioactivity in water samples using Alpha Spectrometry

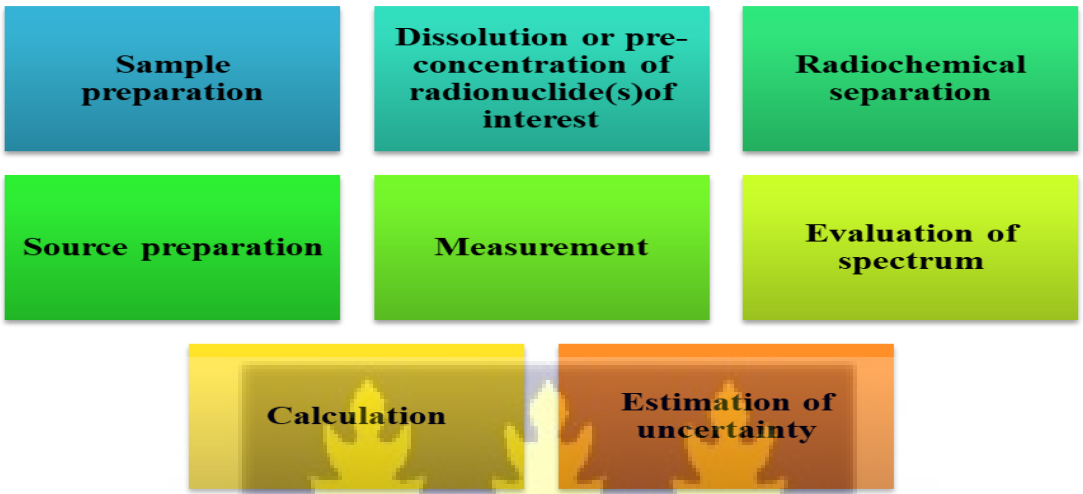

Figure 3.4: Flow chart of the Alpha Particle Spectrometer Steps Source: Author 2024

Sixteen (16) water samples in total were collected from designated areas within the proposed mine concession and nearby communities for alpha spectrometric analysis of uranium, thorium, and polonium.

In the laboratory, each 500 ml water sample was prepared by first measuring its weight in grams. Tracers, specifically ^{232}U, ^{229}Th, and ^{209}Po, were added (about 0.5 g each) to monitor recovery, followed by the addition of 2 ml of 5 mg/ml iron carrier (Fe^{3+}). The mixture was heated to around 50°C using a magnetic stirrer to ensure thorough mixing of

the tracers and iron carrier. The pH of each sample was then adjusted to between 8.3 and 8.5 by adding concentrated ammonia (NH_3) until a brown precipitate formed, which was allowed to settle for one hour.

After precipitation, the samples were centrifuged, and the supernatant was carefully removed. The precipitate was dried under an infrared lamp for approximately one hour and subsequently dissolved in 5 ml of 3M HNO3 to prepare it for radiochemical separation.

Radiochemical separation was performed using a UTEVA resin column. The dissolved sample solution was passed through the resin, with the initial fraction collected for polonium analysis. The column was then rinsed with 10 ml of 3M HNO_3 to retain uranium and thorium. Thorium was extracted using 4 ml of 9M HCl followed by 20 ml of 5M HCl, while uranium was extracted with 10 ml of 0.01M HCl. The fractions containing thorium and uranium were concentrated through evaporation, rinsed with Na_2SO_4, and prepared for electrodeposition onto stainless steel discs. Polonium was analyzed via auto-deposition onto a copper planchet from a hydrochloric acid solution at around 80°C. The planchets containing the deposited uranium, thorium, and polonium were then analyzed using an alpha spectrometry system to quantify the radionuclide levels in the collected water samples.

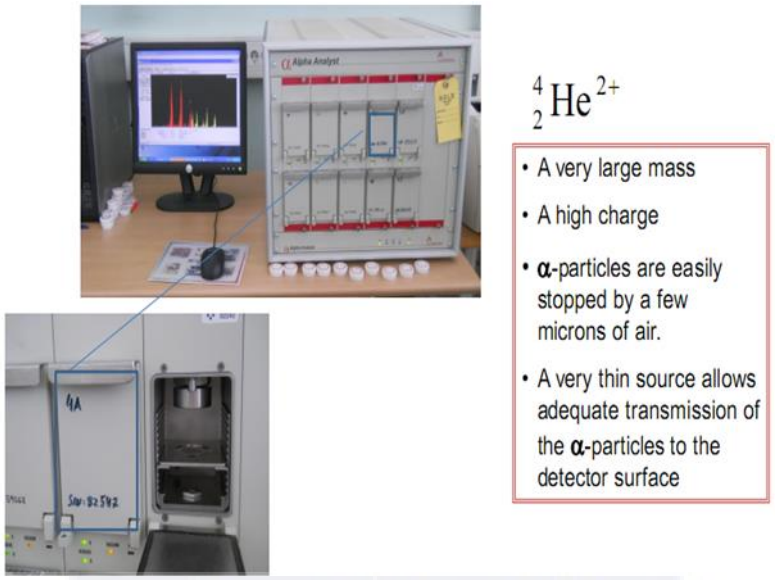

Figure 3.5: Alpha Particle Spectrometer Setup

3.9 Estimation of total annual effective dose

The total annual effective dose (E_T) to members of the public was calculated using ICRP dose calculation method (ICRP, 1991; 2007). The analytical expression for the total effective dose is provided in equation (9).

$$E_T = E_\gamma\ (U, Th, K) + E_{ing}\ (W) \qquad (9)$$

Where;

Eγ (U, Th, K): Represents the effective dose from external gamma radiation due to uranium (U), thorium (Th), and potassium (K) in soil samples.

Eing(W): Denotes the effective dose resulting from ingesting water containing radionuclides.

3.10 Minimum Detectable Activity (MDA)

Alpha spectrometry is a highly sensitive method employed to quantify radionuclides. However, due to statistical fluctuations in background levels and inherent noise within the detection system, results may occasionally show values below zero or near the detection limit. To mitigate this issue, the Minimum Detectable Activity (MDA) is calculated as an essential benchmark for differentiating significant measurements from statistical noise. The MDA indicates the lowest level of activity that can be reliably detected under specified conditions, thereby ensuring the accuracy of reported results.

MDA Determination for Alpha Spectrometry

The MDA is calculated using the following equation, derived from statistical principles established by Currie (1968):

$$\mathrm{MDA} = \frac{k \cdot \sqrt{B + 2.71}}{\epsilon \cdot t} \qquad (10)$$

Where;

k: Represents the statistical confidence factor, determined by the desired level of certainty in the measurement. For instance, k=1.645k corresponds to a 95% confidence level.

B: Refers to the background count rate, measured during a blank or control run within the specific energy range of interest.

t: Denotes the measurement time, typically expressed in seconds.

ϵ: Indicates the detection efficiency, representing the fraction of radioactive decay events successfully detected by the system.

3.11 Statistical Analysis

The data and findings were plotted and tables with the means standard deviation (SD) and ranges. Findings from laboratory analyses were statistically evaluated by one-way ANOVA in Microsoft Excel 2022 and the Statistical Package for the Social Sciences (SPSS) 23.0. The following post-test, Tukey's Multiple Comparison, was used to further examine significant sampling difference up to the 5% level. The results were then compared with drinking water quality guidelines from the Environmental Protection Agency (EPA) and the World Health Organization (WHO), the compiled results being table.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

This chapter presents and interprets the results of the physicochemical analyses and radiological assessments of surface water samples. It discusses the concentrations of key radionuclides, evaluates the estimated radiation doses, and compares findings with international standards and related studies to highlight potential environmental and health implications.

4.1 Analysis of Selected Physicochemical Parameters of the surface water samples from the study area

The average pH of the water samples ranged from 5.36 to 8.05 (refer to Table 4.1). These mean pH values were below the recommended limits set by the Ghana Environmental Protection Agency (EPA), the National Environmental Quality (NEQ), and the World Health Organization (WHO), which are 6.00 - 9.00 and 6.50 - 9.50, respectively. Samples with mean pH values below 6.00 were considered acidic, while those between 7.50 and 8.05 indicated mild alkalinity. The variation in pH among the samples was not statistically significant ($P > 0.05$). The pH value, reflecting hydrogen ion concentration, indicates whether water is acidic or alkaline (WHO, 1996). Human activities, such as industrial processes and improper waste management, can greatly impact water pH (WHO, 1996). Shifts in pH can harm aquatic organisms, which are particularly sensitive to changes in

water chemistry and temperature (Sisioda and Chaturbhuj, 2006). Additionally, pH is vital for sustaining biological life, as most organisms thrive within a limited pH range (Sisioda and Chaturbhuj, 2006), and it also affects the movement and behavior of contaminants in the environment (WHO, 1996).

The results of this study are consistent with those reported by Akinbile (2012), Longe and Balogun (2010), and Chidanand et al. (2013). The slightly acidic conditions found in surface waters may suggest the presence of metals, particularly toxic ones, as highlighted by Chidanand et al. (2013). This acidity might also be associated with low levels of metal contaminants or the breakdown of organic matter in the water, as indicated by Akinbile (2012). Furthermore, the acidic pH levels observed could be attributed to microbial decomposition processes that contribute to increased acidity (Longe and Balogun, 2010).

The pH of water influences the solubility of various toxic and beneficial substances; as acidity increases, many metals become more soluble and potentially harmful (Ali, 2010). Extreme pH levels can affect water taste and present risks to digestive health (Ali, 2010). Moreover, the toxicity of cyanides and sulfides intensifies with decreasing pH, while ammonia becomes more toxic with even slight increases in pH (NGRDC, 2000). According to WHO (2015), health risks are particularly significant at extreme pH levels.

The analysis of Total Dissolved Solids (TDS) indicated significant variations among the sampled surface water bodies ($F = 8.294$, $df = 3$, $p\text{-value} = 0.002$, $p < 0.05$). The highest mean TDS concentration was recorded at CSW-12 (249.95 mg/L), followed by CSW-3

(243.75 mg/L), CSW-32 (178.10 mg/L), and CSW-28 (27.95 mg/L), as presented in Table 4.1. TDS reflects the total concentration of dissolved substances in water (Schwardenbach, 2010) and signifies the water's capacity to dissolve both organic and inorganic materials (Schwardenbach, 2010). Elevated TDS levels can increase water density and lower oxygen solubility, which can be detrimental to aquatic organisms (Bangash et al., 2006). Additionally, TDS levels offer insights into electrical conductivity and the possible presence of heavy metals in the water (EPA, 2001).

Similar research by Taiwo et al. (2011) in Obantoko, Nigeria, reported lower TDS levels at three sampling sites, measuring 270 mg/L, 240 mg/L, and 50 mg/L. The findings of this study align with those of Chidanand et al. (2013), Longe and Balogun (2010), and Taiwo et al. (2011). Lower TDS values indicate minimal surface water contamination from dissolved chemicals, including toxic metals, as suggested by Chidanand et al. (2013). This may also result from reduced sedimentation due to runoff at mining areas, as observed by Longe and Balogun (2010), or be linked to low concentrations of carbonates, chlorides, calcium, magnesium, and sulphates, as noted by Taiwo et al. (2011).

The analysis of turbidity revealed significant differences among the sampled surface water bodies ($F = 3.671$, $df = 3$, p-value = 0.039, $p < 0.05$). The highest average turbidity was observed at CSW-29, while CSW-3 recorded the lowest mean value, with turbidity levels ranging between 4.25 and 3000.00 NTU (refer to Table 4.1). Although no statistically significant differences in turbidity were found among the water samples, all

mean turbidity levels, except for CSW-3, exceeded the Ghana EPA, NEQ, and WHO recommended threshold of 5 NTU.

The American Public Health Association (APHA, 1989) defines turbidity as an optical phenomenon in which light is reflected and scattered rather than reflected straight through a water sample. Water is turbid due to dissolved material in the water: clay, silt, fractionated organic matter, plankton and other microscopic organisms (USEPA, 2013). Water clarity decreases as the concentration of suspended particles increases, resulting in cloudier water (APHA, 1989). Elevated turbidity levels can heighten the risk of disease due to infectious agents associated with particulate matter in the water (WRC, 2003), potentially causing epidemic-level disease outbreaks during periods of high turbidity.

Research conducted by Taiwo et al. (2011) in Obantoko reported lower mean turbidity values at three sampling sites: 27.9 NTU, 40.2 NTU, and 48.4 NTU. The results of this study align with those of Akinbile (2012), Butt and Ghaffar (2011), and Taiwo et al. (2011). The higher turbidity levels observed in this study suggest that soil particles may have entered surface waters due to unstable banks or an increase in suspended materials, as noted by Akinbile (2012). Additionally, Butt and Ghaffar (2011) attributed this to low concentrations of suspended organic matter in leachates and water samples.

High turbidity levels can increase the risk of waterborne diseases; when driven primarily by organic particles, it may also result in dissolved oxygen depletion in aquatic habitats (USEPA, 2013). Elevated turbidity is often associated with a rise in disease-causing

microorganisms, such as viruses and bacteria, which can trigger symptoms like nausea and diarrhea (USEPA, 2013). Turbidity levels above 75 NTU can significantly degrade the aesthetic quality of water while posing health hazards due to infectious agents adhering to suspended particles (USEPA, 2013).

Electrical conductivity levels in the water samples ranged from 45.30 to 406.80 µS/cm (refer to Table 4.1), with the highest mean conductivity observed at CSW-12 and the lowest at CSW-28. Although these differences were not statistically significant among the various water bodies, all mean conductivity levels were well below the Ghana EPA guideline for drinking water quality, which is set at 1500 µS/cm.

Conductivity indicates the presence of ions in water, usually originating from saline sources, and is directly related to the concentration of dissolved ions (NGRDC, 2000). It also provides an estimate of total dissolved solids in water and is affected by temperature higher temperatures typically increase conductivity due to enhanced ion mobility (NGRDC, 2000). Sudden spikes in stream conductivity can suggest nearby sources introducing dissolved ions into the water system, making conductivity measurements a useful tool for quickly assessing potential water quality issues (NGRDC, 2000).

In this study's findings on EC values were lower compared to those reported by Butt and Ghaffar (2011) near Mehmood Boti mine in Pakistan where means ranged from1263 µS/cm –1543 µS/cm. Conversely, Taiwo et al. (2011) reported lower mean EC values ranging from110 µS/cm –530 µS/cm. Akinbile (2012)'s assessment at Akure, Nigeria also

indicated low mean EC values between31 .68 µS/cm –255 µS/cm across three sampling sites. While results here did not align with Butt & Ghaffar (2011)'s findings, they were consistent with those obtained by Taiwo et al. (2011) and Akinbile (2012) Moderate conductivity observed may stem from natural processes introducing inorganic substances into waters many containing metallic ions, bicarbonate, and chloride ions potentially precipitating out from mining activities leading some ions settling due adsorption (Taiwo et al.,2011). Extremely low levels could result from reduced dissolved solids present within leachates, surface waters or lower temperatures since elevated electrical conductivity often indicates pollution (Akinbile ,2012). Health effects associated with EC levels above1500 µS/cm can arise when consuming contaminated drinking waters (WRC ,2000). Typical natural background concentrations found across freshwaters range between 10.0–300.0 µS/cm (NGRDC ,2000); thus, sources exceeding1500µS/cm are generally classified as polluted (NGRDC ,2000).

The average temperature for the sampled waters ranged between24 .20–28 .20 °C(Table4 .1); exceeding permissible limits established by WHO which state ambient temperatures should not surpass23 °C .No statistically significant differences were detected across sampled bodies regarding temperature readings .Temperature fluctuations whether high or low can influence other parameters like conductivity or dissolved minerals(Hach ,2000); affecting chemical reaction rates along with solubility levels present within waters determined using a temperature meter(Hach ,2000) .The observed temperature range reflects its tropical environment(WHO ,2003); influenced largely by atmospheric

conditions during sampling periods .Higher temperatures recorded may correlate directly with increased turbidity/conductivity stemming from suspended materials(DWAF ,1998).

Total Suspended Solids (TSS) averaged between0 .00–1000 .00 mg/l across all sampled bodies; CSW-29 exhibited highest mean value while CSW-28, CSW-32, and SSW-8 showed lowest readings (Table4.1) however these variations lacked statistical significance overall levels were generally lower than recommended limits established by Ghana EPA/NEQ/WHO which set thresholds at50mg/l/20mg/l respectively. Total Suspended Solids (TSS) encompass both algal/non-algal matter including finely ground calcium carbonate particles sourced from limestone (Chidanand et al.,2010); depending upon their origin these substances may impart various colors onto waters determined via spectrophotometry (Hach ,2000).

Table 4.1: Physical parameters of surface water samples from the study area

Station ID	pH	TSS	Temp	Cond	Turb	TDS
CSW 9	8.02	62	24.8	206.6	11.06	133.25
SSW 2	8.05	39	25.5	115.5	5.69	74.1
SSW1	8	110	27.1	138	13.9	85.15
CSW 18	7.55	63	26.9	188.6	12.6	117
CSW 5	7.42	48	26.5	177	11.9	110.5
CSW 24	7.3	39	26.2	119.4	14.1	75.4
CSW 28	5.36	0	27.2	45.3	43	27.95

CSW 26	7.05	44	24.2	119.6	13.5	78
CSW 8	7.02	22	27.8	236	10.98	144.3
CSW 10	7.33	40	28.2	240.3	11.1	145.6
SSW4	7.02	22	27.8	236	10.98	144.3
CSW 32	6.58	0	25.5	280.5	15.5	178.1
SSW 8	7.22	0	26	182.3	25.8	115.05
CSW 3	6.87	7	26.4	387.6	4.25	243.75
CSW 12	7.7	40	27.8	406.8	6.87	249.95
CSW 29	6.27	≥1000	28.2	121.7	≥3000	78
Ghana EPA NEQ Guidelines	9	50	23	1500	5	1000
WHO Drinking Water Guidelines	9.5	20	23	1500	5	1000

4.2 Results of activity concentration of water samples for the study area

Table 4.2: Results of activity concentration of K-40, U-238, and Th-232

Station ID	^{238}U	^{232}Th	40K	Committed effective dose, mSv/year
CSW 9	0.17±0.02	0.48±0.15	1.25±0.20	0.12
SSW 2	1.23±0.58	2.25±0.80	2.55±0.98	0.62
SSW1	0.22±0.08	0.70±0.25	1.40±0.28	0.16
CSW 18	0.21±0.06	0.70±0.19	1.40±0.30	0.15
CSW 5	0.41±0.16	0.65±0.24	1.45±0.29	0.19
CSW 24	0.27±0.08	0.42±0.10	1.05±0.18	0.13
CSW 28	0.22±0.07	0.60±0.24	1.35±0.28	0.15
CSW 26	0.31±0.10	0.65±0.26	1.10±0.28	0.17
CSW 8	0.27±0.08	0.55±0.19	1.40±0.30	0.15
CSW 10	1.25±0.64	2.35±0.88	2.72±0.90	0.65
SSW4	0.26±0.06	0.75±0.26	1.15±0.24	0.18
CSW 32	0.21±0.08	0.65±0.23	0.90 ±0.14	0.15
SSW 8	0.22±0.07	0.60±0.18	1.05±0.19	0.15
CSW 3	0.17±0.03	0.50±0.18	1.10±0.21	0.12
CSW 12	0.85±0.39	2.65±0.72	3.55±1.28	0.62
CSW 29	1.55±0.51	2.20±0.73	3.1±1.25	0.68
WHO Guidance Levels	10	1	0	0.1

The average activity values for ^{238}U, ^{232}Th and ^{40}K in water are listed in Table 4.2. Concentrations averaged out to be: 238U: 0.38 ± 0.29 Bq/L (ranging from 0.07-1.55 Bq/L), 232Th: 0.85 ± 0.61Bq/L (0.21-2.65 Bq/L), and 40K: 1.38 ± 0.62Bq/L (0.60-3.55 Bq/L). The WHO stipulates guideline levels for drinking water of 10.0 Bq/L for 238U and 1.0 Bq/L for 232Th. Activation 238U in all samples was still below this WHO guideline, although around 23 % of samples were above the WHO guideline for 232Th. Despite the availability of boreholes provided by the mine for drinking water, some community members continue to rely on nearby surface water sources for their domestic needs.

The estimated average annual effective dose from these water sample levels was 0.22± 0.16 mSv; the tolerance range was 0.05-0.68 mSv, which is higher than the WHO's recommendation of 0.1 mSv/year (WHO, 2011). Figure 4.2 External gamma dose rates made for higher values when annual effective doses from airborne gamma radiation and water samples were plotted in Table 4.2.

These higher doses from exogenous gamma radiation can be explained by terrestrial and cosmic radionuclides. The average annual effective dose to the public across all exposure routes for all exposure paths was estimated in this study to be 0.476 mSv, below the International Commission on Radiological Protection (ICRP) recommended limit of 1 mSv for public exposure management. These findings align with previous studies

(UNSCEAR, 2008). Overall, the annual effective doses measured across different samples are considered low.

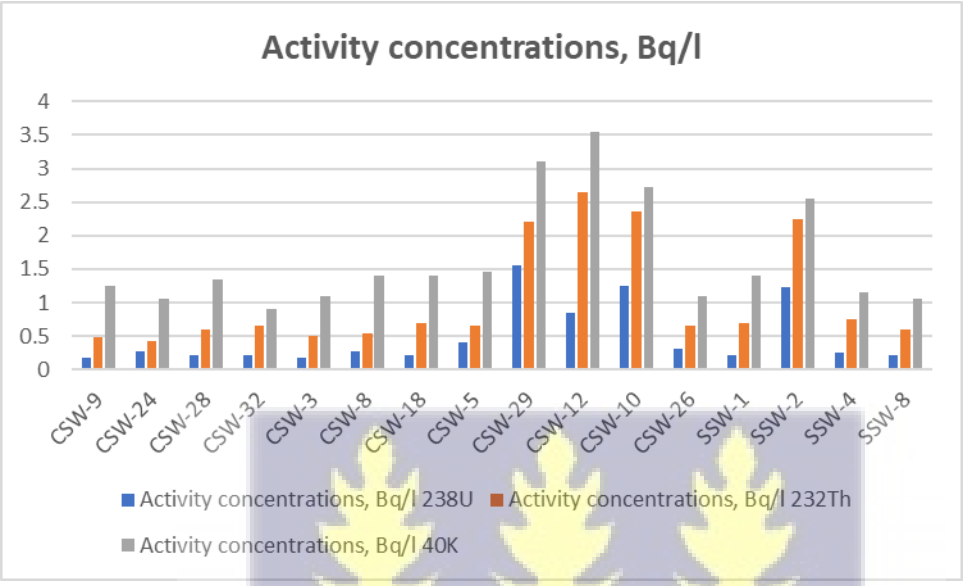

Figure 4.1: Graphical Representation of Average activity concentrations of 238U, 232Th and 40K in water samples in the study area.

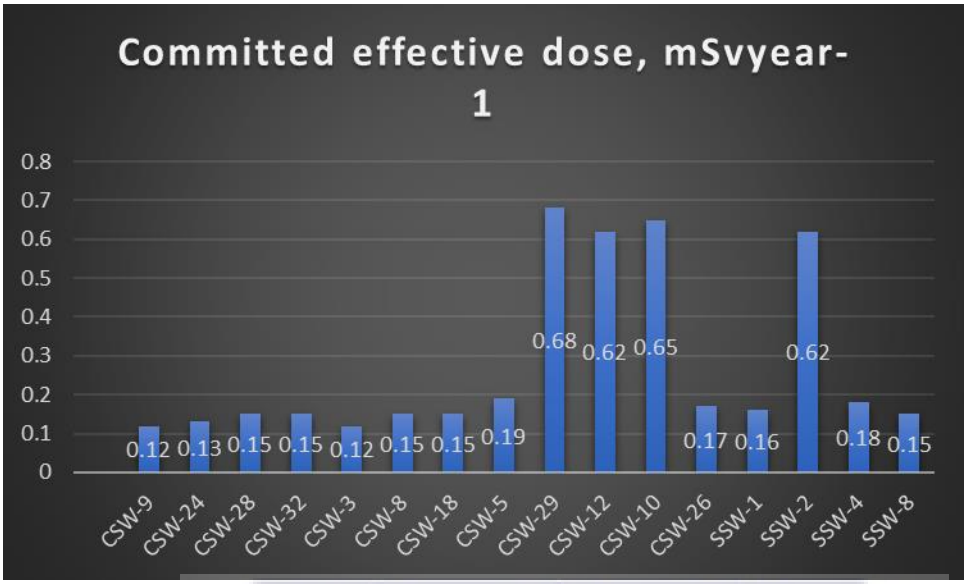

Figure 4.2: Graphical Representation of Annual effective doses due to 238U, 232Th and 40K in water samples in the study area.

4.3 Results of Activity concentrations of gross Alpha and gross Beta in the water samples for the study area

Table 4.3: Activity concentrations of gross-α and gross-β in the water samples

Station ID	Gross Beta	Gross Alpha
CSW 9	0.035	0.00498
SSW 2	0.0445	0.00721
SSW1	0.00531	0.00326
CSW 18	0.03641	0.00373
CSW 5	0.0345	0.00379
CSW 24	0.0346	0.0294
CSW 28	0.0414	0.00557
CSW 26	0.00674	0.00368
CSW 8	0.0372	0.00383
CSW 10	0.0416	0.00514
SSW4	0.0384	0.0043
CSW 32	0.0079	0.00613
SSW 8	0.0089	0.00383
CSW 3	0.00674	0.00367
CSW 12	0.0599	0.00358
CSW 29	0.0521	0.00358
WHO Guidance Levels	1	1
GSA Guidance Levels	1	0.5

Table 4.3 activity levels of gross alpha and gross beta radiation in the sample water. Gross activity concentrations were from 0.0025 Bq/L to 0.0067 Bq/L, and gross concentrations were from 0.0053 Bq/L to 0.0488 Bq/L. The WHO recommends screening levels for drinking water of 0.5 Bq/L for gross and 1.0 Bq/L for gross below which nothing is needed (WHO, 2011). All water samples tested displayed gross Alpha and gross Beta levels below these limits. These values are designed to keep radiation doses under 0.1 mSv/year, based on a 2-litre water intake per day. A comparison of these results with WHO standards confirms that all measured gross α and β values are within safe limits. However, since approximately 23% of the samples exceeded the guideline level for ^{232}Th, it is advisable to conduct ongoing monitoring of water sources intended for drinking and household use in the study area.

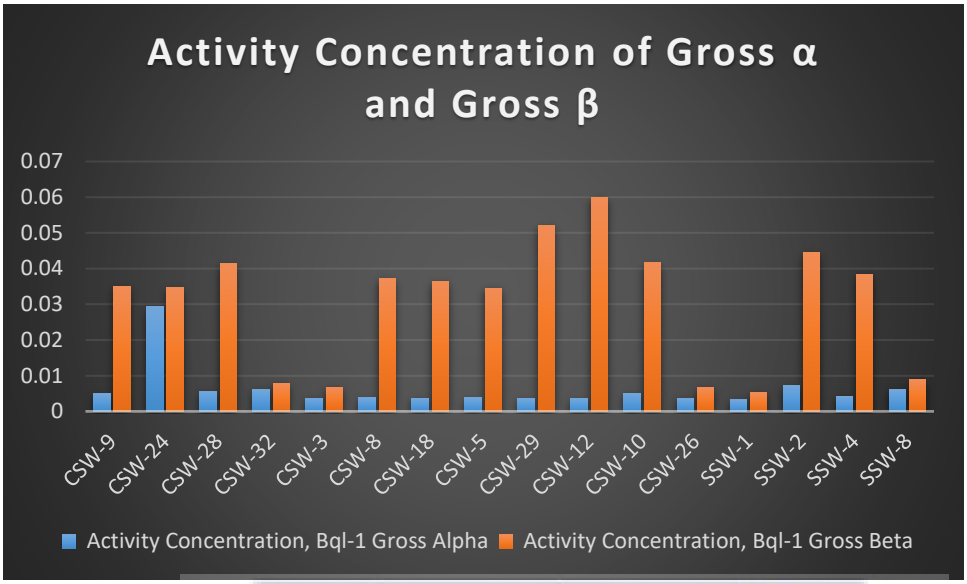

Figure 4.3: Graphical Representation of the Gross-α and gross-β activity concentrations (Bql-1) in water samples from the study area

Table 4.4: Comparison of Gross Alpha Gross Beta (Bql-1) activity Concentration in water sample from the study area with other studies.

Country	Study Location and Reference	Gross Alpha Range **(Bql^{-1})**	Gross Beta Range **(Bql^{-1})**
Ghana	This Study	0.00326 - 0.0294	0.00531 - 0.0599
Ghana	Greater Accra Region Amponsah et al., 2020)	0.003 - 0.033	0.01 - 0.070
Nigeria	Lagos State (Oni et al., 2019)	0.005 - 0.018	0.020 - 0.048

Nigeria	Ogun State (Ademola et al., 2018)	0.002 - 0.022	0.010 - 0.060
South Africa	Western Cape (Mwangi et al., 2021)	0.001 - 0.015	0.015 - 0.055
India	Punjab (Sharma et al., 2017)	0.005 - 0.027	0.015 - 0.068
Jordan	Amman (Ahmad et al., 2018)	0.003 - 0.020	0.010 - 0.045
WHO Guidance	WHO (World Health Organization, 2017)	≤ 1.0	≤ 1.0
GSA Guidance	Ghana Standards Authority (GSA)	≤ 1.0	≤ 1.0

Source: Field work, 2024.

4.4 Alpha Spectrometry Results for Water Samples in the Study Area

Table 4.5: Results for Activity concentration of ^{238}U and ^{234}Uin the water samples.

SAMPLE ID	^{238} U (Bq/kg)	^{234}U (Bq/kg)	^{232}U Tracer (%)
CSW 18	<0.01	9.5±0.475	5.1±0.4
CSW 5	0.5± 0.025	4.2±0.21	29.9±2.1
CSW 24	0.1± 0.005	2.3±0.115	124.9±6.4
CSW8	0.9±0.045	10.4±0.52	33.6±1.7
CSW 26	22.3±1.115	56.5±2.825	81.6±4.2
SSW 2	0.6±0.03	<0.01	19.2±1.1
SSW8	3.3±0.165	12.7±0.635	118.6±6.1
CSW 10	<0.01	21.6±1.08	1.2±8.4

CSW 32	21.1±1.055	23.2±1.16	3.4±0.3
CSW 3	0.5±0.025	1.1±0.055	7.5±0.6
CSW 9	3.1±0.155	10.6±0.53	43.5±2.2
SSW 1	2.2±0.11	4.9±0.245	189±9.7
CSW 12	4.4±0.22	28.4±1.42	16±0.8
CSW 29	3.1±0.155	3.1±0.155	2.3±1.6
SSW 4	19.6±0.98	<0.01	0.1±0
CSW28	2.3±0.115	8.2±0.41	41.4±2.1
MIN	<0.01	<0.01	0.1
MAX	22.3	56.5	189
RANGE	<0.01-22.3	<0.01-56.5	0.1-1.89
AVERAGE	5.6±0.26	12.30±0.63	44.8±2.98

MDA = 0.01

The uranium concentrations in table 4.5 range from <0.01 to 22.3 Bq/kg for U-238, with an average of 5.6 ± 0.28 Bq/kg. These values align with typical ranges seen in natural waters, but the higher end (22.3 Bq/kg in sample CSW 26) suggests specific localized sources, possibly due to geological formations rich in uranium. This aligns with findings from Addo et al. (2012), who reported U-238 values averaging between 1–15 Bq/kg in groundwater from the Upper East and Upper West Regions of Ghana. These levels were relatively higher than averages observed in other regions globally, such as Spain Pérez-López, R., et al. (2010), (0.5–10 Bq/kg) and Salbu, B., et al. (2004) Norway (1–8 Bq/kg), where natural rock formations contain less uranium.

Another study in Ghana by Adu, S., et al. (2020), titled "Assessment of natural radioactivity levels in drinking water sources from Tano North, Ghana" (Journal of Radiation Research and Applied Sciences, 13(2), 326-332), reported uranium concentrations averaging around 2.5 Bq/kg in surface and groundwater sources, which are lower but within a comparable range to those in this study. The combination of these findings indicates that uranium concentration in Ghana varies widely depending on geological characteristics, with some regions showing higher values due to the presence of uranium-rich minerals.

Table 4.6: Results for Activity concentration of ^{230}Th and ^{229}Th in water samples

Sample ID	Th-230 (Bq/kg)	Th-232 (Bq/kg)	Th-229 Tracer (%)
CSW 18	0.5±0.025	< MDA	60.9±4.7

CSW 5	10.7±0.535	< MDA	64.2±10.8
CSW 24	< MDA	< MDA	36.9±6.6
CSW8	30.9±1.545	3±0.15	1.1± 2.3
CSW 26	< MDA	4.9±0.245	1.9±16.4
SSW 2	< MDA	0.8±0.04	7.7±1
SSW8	< MDA	0.2±0.01	5.9±2.6
CSW 10	< MDA	< MDA	2.6±0.6
CSW 32	3.7±0.185	0.4±0.02	3.8±3.1
CSW 3	1.3±0.065	0.1±0.005	19.1±1.5
CSW 9	2.7±0.135	2.1±0.105	66.2±5
SSW 1	< MDA	< MDA	1.4±0.7
CSW 12	8.1±0.405	0.9±0.045	52.8±13.9
CSW 29	20.6±1.03	4.6±0.23	10.6±6.7
SSW 4	< MDA	< MDA	16.3±12.1
CSW28	< MDA	< MDA	6.2±12.6
MIN	< 0.001	< 0.001	1.1
MAX	30.9	4.6	252.8
RANGE	< 0.001 -30.9	< 0.001 -4.6	1.1-252.8
AVERAGE	8.72±0.43	1.54±0.08	53.3±6.29

MDA = 0.001

Thorium concentrations for Th-230 in table 4.6 provided data range from < 0.001 to 30.9 Bq/kg, with an average of 8.72 ± 0.43 Bq/kg, while Th-232 shows an average of 1.54 Bq/kg. These values are slightly lower than those found in regions with mining activities, such as Brazil by Amaral, E.C.S., et al. (1997) or Canada by Michel, J., et al. (1995), where concentrations often range from 5–10 Bq/kg. In Ghana, Adu et al. (2020) reported relatively low Th-232 levels, around 0.4 Bq/kg, in their study of water sources. However, another study conducted by Akaho, E.H.K., et al. (2008), titled *"Evaluation of natural radioactivity in soil and water in the Ahafo gold mining area"* (Journal of Environmental Radioactivity, 99(10), 1460-1464), found increased thorium concentrations in water samples near mining sites, with Th-230 levels as high as 15 Bq/kg, closer to the upper range seen in table 4.6.

This variability across different regions of Ghana reflects the influence of local geology on thorium concentrations, where mining activities and uranium deposits contribute to naturally elevated levels.

Table 4.7:Results for Activity concentration of ^{210}PO in the water samples

SAMPLE ID	Po-210 (Bq/kg)	Po-209 Tracer (%)
CSW 18	< MDA	12.8±1.2
CSW 5	0.49±0.025	26.1±2.1
CSW 24	0.91±0.045	39.1±3.2

CSW8	4.88±0.244	63.1±4.0
CSW 26	1.53±0.077	54.6±3.4
SSW 2	65.5±3.277	7±1.3
SSW8	< MDA	11.4±0.8
CSW 10	< MDA	0.3±0
CSW 32	1.56±0.078	17.6±1.3
CSW 3	31.7±1.589	0.1±0
CSW 9	0.18±0.009	7.6±1.3
SSW 1	26.3±1.315	0.3±0
CSW 12	49.3±2.466	21.7±1.5
CSW 29	18.9±0.949	29.8±2.0
SSW 4	36.5±1.826	38.5±2.5
CSW28	36.9±1.849	31.1±2.0
MIN	< 0.01	0.1
MAX	65.5	63.1
RANGE	< 0.01 – 65.5	0.1-63.1
AVERAGE	21.1 ±1.06 Bq/kg	22.6±1.7 Bq/kg

MDA = 0.01

Po-210 concentrations in table 4.7, water samples range significantly from < 0.01 to 65.5 Bq/kg, with an average of 21.1 ± 1.06 Bq/kg. This wide range is consistent with results from Addo et al. (2012), who observed similar variations, particularly noting higher Po-

210 values in areas with significant geological influences from phosphate and uranium-rich soils. The higher end of the Po-210 concentration spectrum in this dataset (65.5 Bq/kg for sample SSW 2) is greater than values observed in studies conducted in the United States by (Porcelli, D., & Swarzenski, (2003) and Finland by (Aro, L., & Paatero, J. (2005)), where Po-210 averages between 1 and 20 Bq/kg. However, the local geology in parts of Ghana, rich in heavy mineral sands, may contribute to elevated Po-210 concentrations in some water sources.

In the Determination of the MDA, The Activity concentrations below the Minimum Detectable Activity (MDA) were replaced with their respective MDA values. These values represent the lowest detectable activity under the specific conditions of the alpha spectrometry analysis. All results reported as '< MDA' indicate that the radionuclide activity is indistinguishable from background levels.

In Summary, the alpha spectrometry results from table 4.5,6 and 7dataset, compared with both local and international studies, emphasize how environmental and geological factors uniquely shape radionuclide concentrations in Ghana. The values in this study appear elevated relative to background levels observed in other countries, such as Norway, Spain, and Finland, particularly for uranium and polonium isotopes. However, they align well with Ghanaian studies by Addo et al. (2012), Adu et al. (2020), and Akaho et al. (2008),

which found similar radionuclide concentrations influenced by local geological formations, mining activities, and naturally occurring uranium and thorium deposits.

This comparative analysis highlights the need for continuous monitoring and further research on radionuclide sources in Ghana to understand the environmental and health implications. Each study contributes to a more nuanced understanding of radionuclide distribution in Ghanaian waters, demonstrating a range that reflects both natural geological variation and anthropogenic factors.

Table 4.8: Comparison of Alpha Spectrometry Results from this work with other Studies

Country /Study	Isotope	Range (Bq/kg)	Reference
Ghana	U-238	5.24 ± 0.26	Present study
	Th-230	2.02 ± 0.10	Present study
	Po-210	17.5 ± 0.8	Present study
Ghana (Other Study)	U-238	1 – 15	Addo et al. (2012)
		2.5	Adu et al. (2020)
		Up to 15 near mines	Akaho et al. (2008)

	Th-230	-18.6 – 30.9	Akaho et al. (2008)
	Th-232	~0.4	Adu et al. (2020)
	Po-210	-10.4 – 65.5	Addo et al. (2012)
Nigeria	U-238	2-5	Jibiri & Agomuo (2007)
	Th-232	0.3 – 2.5	Jibiri & Agomuo (2007)
	Po-210	~12	Ademola et al. (2008)
	U-238	1-12	Jibiri, N.N., et al. (2009)
	Th-232	0.3-8	Jibiri, N.N., et al. (2009)
	Po-210	0.5-15	Ademola, J.A., et al. (2014).
Spain	U-238	0.5-10	Pérez-López et al. (2010)
Norway	U-238	1-8	Salbu et al. (2004)

Brazil	U-238	5 – 10 near mining sites	Amaral et al. (1997)
United States	Po-210	< 20	Porcelli & Swarzenski (2003)

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusion

In conclusion, this study has established a foundational understanding of natural radioactivity in surface waters near a proposed mining site in Ahafo North, Ghana. The findings provide vital insights into the existing radiological landscape of this area and emphasize the need for vigilant monitoring and protection measures as mining activities begin.

1. **Determining Activity Concentrations of Key Radionuclides**

   This research successfully measured the levels of potassium-40, uranium, and thorium in the water samples collected. Some samples displayed elevated

concentrations of uranium and thorium, which, in part, can be attributed to the region's unique geology and possibly local industrial practices. These baseline measurements serve as essential references, enabling future comparisons and early detection of any changes that could arise as mining operations commence.

2. **Assessing Gross Alpha and Beta Activity**

   The study revealed that gross alpha and beta activity in the samples largely fell within WHO's safety guidelines, although approximately 23% of the samples surpassed the recommended threshold for thorium. This is significant, as it indicates potential radiological risks to communities that rely on these water sources. These results underscore the importance of consistent monitoring and proactive risk management to ensure the health and safety of local residents.

3. **Analysing Specific Radionuclides Using Alpha Spectrometry**

   Through precise alpha spectrometry techniques, this study was able to accurately identify and measure the presence of uranium, thorium, and polonium in the water. These findings align with studies conducted in similar mining regions, lending credibility to our methodology and providing a detailed profile of the radionuclides present. Understanding these specific radionuclide levels is crucial, as they could potentially enter the food chain, impacting both the environment and human health over time.

4. **Estimating the Committed Effective Dose from Radionuclides**

When estimating the committed effective dose due to these radionuclides, we found that, while most samples posed minimal immediate risk, certain water sources did exceed WHO's annual dose recommendations. This highlights a potential health concern if mining intensifies in the future. The data suggests that it would be prudent to enforce strict regulatory oversight and build community awareness about water safety to mitigate health impacts.

This study was guided by four main objectives aimed at evaluating natural radioactivity in surface waters near the proposed Ahafo North mine site. In addressing the first objective, the physicochemical parameters of the water samples were analysed and found to be largely within WHO and GSA standards, with minor deviations in turbidity and alkalinity at select sites. The second objective involved quantifying naturally occurring radionuclides, and the results showed that while ^{40}K and ^{226}Ra remained within safe limits, some concentrations of ^{238}U and ^{232}Th exceeded WHO guideline values, pointing to a possible influence of the region's underlying geology. To meet the third objective, the annual committed effective dose to adults was estimated. Although most values were below the WHO safety threshold of 0.1 mSv/year, a few samples recorded doses above this limit, indicating potential health concerns from prolonged water consumption. Finally, the fourth objective was achieved by comparing the results

with national and international standards, which confirmed that while most locations pose no significant risk, a few require monitoring and intervention. In sum, the study highlights the need for sustained radiological monitoring, especially in areas where elevated radionuclide concentrations were observed. The findings provide useful baseline data for regulatory bodies and suggest that mining-related activities should be accompanied by environmental safeguards to protect public health.

This study assessed the radiological risk associated with natural radioactivity in surface water sources located in communities near the proposed Ahafo North mine site. The findings revealed that the activity concentrations of the key radionuclides—potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th)—varied across sampling locations, with some exceeding WHO guideline values, suggesting potential geogenic influence on water quality.

In relation to the second objective, gross alpha and beta activities were determined for each water sample. While most values were within acceptable limits, a few exceeded recommended thresholds, indicating possible risks from long-term exposure. Detailed alpha spectrometric analysis further revealed the presence and quantification of ^{234}U, ^{238}U, ^{230}Th, ^{232}Th, and ^{210}Po in the samples. These nuclides were successfully isolated and measured, providing insights into the isotopic composition of the water and potential radiotoxicity from ingestion.

The study also estimated the committed effective dose (CED) resulting from ingestion of radionuclide-contaminated water. The results showed that while most values were below the WHO safety limit of 0.1 mSv/year, some sites exceeded this threshold, indicating a potential health concern for individuals who may rely on these sources for daily consumption.

Overall, the results provide a critical radiological baseline for environmental monitoring and policy development. The findings highlight the need for regular water quality assessments in the region and for appropriate stakeholder intervention to ensure public health protection.

Overall, this study emphasizes the necessity of establishing and maintaining rigorous monitoring programs for surface water quality in areas surrounding mining sites. By prioritizing these protections, we can help safeguard public health and ensure sustainable development practices that respect both the environment and the needs of the community.

5.2 Recommendation

Based on the findings of this study, particularly the elevated levels of certain naturally occurring radionuclides in surface waters near the proposed Ahafo North mine site, the

following specific recommendations are proposed to safeguard public health and guide environmental management in the area:

1. Targeted Monitoring of Thorium in Surface Water Sources: Approximately 23% of the samples exceeded the WHO guideline value of 1.0 Bq/L for thorium-232. It is recommended that local authorities implement targeted and routine monitoring of ^{232}Th in surface waters around the Ahafo North concession area particularly at sampling locations CSW-12, CSW-10, and CSW-29 where the concentrations were highest. This will support early identification of health risks and inform control measures before mining operations commence.

2. Restriction on the Use of Surface Water for Drinking in Specific Communities: Despite the presence of boreholes, it was observed that some residents still rely on surface water for domestic use. Given that the annual committed effective dose from ingestion in some areas (e.g., CSW-29 at 0.68 mSv/year) exceeds the WHO limit of 0.1 mSv/year, the use of water from these sources especially CSW-29, CSW-12, and CSW-10 for drinking purposes should be discouraged through community education and signage.

3. Incorporation of Radionuclide Baselines into Environmental Impact Assessments (EIAs): The elevated concentrations of ^{232}Th and the relatively high levels of ^{210}Po observed in the study indicate that baseline radionuclide data should be included as a mandatory component of the Environmental Impact Assessment process for the Ahafo North mining project. This will ensure that changes in environmental radioactivity attributable to mining are traceable and mitigated.

4. Water Treatment Interventions for High-Turbidity Sites: Sites such as CSW-29 recorded extremely high turbidity levels (>3000 NTU) and total suspended solids (>1000 mg/L), which may exacerbate radionuclide mobility and ingestion risks. It is recommended that point-of-use water treatment technologies such as sedimentation and activated carbon filtration be provided to these communities to improve water quality and reduce radionuclide bioavailability.

5. Deployment of Community-Level Radiological Awareness Programs: Given the observed reliance on untreated surface water and the lack of awareness about radiological risks, community-based training should be developed to educate residents especially in high-risk areas on the health effects of long-term exposure to radionuclides and safe water handling practices.

6. These stakeholder-specific recommendations are intended to support regulatory compliance, environmental protection, and public health as the Ahafo North mining project progresses. Based on the findings of this study, it is recommended that Newmont Ghana Gold Limited establish a pre-operational radiological monitoring framework, implement engineering controls to prevent NORM leaching, and provide treated borehole water to nearby communities. The Nuclear Regulatory Authority should strengthen NORM-related regulations, enforce baseline radiological assessments for mining projects, and develop a national database for long-term water quality monitoring. The scientific community is encouraged to conduct longitudinal studies especially on polonium-210 refine local dose models, and promote data transparency to aid collaboration and future research.

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