UNIVERSITY OF EDUCATION, WINNEBA

ASSESSING GROUNDWATER QUALITY IN SELECTED MINING COMMUNITIES IN THE CENTRAL AND WESTERN REGIONS OF GHANA

EMMANUEL AMUAH

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EMMANUEL AMUAH
(200024079)

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DECLARATION

STUDENT'S DECLARATION

I, EMMANUEL AMUAH hereby declare that with the exception of quotations and references to other researched work which have been duly acknowledged, this thesis is the result of my own original work and it has neither in whole or partially been documented elsewhere.

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EMMANUEL AMUAH   **DATE**

(CANDIDATE)

SUPERVISORS' DECLARATION

I, hereby declare that the preparation of this research work was supervised in accordance with guidelines and supervision of thesis outlined by the University of Education, Winneba.

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PROF. EMMANUEL DARTEY   **DATE**

(MAIN SUPERVISOR)

…………………………....   ……………………

PROF. BISMARK DWUMFOUR-ASARE   **DATE**

(CO-SUPERVISOR)

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DEDICATION

I dedicate this thesis to my beloved Mother (Hanna Cudjoe), who has been my inspiration throughout my studies. She has been very supportive, emotionally and financially to the success of my M.Phil.

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LIST OF ABBRAVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
ASGM	artisanal small-scale gold mining
Ci	Concentration
EPA	Environmental Protection Agency
GIS	Geographic Information System
GSS	Ghana Statistical Service
NGO	Non-Governmental Organization
PMGL	Perseus Mining Ghana Limited
Qi	Quality Rating
SIi	Sub- Index
SPSS	Statistical Package for Social Scientists
SRDD	Scottish Research Development Department
WAWQI	Weighted Arithmetic Water Quality Index
Wi	Relative Weight
WHO	World Health Organization
WQI	Water Quality Index
WRC	Water Research Commission
MCDM	Multi-Criteria Decision-making

ABSTRACT

The pollution of groundwater sources is a major issue globally, and particularly for developing countries where the uncontrolled exploitation of natural mineral resources and human activities could lead to the pollution of water resources. The objective of this study was to examine the quality of groundwater in selected mining communities in the Central and Western regions of Ghana. A survey was conducted among the community residents to examine their perceptions of groundwater quality in the study area. A total of fifty (50) water samples collected from boreholes and wells in five mining communities; Ayanfuri, Abenabena, Nkonya, Forbinso, and Gyamang were analyzed for trace metals and physicochemical properties. The Water Quality Index (WQI) method was used to classify the various samples. Respondents expressed concerns of smell and salty taste in groundwater. There was also high arsenic (1.028 mg/l and 1.048 mg/L), iron (0.303 mg/L and 0.304 mg/l) and cadmium (0.189 mg/l and 0.191 mg/l) pollution in the study area which requires urgent attention due to the potential adverse human health effects associated with exposure to high levels of these trace metals. The study revealed high turbidity in some groundwater samples in the study area making them unhealthy for domestic use. In the WQI classification all the groundwater samples apart from Nkonya (Nk-w1, Nk-w2 and Nk-site w) which were considered poor water all were classified as good water. There is the need to control the levels of arsenic, iron, cadmium, and turbidity levels in groundwater in the study area, particularly in Nkonya. Community residents should be educated on the effects of groundwater pollution.

CHAPTER ONE

1.0 INTRODUCTION

1.0 Background to the Study

Mining, is the processes of extracting naturally existing minerals from the earth is considered the second oldest and essential industry in the world after agriculture (Amponsah-Tawiah, 2011). The mining of gold alone has for decades provided employment for most indigenous people and several countries with enormous economic development (Chuhan-Pole *et al.,* 2015). Hirwa *et al.* (2019) identified five stages of mining as the prospecting, exploration, development, exploitation, and reclamation. The African Union in 2009 reported that Africa has the most reserves of gold, platinum, diamonds, manganese, vanadium, and chromite in the world (Duncan, 2020). However, Africa does not enjoy the full benefits of this richness in mineral resources since it is heavily burdened by the environmental effects of mining (Saleem *et al.,* 2008). Many African nations that are blessed with mineral resources are still grappling with the several environmental challenges associated with increasing mining activities such as wastewater discharge, large amounts of mining waste, and dissipative losses among others (Duncan, 2020).

Gold mining has now become unpopular in Ghana because of the levels of pollution associated with it (Rajaee *et al.*, 2015). Afum & Owusu (2016) also reported that there is growing public concern about the condition of fresh waters in Ghana due to the rapid growing nature of the small-scale mining industry. Several researchers have linked the pollution of some surface and groundwater bodies in Ghana to gold mining activities (Bempah *et al.,*2016; Cobbina *et al.,* 2015; Duncan, 2020; Mensah *et al.,* 2015). Poor water quality has been linked to public health concerns, mainly through the transmission of water-borne diseases (Wu *et al.,* 2017). To reduce water related diseases and to improve health in Ghana, a number of boreholes and wells have been built in several rural communities and mining affected areas by the private sector, NGO's and the Ghanaian government. However, the monitoring of water quality is generally ceased once a water source has been improved (Rossiter *et al.*,2010). Even though almost three-fourth of the earth is made of water, only a small proportion of it is actually safe for drinking purposes (Alshikh, 2011). Water is an essential resource for all forms of life and access to a reliable source of drinking water is now recognized by the United Nations as a human right (Cobbina *et al.,* 2015). However, in rural communities and particularly in places where access to clean water is limited, people mostly use untreated water for domestic purposes, including drinking (Macdonald *et al.*, 2015; Cobbina *et al.*,2013). The WHO/UNICEF (2010) reported that almost all of the about 884 million people who do not have access to safe drinking water sources are from developing countries.

Water that is used for drinking purposes must have some level of quality and there are key physical, biological and chemical parameters that determine this quality. The biological parameters include such things as microbial populations; the chemical parameters include cations and anions; and the physical parameters include such characteristics as taste, smell, colour, pH, turbidity, temperature, total dissolved solids, electrical conductivity, total suspended solids and total alkalinity (Asamoah & Amorin, 2011). The protection and management of water quality plays a vital role in agriculture production, environmental sustenance poverty reduction, and sustainable economic development (Singh & Hussian, 2016). It is possible to have seasonal variations in the quality of water but the importance of safe and reliable sources of water cannot be over emphasized. It is therefore important that water is readily available when needed, not just in the right quantity, but also in the right quality devoid of pollutants to meet the various needs for which it is naturally or artificially applied (Akankali *et al.,* 2017). The store house of freshwater and the most commonly used renewable source of water is groundwater (Krishan *et al.,* 2016). Groundwater is an important source of water supply throughout the world. Groundwater occurs almost everywhere beneath the earth surface not in a single widespread aquifer but in thousands of local aquifer systems and compartments that have similar characters (Singh & Hussian, 2016). Groundwater consists of over 90% of the fresh water resources on earth and it is an essential storage of good quality water (Alshikh, 2011). The natural filtration through soil and sediments makes the groundwater free from organic impurities (Saleem *et al.,* 2016).

According to Gao *et al.* (2020), access to clean and safe groundwater a fundamental requirement for a sustainable human and social development. There is an ever increasing need for an enhanced management of surface and groundwater because they are the most readily available source of water for human use, yet the most polluted as a result of anthropogenic activities (Ojekunle & Lateef, 2017). Anthropogenic activities that also pollute water bodies include excessive use of fertilizers and pesticides in agricultural areas (Singh & Hussian, 2016)**.** Unsafe groundwater adversely affects the economy and hinders improvement in the living conditions of rural people (Batabyal & Chakraborty, 2015). Yet groundwater quality and quantity is worsening at a very fast rate due to human activities like mining (Saleem *et al.,* 2016). Water contamination from mining activities results from the discharge of effluents, which contain toxic chemicals such as cyanide and other organic chemicals used in the processing of mineral ores. These chemicals together may result in effluent with high acid levels which can either seep into underground water or flow into surface water bodies, posing a threat to the nearby communities particularly those which depend on such water bodies for drinking and other domestic purposes (Duncan, 2020). Trace metal is any metallic element that has a relatively low density and is not toxic or poisonous at low concentrations. However, excessive concentrations of these trace metals can become detrimental to organisms with unusual high concentrations becoming toxic to aquatic organisms. Trace metals are characterized by concentrations lower than 1mg in natural waters which are obligatory by man in amounts ranging from 50 micrograms to 18 milligrams per day. Acting as catalytic or structural components of larger molecules, they have specific functions are requisite for life (Kulaksız & Bau, 2011). Heavy metals exist as natural constituents of the earth’s crust and are persistent environmental contaminants, because they cannot be degraded or destroyed (Lenntech, 2004).

Some metals are essential to sustain life-calcium, magnesium, potassium and sodium must be present for normal body functions. Also, cobalt, copper, iron, manganese, molybdenum and zinc are required at low levels as catalyst for enzyme activities (Alshikh, 2011). Many of these compounds exist naturally, but their concentration has increased as a result of anthropogenic activities (Huang *et al.*, 2014). Health risks of trace metals include reduced growth and development, cancer, organ damage, nervous system damage, and in extreme cases, death. Exposure to some metals, such as mercury and lead, may also cause development of autoimmunity, in which a person’s immune system attacks its own cells. Heavy metals become toxic when they are not metabolized by the body and accumulate in the soft tissues (Malassa *et al.*, 2013). The leaching of heavy metal oxides into groundwater bodies also poses a threat to communities which depend on such groundwater sources (Huang *et al.*, 2014).

1.2 Problem Statement

There are two major mining activities practiced in the Upper Denkyira West and Wassa Amenfi East communities in the Western and Central region of Ghana; the large-scale mining that uses sophisticated machines and methods in mining and the small-scale mining makes use of simple tools to extract gold from the land. These mining activities have the potential to cause heavy metal pollution of both surface and ground water resources in these communities (Attiogbe & Nkansah, 2017; Bempah *et al.*, 2016; Duncan, 2020). Bempah *et al.* (2016) examined heavy metal concentrations in groundwater in communities in the south-western parts of the Ashanti Region. They found that the levels of As and Fe were higher than the WHO permissible limits.

The results of another study indicated that groundwater is potable but unsuitable for drinking in isolated locations due to high levels of As and Zn (Gyamfi *et al.*, 2019). Also, Macdonald *et al.* (2015) found that sites with associated artisanal small-scale gold mining (ASGM) activities had water qualities that did not meet Ghana national standards for drinking water, with manganese at particularly high concentrations. The results of the above studies showed major variability in the concentrations of various trace metals in groundwater at various geographical locations. The variability in trace metals and physicochemical properties of groundwater in various parts of the country emphasize the need for regular monitoring of all groundwater sources, especially in mining communities (Gyamfi *et al.*, 2019; Kulinkina *et al.*, 2017).

Meanwhile, the selected mining communities have bitterly complained about the poor quality of their water source such as the oil sheeny, smell/odour, taste, salty, and color in the water (Asamoah *et al.*, 2011) the five study area communities largely depend on wells and boreholes sources for drinking purposes. In a news article published by Graphic Online on October-03-2015, residents of the Ayanfuri communities protested bitterly against the unfair treatment of their water bodies which influences the water quality by Perseus mining Ghana limited (Aziz, 2015). Also, in another news article published by Modern Ghana in its special report on May-26-2020, the people of Ayanfuri blamed the operations of Perseus mining Ghana limited for the acute water shortage and ground water pollution in surrounded communities, which affected the economic activities of the inhabitants (Aubyn, 2020).

However, studies on trace metal concentrations and the physicochemical properties of groundwater in Ayanfuri and its environs is scantily documented. Also, despite the worldwide adoption of WQI as an effective way of making conclusions about the quality of drinking water has not been sufficiently utilized in Ghana to assess groundwater quality. Finally, there is a paucity of literature on the perceptions of community residents about groundwater quality in Ghana, even though such perceptions have been found to be a reflection of problems associated with groundwater (Kulinkina *et al.*, 2017).

1.3 Research Questions

1. What are the perceptions of residents of the study area on the quality of groundwater?
2. What are the levels of trace metals and physicochemical parameters in groundwater (boreholes and wells) which affect the quality of groundwater in the study area?
3. What are the types of groundwater samples in the study area based on the water quality index (WQI) method for assessing the quality of drinking water?

1.4 Significance of the Study

Water related diseases can often be attributed to exposure to elevated trace metal concentrations of both organic and inorganic contaminants (Huang *et al.,* 2014). Health risks of trace metals include reduced growth and development, cancer, organ damage, nervous system damage, and in extreme cases, death, Exposure to some metals, such as mercury and lead, may also cause development of autoimmunity, in which a person's immune system attacks its own cells (Malassa *et al.*, 2013; Dupher, 2001). This research studies assessed the levels of trace metals in groundwater to determine whether they are safe for drinking purposes. This will help create the necessary urgency for the protection of the health of these communities and contribute to socioeconomic development. The study also classified the water types in the study area using WQI method for better water quality analysis. This classification will therefore create awareness among the community members about the suitability of ground water in the area for domestic purposes. Moreover, consumer perceptions could be an important symptom of physical, chemical and biological problems associated with drinking water quality (Kulinkina *et al.,* 2017). Therefore, the perceptions of people in the study area will be an essential means of further understanding the issues of water quality in the area. This could also be a means of learning about previous water quality problems since there is the likelihood for seasonal variations in water quality. Finally, the result of the reviewed literature studied, contributes to the body of knowledge about the impact of mining on water quality.

1.3.1 Research Objectives

The main objective of the study was to examine the quality of groundwater in Ayanfuri and surrounding mining communities. The specific objectives of the study were:

1. To assess the perceptions of residents of the study area on the quality of groundwater.
2. To determine the levels of trace metals and the physicochemical parameters in groundwater which affect the quality of groundwater in the study area.
3. To classify the quality of groundwater sources in the study area using the WQI method for assessing drinking water quality.

1.5 Scope and limitations of the Study

The scope of the study is defined by the study area, study period, and the physicochemical parameters of importance to the study. In terms of the study area, five communities which are Ayanfuri (located 1.0 km away from mine site), Abenabena (located 1.0km from the mine site), Nkonya (located 0.05 – 0.07 km away from mine site), Forbinso (located 0.5-0.6 km away from the mine site), and Gyamang (located 0.6-1.0km from the mine site). Also, in terms of the study period, the researcher only took samples in August and September 2021. On the trace metals parameters of interest, the researcher only considered cadmium (Cd), iron (Fe), lead (Pb), manganese (Mn), copper (Cu), arsenic (As), and zinc (Zn) as the trace metals of interest. These metals were considered because several studies in Ghana have shown that they are the most occurring metals in water bodies (Bempah *et al.*, 2016; Cobbina *et al.*, 2015; Duncan, 2020; Gyamfi *et al.*, 2019; Hadzi *et al.*, 2018).

Also, to estimate the WQI, pH, electrical conductivity, total dissolved solid, temperature, dissolved oxygen, total suspended solid and turbidity were the parameters used. The study was not without limitations. The main limitation of this study was the inability of the researcher to collect seasonal data to assess the trends in water quality in the study area. Also, the study did not look at microbial quality of groundwater in the study area. Notwithstanding these limitations, this study provides a useful understanding of the quality of groundwater in the study area.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Physicochemical Parameters of Water Quality

2.1.1 Trace Metals

Trace metals are characterized by concentrations lower than 1mg in natural waters which are obligatory in an amount ranging from 50 micrograms to 18 milligrams per day, a trace element are micronutrients which we need in minute amounts for the growth and development of our body and has a very low density. Acting as catalytic or structural components of larger molecules, they have a specific functions that are requisite for life (Kulaksız & Bau, 2011). Trace metals include cadmium, mercury, zinc, copper, nickel, chromium, cobalt, iron, manganese and lead, some Organisms require trace amounts of some trace metals, including cobalt, copper, iron, manganese, molybdenum, vanadium, strontium, and zinc. Excessive concentrations of these metals can pose serious health risks to humans (Cobbina *et al.,* 2015) and unusually high concentrations in water can be harmful to aquatic organisms (Jhariya *et al.,* 2016). However, excessive concentrations of these metals can become detrimental to organisms with unusual high concentrations becoming toxic to aquatic organisms (Krishan *et al.,* 2016).

Trace metals are characterized by concentrations lower than 1 mg/L in natural waters (Kulaksız & Bau, 2011). Essential trace elements are required in humans in amounts ranging from 50 micrograms to 18 milligrams per day. Acting as catalytic or structural components of larger molecules, they have specific functions are requisite for life. Research during the past decades has identified as essential six trace elements whose functions were previously unknown. In addition to the long-known deficiencies of iron, signs of deficiency for chromium, copper, zinc, and selenium have been identified in free-living populations. Few trace elements were proved to be essential for two or more animal species during the past decade alone. High trace metal concentrations can be considered risk factors for several diseases of public health concern (Alloway, 2012). Trace element studies are of wide application in varied branches of scientific discipline. Concentration of trace elements in water helps in the circulation and distribution of minerals in rock and waters. It has some relationship between water composition and public health, which may be either related to groundwater pollution or to natural condition (Mondal *et al.,* 2010).

Trace elements contribute to groundwater pollution from a variety of natural and anthropogenic sources (Ramessur 2000; Newcomba *et al.,* 2002; Abollino *et al.,* 2004; Leung and Jiao 2006, Mondal *et al.,* 2010). Some of the trace elements like Fe, Mn, Ni, Cu, Zn, and As are needed by the human body to activate vital functions and biological processes. Iron deficiency leads to anemia and iodine deficiency causes goiter, But it is well established that an accrue in trace element beyond the permissible limit can cause several health hazards (WHO 2012). Toxic element especially As, Se and other trace elements in groundwater of Madras city are due to anthropogenic activities such as mining and saltwater intrusion (Selvam *et al.,* 2017).

2.1.2 pH

pH is the negative logarithm of the concentration of hydrogen ion in a solution. It expresses the intensity of the acid or alkaline condition of a solution. The nominal pH value has a scale of 0-14. A solution is neutral if its pH value is 7, acidic if its pH value is less than 7 and basic if its pH value is greater than 7. The pH is an important variable in water quality assessment because it alone affects many biochemical processes within a water body and all processes which affect the supply and treatment of water (Singh *et al.*, 2014). In water pollution studies, the pH plays an important role in helping to determine the extent of an effluent or plume in a water body (Harmon *et al.*, 2018). It also affects the solubility and toxicity of most metals present in the water source (Alloway, 2012). Extreme pH values may also have pronounced effects on the taste of the water; Low pH will give the water source a sour taste, while high pH may result in soapy taste. Directly, very low or high pH values can cause irritation or burning of the mucous membranes of the intestinal mucosa (Mhlongo *et al.*, 2018). The combination of CO_2 with water forms carbonic acid, which affects the pH of the water. The permissible limit of pH is 6.5–8.5. The pH in the groundwater is varied from 6.0 to 8.2.

This may be attributed to the anthropogenic activities like tailings disposal, using sophisticated machines for prospecting, exploration, development, exploitation, and reclamation (Alloway, 2012). Mining operations and acid drainage can also affect pH in groundwater (Jhariya and Chourasia, 2010). Acidic water migrates into groundwater and eventually change it pH level to lose its acidity and able to dissolve heavy metals present in rock and contaminate groundwater quality (Hudson, 2012). Lower values in pH are indicative of high acidity in groundwater, which can be caused by the deposition of acid through mining activities. A high organic content will tend to decrease the pH because of the carbonate chemistry. As microorganisms break down organic material, the by product will be CO_2 that will dissolve and equilibrate with the water forming carbonic acid (H_2CO_3) (Howladar *et al.*, 2017). Other organic acids such as humic and fluvic acids can also result from organic decomposition (Alshikh, 2011).

2.1.3 Temperature

Temperature is a physical quantity that expresses hot and cold. It is the manifestation of thermal energy, present in all matter, which is the source of the occurrence of heat, a flow of energy, when a body is in contact with another that is colder or hotter (Jakeman *et al.,* 2006). Temperature is measured with a thermometer. Temperature is not the equivalent of the energy of a thermodynamic system; e.g., a burning match is at a much higher temperature than an iceberg, but the total heat energy contained in an iceberg is much greater than the energy contained in a match. Temperature, similar to pressure or density, is called an intensive property-one that is independent of the quantity of matter being considered-as distinguished from extensive properties, such as mass or volume (Sargaonkar & Deshpande, 2003).

Three temperature scales are in general use today. The Fahrenheit (°F) temperature scale is used in the United States and a few other English-speaking countries. The Celsius (°C) temperature scale is standard in virtually all countries that have adopted the metric system of measurement, and it is widely used in the sciences. The Kelvin (K) scale, an absolute temperature scale (obtained by shifting the Celsius scale by −273.15° so that absolute zero coincides with 0 K), is recognized as the international standard for scientific temperature measurement (Reza *et al.,* 2009). Temperature changes could trigger changes in physical, chemical, and microbial processes in the subsurface environment, resulting in groundwater quality changes. (Hähnlein *et al.*, 2013, Bonte *et al.*, 2011. Banks, 2008). Temperature is also important because of its influence on water chemistry. The rate of chemical reaction generally increases at higher temperatures. Water , particularly groundwater due to mining activities, with higher temperatures can dissolves more minerals from the surrounding rocks and therefore can have a higher electrical conductivity (Water Science School, 2018).

2.1.4 Turbidity

Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates (Wang *et al.,* 2017). The more total suspended solids in the water, the murkier it seems and the higher the turbidity. Turbidity is considered as a good measure of the quality of water. Turbidity affects the growth rate of algae (micro-aquatic plants) and other aquatic plants in streams and lakes because increased turbidity causes a decrease in the amount of light for photosynthesis (Dogaru *et al.,* 2009). Turbidity can also increase water temperature because suspended particles absorb more heat. Is the measure of relative clarity of a liquid (Kuma *et al.,* 2015). It is an optical characteristic of water and is a measurement of the amount of light that is scattered by material in the water when a light is shined through the water sample (Jhariya *et al.,* 2016).

The higher the intensity of scattered light, the higher the turbidity. Turbidity results from the scattering of light in water by organic and inorganic particles; however, high turbidities usually are caused by suspended inorganic particles, particularly sediment. According to the World Health Organization, water for human consumption should have turbidity levels below 1 NTU, though for some regions, up to 5 NTU is allowed if it can be proven to be disinfected (W.H.O, 2017). Groundwater above 5 NTU turbidity level present significant health implications for the health of people who use them for domestic activities and it is not safe for consumption (W.H.O, 2017).

2.1.5 Conductivity

Conductivity is a measure of the ability of water to pass an electrical current (Nishtha, 2012). Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge) (Wang *et al.,* 2017). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity (Rakotondrabe *et al.,* 2017). For this reason, conductivity is reported as conductivity at 25 degrees Celsius (25 ^{o}C). The reason that the conductivity of water is important is because it can tell you how much dissolved substances, chemicals, and minerals are present in the water. Higher amounts of these impurities will lead to a higher conductivity. The value of EC is between 580 and 7,250 μS/cm. EC measures the ability of a material to conduct an electric current such that the higher EC indicates enrichment of salts in the groundwater (Alloway, 2012).

2.1.6 Total Dissolved Solids

A total dissolved solid (TDS) is a measure of the combined total of organic and inorganic substances contained in a liquid. This includes anything present in water other than the pure H20 molecules. These solids are primarily minerals, salts and organic matter that can be a general indicator of water quality. Interestingly, early epidemiologic studies suggested that “moderately high” TDS concentrations (“high” in this context being less than 1,000 mg/L) protected people against cancer and heart disease (Mukherjee, Zimmerman, & Harris, 2011). The occurrence of high TDS is due to the influence of anthropogenic sources, such as ore extraction, mining of gold and other human activities.

According to WHO specification TDS up to 500 mg/l is the highest desirable and up to 1,500 mg/l is maximum permissible. Degree of groundwater quality can be classified as fresh, if the TDS is less than 1,000 mg/l. The TDS in water comprise inorganic salts and small amounts of organic matter. The principal ions contributing to TDS are carbonate, bicarbonate, chloride, sulphate, nitrates, sodium, potassium, calcium, and magnesium (Wu *et al.,* 2017). Total dissolved solids influence other qualities of underground drinking water, such as taste, hardness, corrosion properties and tendency to incrustation (Singh *et al.*, 2014).

2.1.7 Total Suspended Solids

Total suspended solids (TSS) are particles that are larger than 2 microns found in the water columns. These solids include anything drifting or floating in the water, from sediment, silt, and sand to plankton and algae 1. Organic particles from decomposing materials can also contribute to the TSS concentration (Mazhar & Ahmad, 2020). Total dissolved solids are a measure of the dissolved combined content of all inorganic and organic substances present in a liquid in molecular, ionized, or micro-granular suspended form. TDS concentrations are often reported in parts per million. Water TDS concentrations can be determined using a digital meter (Singh *et al.,* 2014).

2.1.8 Dissolved Oxygen

Dissolved oxygen (DO) is a measure of how much oxygen is dissolved in the water - the amount of oxygen available to living aquatic organisms. The amount of dissolved oxygen in a stream or lake can tell us a lot about its water quality.

A high dissolved oxygen (DO) level in a ground water source due to mining activities is good because it makes underground drinking water taste better (Mazhar & Ahmad, 2020). However, high DO levels speed up corrosion in water storage containers and pipes, a dissolved oxygen meter was used to determine the level (Saleem *et al.,* 2016). For this reason, it is essential to use water with the least possible amount of dissolved oxygen.

2.2 Heavy Metals Pollution of Groundwater

Heavy metal is any metallic element that has a relatively high density and is toxic or poisonous even at low concentrations. However, excessive Concentrations of these metals can become detrimental to organisms with unusual high concentrations becoming toxic to aquatic organisms. Heavy metals are a group of metals and metalloids which has an atomic density greater than 4g/cm^3 or 5 times or more great than water. The toxicity of heavy metals is a problem of increasing significance for ecological, nutritional, and environmental reasons Hannatu *et al.* (2014). Several studies on water quality have focused on the pollution of groundwater sources by heavy metals. Singh *et al.* (2014) assessed the impact of pH dependence leaching features of some heavy metals on the quality of ground water at a coal mining site in India. The results of the study showed that Cadmium (Cd), Copper (Cu), Iron (Fe), and Chromium (Cr) levels in groundwater were above the accepted levels for drinking water quality. Reza *et al.* (2009) assessed the quality of drinking water by examining heavy metals levels in groundwater in Orissa, India using the Atomic Absorption Spectrophotometer. They collected groundwater samples from 19 sites in both industrial and residential locations and compared heavy metals levels in the water samples with the Indian Standards for drinking water. Copper (Cu), Cadmium (Cd), Lead (Pb), Zinc (Zn), Nickel (Ni), Iron (Fe), Mercury (Hg), Cobalt (Co), Arsenic (As) were found to be below detection levels in most samples (Reza *et al.*, 2009). With the exception of cadmium, the concentration of the metals were found to be with acceptable limits when compared to the Indian standards in a few samples (Reza *et al.,* 2009). The authors found that the levels of cadmium were slightly higher than levels accepted for portable water in India. Hannatu *et al.* (2014) assessed the concentration of seven heavy metals in both surface and groundwater samples in the Abakaliki shale area of Nigeria. They collected water samples from abandoned mine pits and boreholes that supply portable water to residents of the area for the assessment.

The levels of Zn, Pb, Cu, Cd, Ni, Co, were all found to be below the permissible limits by the WHO standards in both surface and groundwater samples (Hannatu *et al.,* 2014). However, As levels were within the range of 0.11-0.139 mg/L for the samples from the mining pits and 0.010-0.492mg/L for the samples from the boreholes. The levels of As in both water types were above the WHO standard of 0.01 mg/L (Hannatu *et al.,* 2014). Also, the results show that the levels of As in the groundwater samples were found to be higher than in surface water (Hannatu *et al.,* 2014). In a study by Ardakani and Razban (2014), groundwater samples were taken from 20 selected wells and the concentrations of heavy metals in the samples were determined by ICP. The researchers used SPSS to do the statistical data analysis and used ArcGIS to generate a spatial distribution map of the metals. The results showed that mean concentrations of As, Zn, Pb and Cu in groundwater samples in the spring were 7.5 ± 1.2, 13.7 ± 2.1, 2.5 ± 0.4 and 9.2 ± 2 ppb, respectively, and mean concentrations of these elements in groundwater samples in the summer were 9 ± 1.2, 7.1 ± 1.9, 2.8 ± 0.65 and 9.3 ± 1.2 ppb, respectively (Ardakani & Razban, 2014). Also, the results of one sample t-test, comparing the mean concentrations of evaluated metals in groundwater samples with WHO and ISIRI showed a significant difference with permissible limit ($P < 0.001$), so that the mean concentration of all metals were lower than the standard limit. The mean concentration of Zn was significantly lower in the summer than in the spring ($P = 0.003$). Ardakani and Razban (2014) concluded that although the current groundwater resources of Qahavand Plain are not exceedingly polluted with heavy metals, long-term and excessive use of agricultural inputs and construction of polluting industries can threaten the groundwater resources of this area, followed by irreversible consequences such as health-related risks for consumers.

Umer *et al.* (2018) assessed the pollution of groundwater by heavy metals and anions in Kwashe industrial Area in Iraq. The researchers collected groundwater samples from 10 artesian wells to assess the impact of industrial effluents and landfill leachate in contaminations of these wells. Umer *et al.* (2018) found out that the sulfate content is under risk limit of WHO (3-150 µg/L) in ground water, but there is evidence that a little contamination plume is created in Girresh 28.63 ± 1.25 mg/L location. The Cl as typically recommended by WHO in ground water is 1-70 mg/L and are low in 5 artesian wells upper industrial area and magnified in the rest of the 5 artesian wells downward industrial area with high levels recorded in Girrash 30.33 ± 1.53 mg/L. WHO standard of NO_3 in ground water is 2-20 mg/L (Umer *et al.*, 2018). The locations Kwashe 3, 4, 5 were better sites of NO_3 in upper industrial area ranging between 5.13 ± 0.15 to 5.50 ± 0.20 and the three wells are safe for drinking. The rest of the four wells Girresh, Marina, Moqeble, and Sarshour located down ward industrial effluents and landfill leachate are significantly affected toward increasing to reach hazardous levels in three location Sarshour 19.70 ± 1.45 mg/L, Marina location 22.67 ± 0.85 mg/L and the center of toxin plume recorded in Girrish of 55.33 ± 0.25 mg/L which is not safe as drinking water for adults according WHO standards (Umer *et al.*, 2018). The typical soil properties like high pH value (7.9), huge amount of active/total $CaCO_3$ (62.62 %) and high clay content (381.68 g/kg), makes the condition optimum for heavy metals precipitation (Umer *et al.,* 2018). Adeyemo *et al.* (2019) assessed the physicochemical parameters, heavy metal concentrations and bacterial constituents of selected wells within Bodija municipal abattoir which serves as the main source of water used for meat processing.

Samples of water from the wells in the abattoir and some wells in the neighborhood were collected and analyzed according to standard laboratory procedures (Adeyemo *et al.,* 2019). The results obtained revealed the order of mean of heavy metal concentration in sampled abattoir wells as Fe (0.67 ± 0.26) > Mn (0.27 ± 0.26) > Pb (0.16 ± 0.08) and the order in sampled residential wells (WR) as Pb (0.64 ± 0.33) > Fe (0.54 ± 0.22) > Cu (0.35 ± 0.021) > Mn (0.20 ± 0.03). Abattoir wells had significantly higher coliform and enterobactericeae counts than the residential wells. Virtually all the figures obtained were considerably higher than the permissible standard for drinking water (Adeyemo *et al.,* 2019). The study also showed that the health status, social and environmental qualities of residents of Bodija abattoir neighborhood will severely be affected. Globally, studies on heavy metal concentrations in groundwater have shown very low to very high concentrations when compared to national and international standards (Umer *et al.,* 2018; Wang *et al.,* 2017). The geographic variations in heavy metal concentrations depict the unique nature those areas in respect of both the natural processes and the prevailing human activities (Yolcubal *et al.,* 2016). This therefore shows the need for research into heavy metal concentrations in the present study area since at the time of this study no work has been published about metal concentrations in the underground drinking water of the communities around Ayanfuri.

2.3 Classification of Water Types Using the Water Quality Index (WQI)

The water quality index (WQI) is considered a mathematical tool that significantly minimizes the complex water quality data sets and provides a single classifying value that describes the water quality status of water bodies or degree of pollution. Furthermore, WQI is a single dimensionless number that describes the overview of the overall water quality status in a simple way by aggregating the measurements of selected parameters such as pH, nitrate, dissolved oxygen (DO), heavy metal (Abbasi & Abbasi, 2012). As early as 1965, this method was introduced through mathematical equations to determine water quality status in the river by Horton (Horton, 1965).

The WQI is determined based on various biological, physical, and chemical parameters that define the various purposes of utilization of water bodies for human consumption, such as recreation, drinking, industries, irrigation, and domestic. After the proposed WQI method by A Horton, the numbers of WQI methods have been developed for various purposes by numerous organizations across the globe, such as the National Sanitation Foundation Water Quality Index (NSFWQI) (Brown *et al.,* 1970), Scottish Research Development Department (SRDDWQI) (SRDDWQI, 1976), River Status Index (RSI) (Liou *et al.,* 2004),Weighted Arithmetic Water Quality Index (WAWQI)(Brown *et al.,* 1970), Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) (CCME, 2001), British Columbia Water Quality Index (BCWQI) (Zandbergen & Hall, 1998), Overall Index of Pollution (OIP) (Sargaonkar & Deshpande, 2003), Oregon Water Quality Index (OWQI) (Cude, 2001), Bhargava Method Water Quality Index (BMWQI) (Bhargave, 1985), Malaysia Water Quality Index (MWQI) (Shuhaimi-Othman *et al.,* 2007), Water Contamination Index (WCI) (Nemerow, 1971), Vaal Water Quality Index (Vaal WQI) (Banda & Kumarasamy, 2020), etc. Moreover, four common steps have been used in the WQI method, including the parameters selection, sub-indices establishment, assigning of weights (equally or unequally), and aggregation of sub-indices to obtain the final index (Abbasi & Abbasi, 2012). Previous studies have shown that most researchers have applied all steps (because they used unequal weights, such as NSFWQI, SRDDWQI, WAWQI, MWQI, etc.). Some of them used three steps (equal weights, such as OIP, WCI, RSI, etc.), but few of them reported that they directly used the formula for water quality assessment (CCMEWQI) (Banda & Kumarasamy, 2020).

Furthermore, the WQI method has been applied for different purposes, but mainly for surface water quality (especially for river water) (Qu *et al.*, 2020), groundwater quality (Jha *et al.,* 2020), and wetland (Fathi *et al.,* 2016) across the world. Moreover, the Environmental Protection Agency (EPA) of the Republic of Serbia also utilizes WQI to inform about the overall status of the river water system (Mladenović-Ranisavljević *et al.*, 2018). In this technique, a large resource of water is easily accessed for water quality assessment because of the consistent scale using the WQI equation. Multiple parameters are used to calculate in a single number and the flexibility of selecting the characteristics of water quality. However, the calculation of WQI is a prolonged process in which numerous national and international standards are taken into consideration, in terms of criteria of water consumption. This makes the process more complicated, despite having simple calculations. Moreover, it is easy to bias the process of selecting parameters and calculating the individual weighting values. Therefore, the covered parameters cannot be definite in number that they would give a simple WQI; it may not be enough to understand, as a whole, the WQI of a large water body because certain parameters can influence the water quality in a wider manner, which can be neglected during the calculation. The literature reviewed indicates that all of the indices have their limitations and strengths; therefore, many organizations and agencies do not consider this methodology for developing a WQI worldwide (Abbasi & Abbasi, 2012; Sarkar & Majumder, 2021). However, it is pertinent to mention that the strengths and weaknesses of the processes in establishing WQI for water quality assessment can be simplified by multi-criteria decision-making (MCDM) approaches to evaluate the parameter's weight separately.

In previous years, analytical techniques have significantly increased to resolve the problems related to water resources, where MCDM procedures are generally regarded as very effective in addressing water management problems (Chung *et al.*, 2017). The effectiveness of such procedures depends on the conceptual framework of assessment processes and on the common language used to identify and address complex water challenges. In previous decades, several authors have applied the MCDM method to various purposes in water resource management, assessment of water quality (Jakeman *et al.*, 2006; Talukder *et al.*, 2017) as well as in other areas, to solve problems surrounding the environment, energy, and sustainability (Soltani *et al.*, 2015), safety and risk management (Oztaysi, 2014), and technology and information management (Ilangkumaran *et al.*, 2014). There are numerous MCDM approaches available for solving problems related to water resources, such as analytical network process (ANP), analytical hierarchical process (AHP), data envelopment analysis (DEA), fuzzy decision-making (FDM), measuring attractiveness by a categorically based evaluation technique (MACBETH), simple additive weighting (SAW), supply chain management (SCM), a technique for order preference by similarity to ideal solution (TOPSIS), compromise programming (CP), etc. (Alamanos *et al.*, 2018; Ceballos *et al.*, 2016; Wang *et al.*, 2017). In general, WQI is the comparison of the amount with an arbitrary or scientific standard or with a pre-specified base. Therefore, the WQI monitored and reported environmental status and trends on standards quantitatively. The WQI method provides effective information on the degree of purity and pollution of water, by avoiding an overwhelming quantity of data to demonstrate water quality (Bharti & Katyal, 2011).

The WQI tool also facilitates a perfect quality monitoring system accessible. Almost every WQI relies on normalization, the data parameter-by-parameter, as per the predicted concentration levels, and the interpretation of “bad” versus “good” levels. After this, index is calculated as a weighted average for all observed values, with weighted parameters according to their perceived significance to overall water quality. The purposes of the WQI method are, particularly, for the evaluation of the overall status of water quality (parameters of physical, biological, and chemical) and the use of water resources for multiple purposes.

Notwithstanding the limitations of WQI, it has been used by various researchers in different parts of the world to analyses water quality data (Mahagamage & Manage, 2014). Using the CCME WQI Gunarathna and Kumari (2016) assessed the water quality of Malwathu Oya cascade-I in tropical Sri Lanka for drinking, fish & aquatic life, irrigation & agriculture and recreational use. The researchers analysed electrical conductivity, dissolved oxygen level, turbidity, pH, nitrate nitrogen, phosphate and sodium in water samples collected from 10 tanks using standard instruments and procedures. Average values of CCME WQI showed that water quality was poor for drinking, fish & aquatic life and irrigation & agriculture while marginal for recreational use (Gunarathna & Kumari, 2016). According to Gunarathna and Kumari (2016), WQI therefore serves as an easy and meaningful way of drawing conclusions about water quality. Saleem *et al.* (2016) analyzed the underground water quality of Greater Noida region, India by water quality index. Nine physico-chemical parameters such as Calcium, Magnesium, Chloride, Sulphate, Total Hardness, Fluoride, Nitrate, Total Dissolved Solids, and Alkalinity were assessed in groundwater samples collected from 10 different locations. The researchers used the three step procedure of estimating WQI (Hameed *et al.*, 2010).

Saleem *et al.* (2016) in their study of ground water quality found that 90 % water samples were of good quality and only 10 % of the water samples fell under poor category. The water quality index ranged from 16.49 to 64.65 (Saleem *et al.*, 2016). In another study, the groundwater quality, seasonal variations and its suitability for drinking, irrigation and industrial usage in the Tefeni plain in Turkey were evaluated (Varol & Davraz, 2015). In this study, 56 water samples were collected from springs, wells, and a lake in dry and wet seasons. $Ca–Mg–HCO_3$, $Mg–Ca–HCO_3$, $Na–CO_3–Cl$, and $Na–HCO_3–Cl$ water types were the dominant water types in the investigation area (Varol & Davraz, 2015). Parameters, which were controlled to chemical variations of groundwater, were analyzed with R-mode factor and correlation analysis. According to R-mode factor analysis, total dissolved solids, Na, Cl, HCO_3, and NH_3 were the most important parameters. In addition, Water Quality Index (WQI) was applied to suitability for drinking purpose and to investigation of groundwater quality. Quality of groundwater was found to be suitable for drinking both in the dry and wet seasons in study area (Varol & Davraz, 2015). Also, Varol and Davraz (2015) concluded that generally groundwater was suitable in the dry season but was not suitable in the wet season for irrigation and industrial usage. Using 24 water samples collected from Anna Nagar, India and analysed for pH, electrical conductivity, total dissolved solids, carbonate, bicarbonate, chloride, sulphate, nitrate, calcium, magnesium, sodium, potassium and total hardness, Kuma *et al.* (2015) reported that WQI results showed that majority of the samples fell under excellent to good category and suitable for drinking water purposes. Assessing similar water quality parameters in a similar study, Taloor *et al.* (2020) reported similar findings. The water quality index (WQI) showed that 45% of samples fall in the excellent category and 50 % of spring samples fall in good categories for drinking purposes (Taloor *et al.,* 2020).

Also, Varol (2020) reported mean WQI values from 87.6 to 95.3, indicating “good” to “excellent” water quality in the Sürgü Stream, located in the Euphrates River basin of Turkey. However, another recent study in China categorized water samples based on WQI values that ranged from 37.6 to 90.0, indicating “bad” to “excellent” water quality in the upper and middle streams of the Luanhe River (Tian *et al.,* 2019). In the Indian city of Raipur, efforts were made to understand the groundwater quality for drinking purpose utilizing Water Quality Index (WQI) and Geographic Information System (GIS) techniques. Khan and Jhariya, (2017) assessed pH, chloride, fluoride, calcium, magnesium, alkalinity, hardness and nitrate levels in thirty-four groundwater samples. The Bureau of Indian Standard (BIS, 2009) was used to assess the suitability of groundwater for drinking purposes and for the calculation of WQI. This study revealed that 76 % of the samples fell under excellent, very good and good category while 24 % of the samples fell under poor, very poor and unfit category as per the WQI classifications (Khan & Jhariya, 2017). The authors concluded that anthropogenic activities were influencing the groundwater quality of the study area. Hosseini-Moghari *et al.* (2015) used fuzzy water quality indexes (FWQIs) which were developed based on the Mamdani fuzzy inference system (FIS) to evaluate to evaluate the water quality of 17 wells in Saveh Plain, Iran. According to the results, some 35 % of wells were of proper drinking water quality, while approximately 30 % and 35 % of them were of unsuitable and very poor drinking water quality respectively (Hosseini-Moghari *et al.*, 2015). In another study, Adimalla *et al.* (2018) undertook a water quality assessment of 105 groundwater samples collected from the rock dominant semi-arid region of central Telangana, India.

They analysed for pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulphate (SO_4^{2-}), nitrate (NO_3^{-}), and fluoride (F^{-}). Results revealed that 51 % and 71 % of groundwater has more than the maximum acceptable limits of fluoride (1.5 mg/L) and nitrate concentrations (45 mg/L), respectively, thus making the groundwater unsuitable for drinking purpose (Adimalla *et al.*, 2018). According to the water quality index (WQI), 60 % and 36 % of groundwater samples fell in excellent and good categories for drinking purpose. Also, 90 % of groundwater in the study region were well suitable for irrigation (Adimalla *et al.*, 2018). Aly *et al.* (2015) evaluated and compared the treated and untreated groundwater quality in Hafar Albatin, Saudi Arabia for drinking purpose using water quality index (WQI). The WQI calculations required several physiochemical water parameters including EC, pH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and NO_3^{-}. The results of their study showed that more than 47 % of the untreated wells were considered unsuitable (class V), 39 % considered very poor water (class IV), and 14 % considered poor water (class III) for drinking purposes. The treatment of groundwater improved its quality to poor (class III) and even good (class II) (Aly *et al.*, 2015). Also approximately 64 % of all treated waters were of good quality; however, the rest remained poor (Aly *et al.*, 2015). Also, evidence have been presented by Shabbir and Ahmad (2015) to show that greater proportion 22 samples of groundwater collected in Rawalpindi and Islamabad exhibited poor quality for drinking due to over-exploitation of groundwater resource, agricultural impact and direct release of contaminants. In a recent study in the Greater Noida sub-basin, Uttar Pradesh, India, 47 groundwater samples were subjected to a comprehensive physicochemical and biological analysis of 11 parameters such as pH, calcium, magnesium, chloride, nitrate, sulphate, total dissolved solids, fluorides, bicarbonate, sodium and potassium (Singh & Hussian, 2016). The WQI index for the samples ranged from 53.69 to 267.85. The WQI values obtained indicate the very poor quality water in the area dominated by industrial and construction activities (Singh & Hussian, 2016).

In the Upper East Region of Ghana, Boah *et al.* (2015) calculated the Water Quality Index (WQI) of Vea Dam in order to assess its suitability for drinking purposes. Water samples were collected from the Vea Dam in sterile bottles (1 litre capacity) under aseptic conditions. The samples were put in ice chest containing ice and then transported to the laboratory for analysis. Samples were assessed for ten (10) physico-chemical parameters namely pH, Electrical Conductivity, Total Dissolved Solid, Total Hardness, Nitrates, Sulphates, Chlorides, Calcium, Dissolved Oxygen and Biochemical Oxygen Demand. The calculation of the WQI was done using weighted arithmetic index method. The WQI was found to be 54.21 indicating clearly that untreated water from the Vea dam is of poor quality and must therefore be treated before use to avoid water related diseases (Boah *et al.*, 2015). Another study has looked at the quality of waste water and drinking water using the WQI method. In the work of Wanda *et al.* (2016), the WQI index ratings of wastewater and drinking water samples were computed according to the levels of pH, electrical conductivity (EC), biochemical oxygen demand (BOD), E. coli, temperature, turbidity and nutrients (nitrogen and phosphates) found in water samples collected from two provinces in South Africa between June and December, 2014. Wanda *et al.* (2016) isolated three groups of WQ-rated waters, namely: fair (with a WQI range = 32.87–38.54 %), medium (with a WQI range = 56.54–69.77 %) and good (with a WQI range = 71.69–81.63 %). The results of the study showed that, 23 %, 23 % and 54 % of the sampled sites registered waters with fair, medium and good WQ ratings respectively.

None of the sites sampled during the entire period of the project registered excellent or very good water quality ratings, which would ordinarily indicate that no treatment is required to make it fit for human consumption (Wanda *et al.,* 2016). Şener *et al.* (2017) provided physical and chemical analyses of water samples taken from 21 locations through the flow path of the Aksu River in Turkey. The researchers compared the analysis results with maximum permissible limit values recommended by World Health Organization and Turkish drinking water standards. The water quality for drinking purpose was evaluated using the water quality index (WQI) method. The computed WQI values were between 35.6133 and 337.5198 in the study. The prepared WQI map showed that Karacaören-1 Dam Lake generally has good water quality. However, water quality was poor and very poor in the north and south of the river basin (Şener *et al.,* 2017). In a more recent study, Nitrate, temperature, phosphate, turbidity, dissolved oxygen, biological oxygen demand, electrical conductivity, total solids, and pH were measured at five selected stations along the river over 6 months using standard methods (E. Fathi *et al.,* 2018). The study results showed that water quality varied in the selected stations between average and good and that pollution in this section of the Beheshtabad River increases from upstream to downstream. Kangabam *et al.* (2017) assessed a water quality index (WQI) of the Loktak Lake, an important wetland which has been under pressure due to the increasing anthropogenic activities. Physicochemical parameters like temperature (Tem), potential hydrogen (pH), electrical conductivity (EC), turbidity (T), dissolved oxygen (DO), total hardness (TH), calcium (Ca), chloride (Cl), fluoride (F), sulphate (SO_4^{2-}), magnesium (Mg), phosphate (PO_4^{2-}), sodium (Na), potassium (K), nitrite (NO^2), nitrate (NO^3), total dissolved solids (TDS), total carbon (TC), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) were analyzed using standard procedures.

The researchers compared the values obtained with the guidelines for drinking purpose suggested by the World Health Organization and Bureau of Indian Standard and the result showed a higher concentration of nitrite in all the locations beyond the permissible limit. Also, according to Kangabam *et al.* (2017) the WQI values ranged from 64 to 77 indicating that the Lake water is not fit for drinking, including both human and animals, even though the people living inside the Lake are using it for drinking purposes. Despite the worldwide adoption of WQI as an effective way of making conclusions about the quality of drinking water, several studies have for the most part presented conflicting results on the same water quality parameters. This calls for more research to provide a comprehensive understanding of the contextual suitability of various WQI models.

2.3.1 Types of Water Quality Indices

As early as 1965, this method was introduced through mathematical equations to determine water quality status in the river by Horton (Horton, 1965). The WQI is determined based on various biological, physical, and chemical parameters that define the various purposes of utilization of water bodies for human consumption, such as recreation, drinking, industries, irrigation, and domestic. After the proposed WQI method by A Horton, the numbers of WQI methods have been developed for various purposes by numerous organizations across the globe, such as the National Sanitation Foundation Water Quality Index (NSFWQI) (Brown *et al.,* 1970), National Sanitation Foundation (NSF) developed NSFWQI in 1970 based on specific selection and assigning different weights for water quality parameters (Brown *et al.,*1970). This method was developed by to provide a standardized method for comparing the water quality of various bodies of water using water quality parameters; pH, temperature, turbidity, fecal coliform, dissolved oxygen (DO), biochemical oxygen demand (BOD), total phosphates, nitrate and total solids.

Results obtained for each parameter are compared to the weighting chart curve and a numerical value (Q – value) is obtained and used in the mathematical expression below for NSF WQI: Many studies have employed the National Sanitation Foundation Water Quality Index (NSFWQI) with non-original rather than originally defined parameters of the model, particularly when incorporating fecal coliform (FC), total solids, and total phosphates as inputs. Merit; data in a single index value in an objective, rapid and reproducible manner. Evaluation between areas and identifying changes in water quality. Index value relate to a potential water use. Facilitates communication with lay person. Demerit; Represents general water quality, it does not represent specific use of the water. Loss of data during data handling. Lack of dealing with uncertainty and subjectivity present in complex environmental issues Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) Canadian Council of Ministers of the Environment (CCME) (2005) provides an overall measure of the suitability of water bodies to support aquatic life at selected monitoring sites in Canada. The indicator is based on applications of the Water Quality Index (WQI). Given that aquatic life can be influenced by the presence of hundreds of both natural and anthropogenic substances in water, the WQI provides a useful tool that allows experts to translate vast amounts of water quality monitoring information into a simple overall rating. The CCME WQI relates water quality data to the various beneficial uses of water by using relevant water quality guidelines as benchmarks.

Each index is calculated for an individual monitoring site during a chosen reference period. Water samples collected over this period of time are analyzed for a suite of water quality parameters. The measured values of each parameter are compared to the appropriate water quality guideline. These are called tests. The percentage of parameters and tests that fail to meet the guidelines, as well as the deviation from the guideline for tests that do not meet guidelines, are captured in three factors used in the calculation of the index. These factors are scope (F1), frequency (F2), and amplitude (F3). The index yields a number between 0 and 100. A higher number indicates better water quality (CCME, 2001). Merit; Flexibility in the selection of input Parameters and objectives. Adaptability to different legal requirements and different water uses Statistical simplification of complex multivariate data. Demerit; Missing guidelines about the variables to be used for the index calculation Missing guidelines about the objectives specific to each location and particular water use Easy to manipulate (biased).

Oregon Water Quality Index (OWQI) creates a score to evaluate the general water quality of Oregon’s stream and the application of this method to other geographic regions, which combines eight water quality variables into a single number. The parameters covered in this method are temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD), pH, ammonia and nitrate nitrogen, total phosphorus, total solids and fecal coliform. The original OWQI was designed after the NSFWQI where the Delphi method was used for variable selection. It expresses water quality status and trends for the legislatively mandated water quality status assessment. The index is free from the arbitration in weighting the parameters and employs the concept of harmonic averaging. The index is free from the arbitration in weighting the parameters and employs the concept of harmonic averaging.

Merit; Un-weighted harmonic square mean formula used to combine sub-indices allows the most impacted parameter to impart the greatest influence on the water quality index. Method acknowledges that different water quality parameters will pose differing significance to overall water quality at different times and locations. Formula is sensitive to changing conditions and to significant impacts on water quality. Demerit; Does not consider changes in toxics concentrations, habitat or biology. To make inferences of water quality conditions outside of the actual ambient network site locations is not possible. Cannot determine the water quality for specific uses nor can it be used to provide definitive information about water quality without considering all appropriate physical, chemical and biological data. Cannot evaluate all health hazards (toxics, bacteria, metals, etc.). Weighted Arithmetic Water Quality Index (WAWQI) Brown et al. (1970) The Weighted Arithmetic Water Quality Index (WAWQI) is used to calculate the treated water quality index. WAWQI method is a multiple decision making method. It has been used widely in water quality assessment and management (Tyagi *et al.,* 2013), Water quality Index are classified into five categories as excellent, good, poor, very poor, and unsuitable for human consumption based on WQI values (Boateng *et al.,* 2016) The WAWQI is selected for formative the WQ of a definite place for consumption purpose. It is easy and simple to use by the researchers. One of the benefits of WQI is that it summarizes the bulky data into simple terms (Hulya, 2009). The WQI provides a single number that expresses overall WQ at a definite position and time based on a number of WQ parameters. The WQI can be applied as a tool in comparing the WQ of unlike sources of water and public can unravel a variety of water related problems (Jagadeeswari and Ramesh, 2012).

That’s why I have chosen this WAWQI for fortitude of GW quality. There is various information present in work connected to GW quality Hameed *et al.* (2010). Merit; Incorporate data from multiple water quality parameters into a mathematical equation that rates the health of water body with number. Less number of parameters required in comparison to all water quality parameters for particular use Useful for communication of overall water quality information to the concerned citizens and policy makers. Reflects the composite influence of different parameters i.e. important for the assessment and management of water quality. Describes the suitability of both surface and groundwater sources for human consumption. Demerit; WQI may not carry enough information about the real quality situation of the water. Many uses of water quality data cannot be met with an index. The eclipsing or over-emphasizing of a single bad parameter value A single number cannot tell the whole story of water quality; there are many other water quality parameters that are not included in the index. WQI based on some very important parameters can provide a simple indicator of water quality.

2.4 Consumer Perception of Water Quality

The perceptions of consumers on the quality of drinking water is not a new concept (Sajjadi *et al.,* 2016). People, in the past held the believe that water should be nutritive, transparent, cold and portable in order to be considered good for drinking (Kozisek, 2005). Even today, there are still occasional reports of taste and odor problems in drinking water (Küppers *et al.,* 2019). Mirzabeygi *et al.* (2016) opined that it should not always be the expectation that the quality of piped water is enough for human consumption even though availability of a public water supply network is usually an indicator of suitable water supply in developing countries. Natural processes and human activities which is associated with the varying levels of gases, natural organic matter and minerals in water, leads to changes in water quality (Sajjadi *et al.,* 2016).

Natural processes such as weathering and soil erosion increases the contents of dissolved solids (as an indicator for salty water) beyond permissible standards (Gelca *et al.*, 2016). People in such areas may prefer other sources of drinking water like artificially-produced demineralized water (Mohammadi *et al.,* 2015) or bottled water since the quality of tap water is not favorable for drinking (Sajjadi *et al.,* 2016). According to Sajjadi *et al.* (2016), consumers in this situation will use other sources of drinking water based on their economic status and what they perceive of the alternative water sources. Some recent water quality studies have looked at consumer perception of water quality from various perspectives. Kruger *et al.* (2017) studied the relationship between self-reported tap water quality and health conditions. The results of their survey showed that participants rated their tap water quality (taste, smell, appearance) as Poor (57 %), Fair (20 %), Good (13 %), Very Good (6 %), and Excellent (3 %). According to the authors, these experiences were associated with self-reported mental and physical health among the participants. In a different study in Ghana, Kulinkina *et al.* (2017) examined the Physicochemical parameters associated with the perception of the water quality from 68 boreholes in the rainy season. The researchers interviewed consumers at each borehole on five problems associated with water quality (salty taste, presence of particles, unfavorable scent, oily sheen formation on the water surface, and staining of starchy foods during cooking). The results of the study showed that concentrations of total dissolved solids (TDS) above 172 mg/L were associated with salty taste complaints. Also, Iron concentrations above 0.11, 0.14 and 0.43 mg/L were associated with complaints of unfavorable scent, oily sheen, and food staining, respectively. The study of Kulinkina *et al.* (2017) was important because it helped clarify the relationship between consumers' perceptions about water quality and the actual quality of drinking water.

In another study, Sajjadi *et al.* (2016) investigated the consumer perception of tap water quality and other drinking water sources in Gonabad, Iran. Results showed that demographic variables had a significant relationship with consumer satisfaction ($p < 0.05$). Office employees, women and poor families had the most satisfaction from tap water quality. Peoples' preferences for tap water, commercial softener, domestic softener, ghanat (a type of underground cistern) and bottled water were 27.8, 19, 27.8, 40.4 and 3.5% respectively. Dissatisfaction from production of foam, unsuitable taste, unacceptable appearance and other problems in tap water was 11.1, 95.6, 27.8 and 0.4 % respectively (Sajjadi *et al.,* 2016). Consumer reasons for using domestic water softeners are: suitable taste (80 %), easy availability (71 %), economical (56 %) and low health side effects (34 %) (Sajjadi *et al.,* 2016). Also, Nwuko, (2014) opined that total dissolved solids, colour, odour, temperature, total hardness and turbidity are the physical characteristics of water that may inform the perceptions of consumers.

Generally, studies on the perceptions of consumers about the quality of drinking water have not been sufficient. Even though consumer perceptions could be an important symptom of physical, chemical and biological problems associated with drinking water quality (Kulinkina *et al.,* 2017), little research have been done in Ghana about the perceptions of consumers on drinking water quality and particularly in mining communities. More research is needed in this direction to clarify the perception of consumers on groundwater quality in mining communities in Ghana since these perceptions have the potential of leading inhabitants of these areas to alternative sources of water (Sajjadi *et al.,* 2016) which may not be wholesome for consumption. The selected communities of the study area has a perception that their poor water quality such as the oil sheeny, smell/odour, taste, salty, and colour in the water are mostly as a results of the mining practicing in the area. The five study area communities largely depend on wells and boreholes (underground water) for drinking purposes.

2.5 Impact of Mining on Water Quality

The pollution of water bodies is one of the key issues in mining operations (Hudson, 2012). The quality of water usually depends on natural and anthropogenic factors affecting the composition of the water (Sajjadi *et al.,* 2016). According to Rakotondrabe *et al.* (2017), water quality in areas with little or no mining activities is likely to be excellent (based on WQI values) when compared to areas where there are extensive mining activities. Sand mining for example has been found to not only lead to the degradation of water quality but also damage of the river channel (Lusiagustin & Kusratmoko, 2017). According to Lusiagustin and Kusratmoko (2017), this also affects the friction of rivers as well as their pattern of flow which leads to widening and constriction.

Some researchers have argued that the quality of water is degraded by surface runoff from overburdened mining pits and leachate from mining operations or the discharge of effluent containing harmful chemicals which find their way into water bodies (Hudson, 2012; Karmakar & Das, 2012). Jhariya *et al.* (2016) confirmed that the erosion of harmful materials, the inadvertent spill of harmful chemicals or the discharge of contaminated water from mining operations can degrade streams and even ocean water in some situations. Moreover, the leakage of wastewater into groundwater through surface water and the hydraulic network between surface water and groundwater leads to the degradation of groundwater quality (Jhariya *et al.*, 2016). To prevent leakages like acid drainage into groundwater, it is usually important to put a barrier that is impermeable at the base of the tailing pond (Jhariya *et al.*, 2016). Karmakar and Das (2012) suggest the creation of a cone of depression in the groundwater table to reduce infiltration of toxic substances from mining pits into groundwater.

Several empirical studies in recent times have investigated the impact of mining activities on water quality. Efimov *et al.* (2019) found from their study the present hydrological and hydro-chemical status of Khibiny Rivers in Russia that changes in water quality resulting from mining activities include increase of water turbidity, concentrations of major ions and trace elements. They further established that the impact of mining operations on the rivers was traceable over 34 km downstream. In another study, the environmental impact of Murgul mine, one of the longest operated open-pit copper mines in Turkey (Yolcubal *et al.*, 2016). A long-term monitoring study was conducted on the surrounding surface water bodies to assess the degree of deterioration/recovery in water quality. Stream water, sediment and mine discharge samples were collected along the flow direction from the drainages under the influence of the mine. The results of the study showed that the impact of discharges from mine on Murgul streambed was enormous, and Murgul stream was classified as heavily polluted water (class IV) according to Turkish inland water quality regulations. Significant increase was also observed in metal contents of the stream sediments taken from the downstream from mine, especially for Cu, S, Zn, As, Ba and Mo (Yolcubal *et al.,* 2016). In a ground-breaking work, Corzo and Gamboa (2018) reported for the first time, the use of an interdisciplinary approach to investigate the environmental effects of mining liabilities and small-scale mining on peasant communities in Peru. The researchers used both physical and chemical methods which included microscopy and spectrometry to establish the presence of sulfides and to measure the essential water quality parameters.

Also, they employed the ecological approach to collect socioeconomic information from both communities; social actors and their statements regarding tailing problems were identified by social multi-criteria evaluation. Corzo and Gamboa (2018) found that the tailings contained sulfides that provide arsenic, cadmium, copper, zinc and manganese to Aruri and Rimac rivers in levels that exceed State of Oregon (USA) standard limits. It was also observed that both communities use this water to irrigate potato and alfalfa crops, well-known bioaccumulators. The tailings were classified as high risk to the environment by the Peruvian General Direction of Mining (Corzo & Gamboa, 2018). In a study in the Chinese city of Yulin, it was found that even though the non-carcinogenic risk of Cu, Mn, Ni, Pb, Sb and Zn in drinking water, lake and river water were acceptable, the carcinogenic risk caused by Cr in both drinking water and surface waters exceeded the values of 5.00E-05 and 1.00E-06 recommended by three international health organizations respectively (Zhou *et al.*, 2020). This according to the researchers should be monitored continuously in order to comprehensively understand the pollutants and the anthropogenic impact on water security and ecosystems, and also to ensure the sustainable clean energy and ecological coal mining. In a recent study in the African country of Mali, Bokar *et al.* (2020) established that most of the metals and toxic contaminations found in 45 water supply boreholes, 13 shallow wells, 20 piezometers of the mine, 12 surface water, 46 stream sediment samples, 10 mine soil samples and 57 plant samples, were from geogenic origin, but mining activities were likely to also play a substantial role by increasing the level of these contaminants in water, soil and plants within the mining environment. Harat *et al.* (2015) opined that water sources that are located in areas, which are immensely affected by mining activities are composed with saline mine waters. However, Howladar *et al.* (2017) found evidence to show that The general results of multivariate analysis and Water Quality Index implies that most of the areas around the Maddhapara Granite Mining area, Dinajpur, Bangladesh are dominated by the good to excellent quality water.

Contrary to these findings (Howladar *et al.*, 2017), evidences provided by Akankali *et al.* (2017) show that water samples collected from Okoro Nsit stream was contaminated as a result of sand mining activities at Iso Esuk River, Ikot Akpa Ekpu in Nigeria. In another recent study in the African country of Rwanda, the impact of mining activities on water quality status at WMP sites at Gifurwe, Burera was investigated (Hirwa *et al.*, 2019). The researchers found that most physical and chemical parameters were within permissible limits (i.e. temperature, total dissolved solids, and conductivity), while others were above permissible limits (i.e. manganese and iron). These findings is generally in line with Howladar *et al.* (2017) who found no significant impact of mining activities on water quality. Also, in another study in Africa, Mhlongo *et al.* (2018) examined the trends in water quality and mineral footprint along the catchment of a dam located in a coal mining area and water-stressed region in South Africa. By using allowable mineral concentration limits and thresholds, a statistical process capability index was calculated to determine the efficiency of controls on the potential of water being contaminated by land use and mining activities. The results showed that the coal mining area was associated with adverse effects on the raw water quality (Mhlongo *et al.*, 2018).

2.6 Studies on the Impact of Mining on Water Quality in Ghana

Several studies in recent times have investigated the impact of mining on water quality in Ghanaian mining communities. For example an early study by Adetunde *et al.* (2014) investigated the effects of mining activities on the quality of drinking water in the Obuasi mine area and its adjourning communities and found that with the exception of Fe all the physico-chemical parameters were within the WHO permissible limits. Mensah *et al.* (2015) concluded that major surface water bodies in the western region of Ghana have been heavily polluted, especially by illegal small-scale mining; land in areas surrounding mines has been rendered bare and susceptible to increased erosion and loss of viability for agricultural purposes, among other uses.

In another study in the same year, this time in the Northern Region of Ghana, Cobbina *et al.* (2015) examined heavy metal concentrations in underground drinking water sources in Nangoli and Tinga, both small-scale mining areas. Cobbina *et al.* (2015) found higher concentrations of Hg, As, Pb, Zn, and Cd in water from Nangodi, above the WHO permissible limits and higher concentrations of Hg, Pb, and Cd in Tinga, above WHO permissible limits. The researchers concluded that the intake of water from such sources with high levels of Hg, As, and Cd presents serious health risks to these people in the two mining communities. Moreover, Macdonald *et al.* (2015) found that sites with associated artisanal small-scale gold mining (ASGM) activities had water qualities that did not meet Ghana national standards for drinking water, with manganese at particularly high concentrations. Also, temporal variability in water quality parameters, likely due to the combination of fluctuating ASGM activities and the natural seasonal hydrology of tropical river systems (Macdonald *et al.*, 2015). Bempah *et al.* (2016) examined the impact of mining on groundwater quality in the south-western parts of the Ashanti Region. The concentrations of the major ions and trace elements (As, Fe, Cu, Mn and Zn) present were determined in 63 groundwater wells at dry and wet seasons. The researchers found that Mn, Cu, and Zn concentrations were below WHO permissible limits while As and Fe were higher than WHO permissible limits.

The researchers attributed the high concentrations of As and Fe to the incessant use of arsenic-containing substances in the processing of ore. Also, the phenomena which has the possibility of leaching soluble As and Fe from mine wastes into groundwater (Bempah *et al.*, 2016). Also, the very low levels of Cu, Mn, and Zn was possibly as a result of the unique mobility and solubility of these elements in soil and groundwater during their transport (Bempah *et al.*, 2016). In another study in the same region, that analysed the suitability of water in the West District, various water parameters were measured from water samples from 21 locations (Quansah *et al.*, 2016). The results of the study showed that all the irrigation water quality parameters, pH, temperature, EC, TDS, Ca, Mg, Na, K and SAR were within the permissible limit and suitable for irrigation. Also, heavy metals (Fe, Pb and Cd) levels were all within allowable limits (Quansah *et al.*, 2016). However, just like the other study (Bempah *et al.*, 2016) in the region, Mn and Zn above the permissible limits (Quansah *et al.*, 2016).

Nukpezah *et al.* (2017) investigated the effect of small-scale mining on the quality of water for irrigation from some selected sites along a river and a reservoir which was used as a control. The results of their study showed that several of the physicochemical parameters (turbidity, pH, conductivity, TDS) and heavy metals such as Pb and Hg were significantly higher (5 % level of significance) at the river sites compared to the reservoir. It was concluded that the operations of small-scale miners along river bodies affect the quality of water (Nukpezah *et al.,* 2017). The conclusion of Nukpezah *et al.* (2017) is supported by that of (Attiogbe and Nkansah (2017) who attributed high levels of TSS in the Pra River to illegal mining activities upstream affecting the quality of the water. (Hadzi *et al.*, 2018) assessed heavy metal pollution of various rivers around gold mining areas. Water samples were collected from major mining and eight pristine areas. The samples were acid digested with aqua-regia and analyzed with ICP-MS for As, Cd, Hg, Zn, Cu, Mn, Fe, Cr, Al, V, Co, Ni, and Pb.

With the exception of Al, Fe, and Mn, the metals level were found to be within the WHO and USEPA guideline limits (Hadzi *et al.,* 2018). Gyamfi *et al.* (2019) assessed water quality using the World Health Organisation (WHO) guideline values for drinking water. The results, generally, indicated that groundwater in the community is potable but unsuitable for drinking in isolated locations due to high levels of As and Zn (Gyamfi *et al.*, 2019). The stream, however, recorded high concentrations of Mn, Fe, and pH above the acceptable WHO drinking water guidelines (Gyamfi *et al.*, 2019). In a more recent study, Duncan (2020) examined heavy metal pollution in Fena River, in the Ashanti Region due to the illegal mining activities. The study found that three metals (Cd, Pb, and Fe) exceeded the safe drinking water guidelines making water generally unsafe for drinking and domestic purposes. However, of the polluting metals, only Cd polluted all the six sampling sites, whereas Pb polluted five out of the six sampling sites (Duncan, 2020). The researcher concluded that the high levels of heavy metals polluting water and the deteriorating water quality are due to the illegal mining activities occurring within and around Fena River. Generally, varying levels of various physicochemical parameters of water quality have been reported in mining communities. In several studies, both groundwater and surface water sources have concentrations of parameters within permissible standards while several others have report values with permissible limits. These findings represent the unique hydrogeological characteristics of the variuous study areas. There is therefore the need for continuous monitoring of water resources in mining communities.

However, at the time of this study, no study have been published on communities within the five selected areas. Given the fact that all the reported studies have found some physicochemical parameters of wtaer quality above permissible standards, it has become imperative for a study in the five selected mining communities around Ayanfuri in the central and western region of Ghana to assess the impact of the mining activities on the quality of groundwater. Moreover, most of the studies in recent times have assessed the impact of mining activities on surface water. Research on the impact of mining on groundwater quality have been lagely insufficient and as such the current study seeks to fill this gap in the literature.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Area

The study was conducted in five mining communities in the Wassa Amenfi East and Upper Denkyira-West District of the Western and Central Regions of Ghana respectively. These five communities were selected because of the mining activities in the area. The recent history of extensive mining activities (Ghana News Agency, 2020), the challenges with water supply (Amponsah *et al.*, 2015), and the paucity of literature on groundwater quality in the study area make it an appropriate area for the current study. Ayanfuri lies along the sealed highway from Ghana's second largest city, Kumasi, located 107 km by road to the north and the port of Takoradi, located 186 km by road to the south. Other cities located on the Takoradi to Kumasi highway include the major mining centres of Obuasi (46 km by road to the north) and Tarkwa (95 km by road to the south). The study areas are located both in the central region and the western region of Ghana, of which one large scale mining company which is Perseus mining Ghana limited (PMGL), is located in Ayanfuri in the central region, and also three quarters of the study areas is in the part of central region in Upper Denkyira-West district, (Diaso), consisting of the five communities of the study area of the project, namely Abenabena, Ayanfuri, Forbinso, Gyamang and Nkonya.

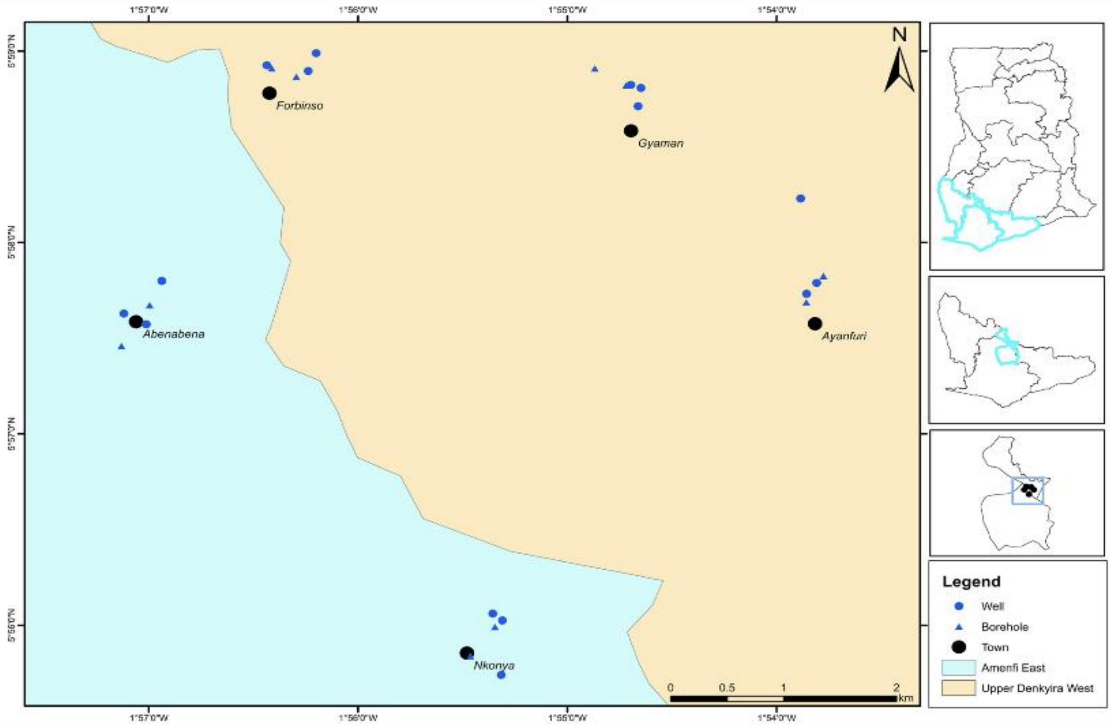

Figure 3.1 Map of the study area showing sampling sites and location

3.1.1 Population and economic activity

The Upper Denkyira West District has a population of 60,054 (GSS, 2014) with 3,935 of the population residing in Ayanfuri (Amponsah *et al.*, 2015) and Wassa Amenfi East municipality with a population of 94,121, (GSS, 2014). The Agriculture industry is the largest in the two District, Upper Denkyira West District engaging 71.1 % of the employed population and Wassa Amenfi East with (69 %), Next is the Mining and quarrying industry with (8.6 %) in Upper Denkyira West and (9 %) in Wassa Amenfi East, wholesale and retail, repair of motor vehicles and motorcycles (8.6 %) in Upper Denkyira West District and (8.2) in Amenfi East District (GSS, 2014).

3.1.2 Climate

The districts fall within the semi equatorial zone with its characteristics. The mean annual temperatures are 30 ºC on the hottest months and about 26 ºC in the coolest months. There are two rainfall regimes (double-maxima rainfall) and the total annual mean rainfall is between 1,200 mm and 2,000 mm. The first rainy season spans from May to June with the heaviest in June, while the second rainy season is from September to October. The main dry season is from November to February (GSS, 2014).

3.2 Data Collection for Water Quality Analysis

3.2.1 Selection of sampling points

A total of 25 sampling points were identified and selected in the five communities. A total of fifty (50) samples were collected from the 25 sampling points, which included 10 boreholes from the communities, 15 hands dug wells from the communities. The sampling points were assigned codes as shown in Table 3.1.

Table 3.1 Water sampling points

Sampling location	Code	Total number of samples
Abenabena	Ab-borehole 1	2
	Ab-borehole 2	2
	Ab-well 1	2
	Ab-well 2	2
	Ab-site well	2
Ayanfuri	Ay-borehole 1	2
	Ay-borehole 2	2
	Ay-well 1	2
	Ay-well 2	2
	Ay-site	2
Forbinso	Fb-borehole 1	2
	Fb-borehole 2	2
	Fb-well 1	2
	Fb-well 2	2
	Fb-site well	2
Gyamang	Gy-borehole 1	2
	Gy-borehole 2	2
	Gy-well 1	2
	Gy-well 2	2
	Gy-site well	2
Nkonya	Nk-borehole 1	2
	Nk-borehole 2	2
	Nk-wel 1	2
	Nk-well 2	2
	Nk-site well	2

3.2.2 Sample collection from groundwater

The bottles used for sample collection were 500 ml plastic bottles. They were soaked in nitric acid the night before sample collection, wash with liquid soap, rinse three times with distilled water and dry in a cupboard. The method used for this study is the Water Research Commission (WRC) guideline (WRC, 2000). In other to prevent light from affecting the physicochemical parameters of the water samples, the plastic bottles were covered with black polythene bags. The bottles were acid sterilized bottles and before the collection of a sample, the bottles were rinsed five times with water from the borehole or well. Samples were taken from the boreholes after it has been pumped for five (5) minutes. For samples from the wells, water was drawn using a sterilized bailer and poured into the bottles. A lid was used to immediately cover the bottles and appropriately labeled with the sample code and date of sampling.

3.2.3 Sample preservation technique

In order to reduce errors and the possibility of unreliable results as a result of contamination, a trip blank that was prepared with distilled water was added to the samples and properly labeled. These were done to assess the extent of the contamination during the collection of samples at the field. The collected samples in the field and trip blanks were kept in ice chest at 4 ^{o}C and were immediately transported to the Soil Testing Laboratory of Soil Research Institute, Kwadaso Kumasi for immediate analysis.

3.3 Community Perception Survey

3.3.1 Survey design and sampling

The survey adopted a descriptive design. A descriptive design is used to collect data to provide a detailed description of phenomena. In all, a total of 385 households were selected at random using the systematic random approach where the researcher selected adjourning households in line after leaving out five households. Since the total number of households in the study communities were not known, the minimum sample of 385 needed for quantitative surveys was used (Pennsylvania State University, 2017). In each household an adult (someone aged 18 years or above) was selected at random using the lottery method for inclusion in the survey. In all, 303 community members from the selected households responded to the survey. The instruments used for the data collection were a structured questionnaire with close ended items. The researcher used recruited three educated community members who were trained to assist in the administration of the questionnaire to the respondents. The data collected using the questionnaires were analyzed quantitatively. Percentages and frequencies were estimated using the Statistical Package for Social Scientists (SPSS, version 25) and presented in figures.

3.4 Physicochemical Analysis of water samples

3.4.1 Trace metals

The concentration of trace metals (Cd, Fe, Pb, Mn, Cu, As, and Zn) were determined using Spectra AA220 Atomic Absorption Spectrophotometer (AAS) (Cobbina *et al.*, 2015), 50 ml of the water samples was filled into 100 ml volumetric flask. 30 ml concentrated HNO_3 was added and 20 ml concentration of hydrochloric acid (HCl) was added in a digestion tube, heated in digestion block at 105 degree Celsius for 30 minutes (Alloway, 2012). The solution was cooled, 5 ml of Kl were added for 1 hour, and a minimum amount of Ascorbic acid powder was added to discharge any yellow colour of iodine. Filled into a 50 ml volumetric flask and made to the mark with distilled water. They were then analysed for their metal levels, Arsenic were determined using hydride generation AAS. Triplicate analyses of samples, blanks and standards were done.

Samples that were not analysed immediately were stored in a fridge (Alloway, 2012). Reliability of the results was checked using individual elemental standards (certified reference materials, CRMs) by the IRMM (Joint Research Centre European Commission) for a standard Reliability of chemical analysis.

Standards solutions (5, 10 and 15 mg/L) were prepared by dilution of 1000 mg/L stock solutions. Approximately 30 ml of each standard was taken through the treatment processes and their concentrations were measured.

3.4.2 pH, Temperature, Total Dissolved Solids and Electrical Conductivity

The PC 300 Waterproof Handheld pH/Conductivity/TDS/Temperature meter was used in measuring the above parameters. A digital reading appears upon inserting the probes into the sample indicating first the values of pH and temperature. The sample was stirred and the digital reading allowed stabilizing before recording. The “MODE” button which allows switching to other parameters was then used to read the values of TDS and EC. All probes were calibrated at 25 ^{o}C. The pH probe was calibrated with Orion Thermo scientific standard buffer solutions of pH 4.00, 7.00 and 10.00. The probe was immersed into each buffer solution and the control knob was adjusted to read the target pH. The conductivity probe was calibrated by immersing its electrode 30 ml standard 0.01 N KCl solution.

3*.4.3 Turbidity*

The Hanna turbidity meter (HI 93414 model) was used for turbidity measurement. Formazine standard solution made up of hydrazine sulphate ($(NH)_2.H_2SO_4$) and hexamethylenetetramine ($C_6H_{12}N_4$) was used to calibrate the meter. A clean, dry glass cuvet was filled with 10 ml of the sample. Silicone oil was applied on the cuvet and wiped with a lint-free cloth to obtain an even film over the entire surface of the cuvet. The cuvet was placed into its holder in the Hanna (HI 93414V) turbidity and free/total chlorine meter with its mark aligned with that of the instrument. The turbidity range was selected. When READ/ENTER was pressed, the display showed blinking dashes, after which the result in NTU was displayed and recorded accordingly.

3.4.4 Statistical Analysis of Physicochemical Properties of Water

The data on physicochemical properties of ground water were summarized according to town of sample. Means and standard deviations were estimated using SPSS Version 25. The mean concentration for each site was then compared to the WHO and EPA-Gh guideline values for water quality. Also, One-Way ANOVA was used to explore differences in mean concentrations of the physicochemical properties among the five towns. Tukey Post-Hoc analyses were performed in cases where significant differences were found among towns in the ANOVA test. Statistical analyses were done at the 0.05 % level of significance.

3.4.5 Estimation of Water Quality Index

Horton (1965) has firstly used the concept of WQI, which was further developed by Weighted Arithmetic Water Quality Index (WAWQI) Brown *et al.* (1970). The WAWQI method was adopted in this study because of its wide applicability for different geographical settings (Banda & Kumarasamy, 2020; Hameed *et al.*, 2010) In the first step each of all the water quality parameters under study is assigned a weight (wi) according to its relative importance on the comprehensive quality of water which range from 1 to 5, A maximum weight of 5 is assigned to the parameter(s) which influence more significantly the water quality and a minimum weight of 1 is assigned to the least influential water quality parameter. The relative weight (Wi) is then computed from the following Equation 01.

$$\mathrm{W} = \frac{\mathrm{wi}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{wi}} \qquad \text{Equation 01}$$

Where Wi and wi is the relative weight and weight of each parameter respectively and total number of parameters is n.

In the second step, the quality rating scale for each parameter is calculated by dividing its concentration in each water sample by its respective standards and multiplying the results by 100 as shown in Equation 02.

$$\mathrm{qi} = \left(\frac{\mathrm{Ci}}{\mathrm{Si}}\right) \times 100 \qquad \text{Equation 02}$$

Where qi is the quality rating

Ci is the concentration of each chemical parameter in each sample in milligrams per liter

Si is the standard for each chemical parameter in milligrams per liter.

In the third and final stage, the sub-index (SI) of each parameter is first determined and the sum of SI values for each parameter gives the water quality index (WQI) for each water sample.

$$\mathrm{SI} = \mathrm{Wi} \times \mathrm{qi} \qquad \text{Equation 03}$$

$$\mathrm{WQI} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{SIi} \qquad \text{Equation 04}$$

Where SIi is the sub-index of the i^{th} parameter, Wi is the relative weight of the parameter, WQI is the water quality index and n is the number of parameters. The assigned weights for the parameters used in the WQI estimation and their sources have been reported in Table 3.2.

Table 3.2 Assigned and Relative Weights of each Parameter

Parameter	WHO Guideline Value[a]	Assigned Weight (wi)	Relative Weight (Wi)	Source of Assigned Weight
pH	8.5	2.54	0.158	Kangabam *et al.* (2017)
Turbidity (NTU)	5	2.43	0.152	Kangabam *et al.* (2017)
TSS(mg/L)	50	1	0.062	Saleem *et al.* (2016)
EC (µS/cm)	1500	3.22	0.201	Kangabam *et al.* (2017)
DO (mg/L)	5	4.09	0.255	Kangabam *et al.* (2017)
TDS (mg/L)	1000	2.75	0.172	Kangabam *et al.* (2017)

[a] *(W H O, 2017).*

CHAPTER FOUR

4.0 RESULTS

4.1 Water Quality Perceptions

4.1.1 Socio-demographic Data

The results of the analysis on the sociodemographic characteristics of respondents have been presented on Table 4.1. The average age of the respondents was 35.5 ± 10.5 years. Majority of the respondents recruited from Ayanfuri were female (78.9 %), and male (33.7 %), respondents with basic education (35.3 %), respondents who were employed (56.4 %), respondents who have lived in the study area for 1-5 years (25.1 %).

Table 4.1 Socio-demographic Characteristics of Survey Respondents

Variable		Distribution, n (%)
Community		
	Nkonya	63 (20.8)
	Ayanfuri	102 (33.7)
	Abenabena	50 (16.5)
	Gyamang	61(20.1)
	Forbinso	27 (8.9)
Sex		
	Male	64 (21.1)
	Female	239 (78.9)
Level of Education		
	No formal education	105 (34.7)
	Basic education	107 (35.3)
	Secondary education	71 (23.4)
	Tertiary education	20 (6.6)
Employment Status		
	Unemployed	132 (43.6)
	Employed	171 (56.4)
Years of Residency in Ayanfuri Study Area		
	< 1 year	34 (11.2)
	1-5 years	76 (25.1)
	5-15 years	68 (22.4)
	15-25 years	54 (17.8)
	> 25 years	71 (23.4)

4.2 Groundwater use and quality perceptions

The results of the data on the groundwater use and perceptions of the quality of groundwater among the residents have been presented in Figures 4.1, 4.2 and 4.3.

4.2.1 Distribution of use of groundwater (well/borehole) in study areas

In Figure 4.1. The results showed that majority of the residents rely on groundwater for domestic activities sometimes (40.9 %) and minority of the respondent (6.9 %) never rely on groundwater

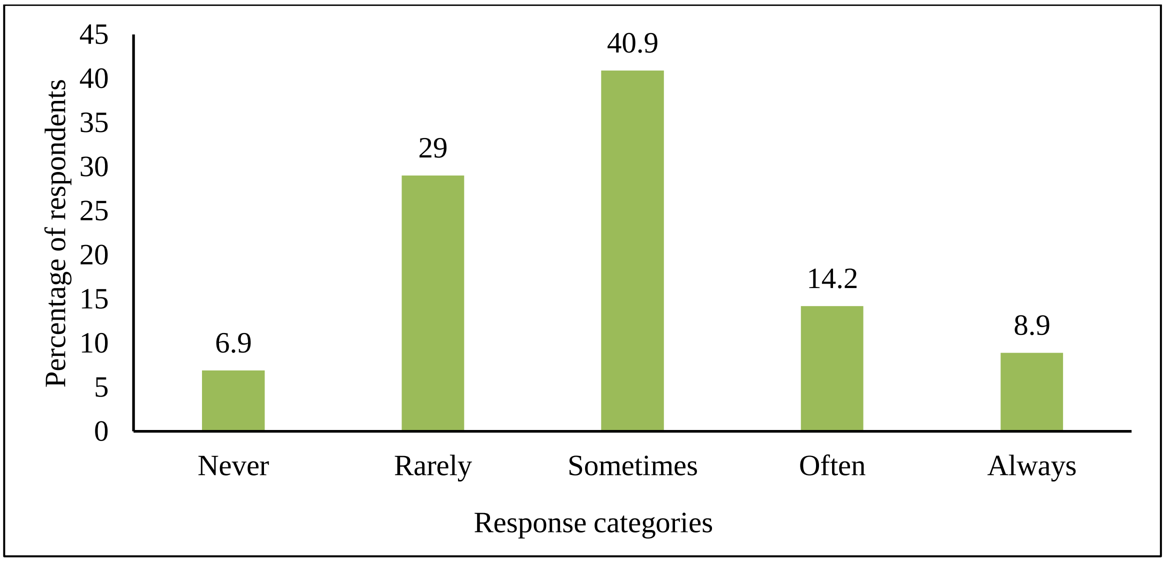

Figure 4.1 Percentage distribution of use of groundwater (well/borehole) in study areas

4.2.2 Distributions of community observations of groundwater quality

The results of the data on the distribution of community observation and perceptions of the quality of groundwater among the residents have been presented in Figure 4.2. Majority of the respondents said sometimes groundwater is seen to have colour (53.8 %) and sediment (62.7 %). Also, majority of the respondents reported that often times groundwater in the area has smell (57.8 %) or salty taste (52.5 %).

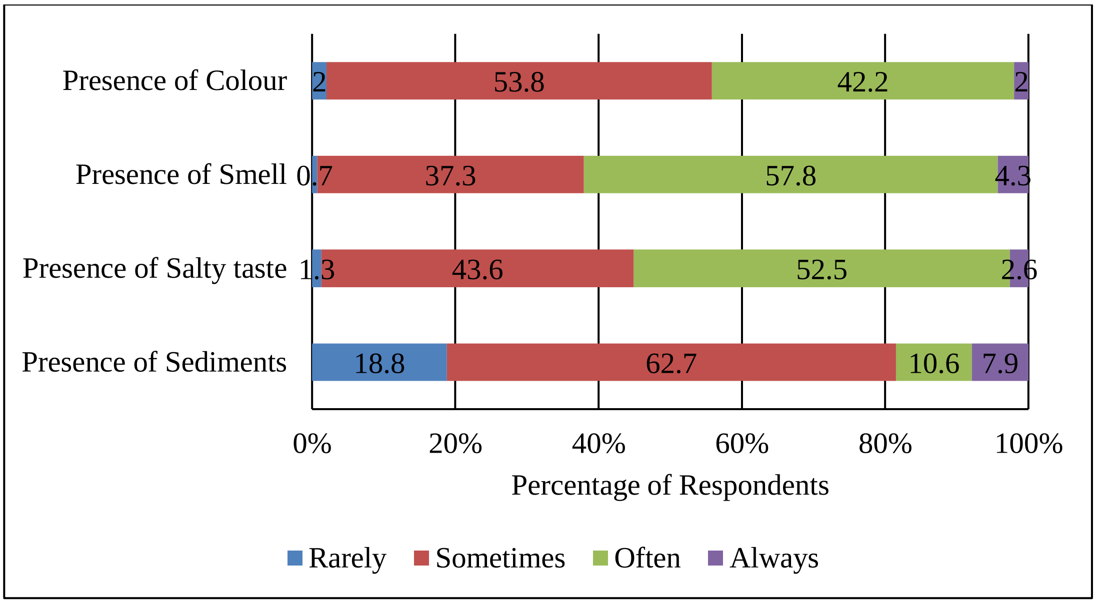

Figure 4.2 Percentage distributions of community observations of groundwater

4.2.3 Distributions of public rating of groundwater quality

The results of the data on the distribution of public rating and perceptions of the quality of groundwater among the residents have been presented in Figure (4.3). The majority of the respondents rated the quality of groundwater as acceptable (67.0 %), (8.9 %) rated the water as poor and the minority also rated the water as excellent (2.3).

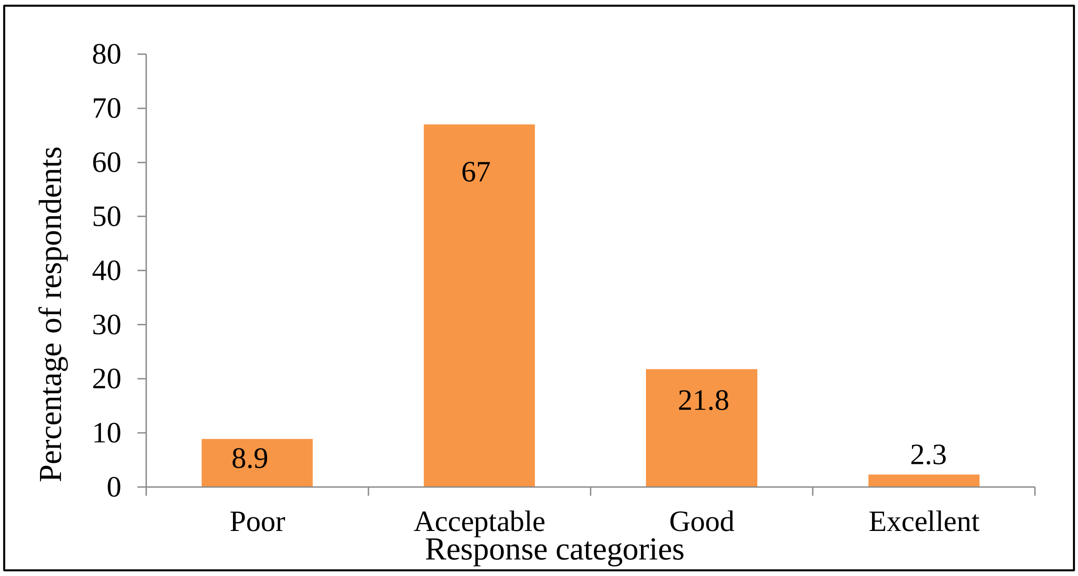

Figure 4.3 Percentage distribution of public rating of groundwater quality

4.3 Properties of Groundwater in the Study Areas.

4.3.1 Concentration of Trace Metals in Groundwater in Abenabena

The levels of trace metals in ground water from the various sampling sites have been presented in Table 4.2. The range of the levels of zinc (0.038-0.042 mg/L), copper (0.114-0.236 mg/L), manganese (0.086-0.17 mg/L), and lead (0.002-0.003 mg/L) were all below the WHO/EPA guideline values. The levels of arsenic (0.64-1.31 mg/L) and cadmium (0.124-0.144 mg/L) were above the WHO and EPA acceptable limits for potable water. However, lead levels in samples from three sites (Ab-w1, Ab-w2 and Ab-site) were above the EPA-Gh guideline value of 0.3 mg/L.

Table 4.2 Concentration of Trace Metals in Groundwater in Abenabena

	Site Code					Guideline Values	
Parameters	Ab-b1	Ab-b2	Ab-w1	Ab-w2	Ab-site	WHO[a]	EPA[b]
Zinc (mg/L)	0.038	0.04	0.042	0.04	0.041	N.A	5
Arsenic (mg/L)	0.64	0.79	1.31	1.24	1.26	0.01	0.01
Cadmium (mg/L)	0.127	0.124	0.141	0.14	0.144	0.003	0.1
Copper (mg/L)	0.117	0.114	0.221	0.22	0.236	2	5
Iron (mg/L)	0.159	0.16	0.466	0.456	0.463	N.A	0.3
Manganese (mg/L)	0.17	0.16	0.086	0.092	0.101	0.4	N.A
Lead (mg/L)	0.003	0.002	0.002	0.003	0.003	0.01	0.1

[a]*(WHO 2017);* [b]*(EPA-Gh, Environmental Protection Agency).*

4.3.2 Physicochemical Properties of Groundwater in Abenabena

The results of the physicochemical properties of groundwater in Abenabena have been presented in Table 4.3. All the samples were slightly acidic with pH values ranging from 5.8 to 6.04. All the pH values of the samples were outside of the WHO range of 6.6-8.5 while the pH values from Ab-b1 (5.8), Ab-b2 (5.82) and Ab-w2 (5.97) were outside of the EPA-Gh range of 6-9. The mean Turbidity level across samples was 7.476 NTU which is above the WHO/EPA guideline value of 5 NTU. A close inspection of Table 4.3 reveals that Turbidity of two samples (Ab-w1 and Ab-w2) were above the WHO/EPA guideline values. Also, the levels of T.S.S (4.0-12.1 mg/L), E.C (240-276 µS/cm), and T.D.S (148-170 mg/L) from all the samples were below the WHO/EPA guideline values. However, the levels of D.O (5.52-5.91 mg/L) from all the samples were above the WHO/EPA guideline values.

Table 4.3 Physicochemical Properties of Groundwater in Abenabena

	Site Code					Guideline Values	
Parameters	Ab-b1	Ab-b2	Ab-w1	Ab-w2	Ab-site	WHO[a]	EPA[b]
pH	5.8	5.82	6	5.97	6.04	6.5-8.5	6-9
Turbidity (NTU)	2.64	2.63	15.3	15.42	1.39	5	5
T.S.S (mg/L)	4	4	11	12.01	12.11	50	50
E.C (µS/cm)	240	243	270	275	276	1,500	1,500
D.O (mg/L)	5.58	5.52	5.81	5.84	5.91	5	N.A
T.D.S (mg/L)	149	148	167	168	170	1000	1,000

[a](WHO 2017); [b](EPA-Gh, Environmental Protection Agency).

4.3.3 Concentration of Trace Metals in Groundwater in Nkonya

The levels of trace metals in groundwater samples collected from Nkonya have been presented in Table 4.4. In terms of the trace metals, the levels of Zn (0.053-0.056 mg/L), Cu (0.22-0.24 mg/L), Mn (0.004-0.006 mg/L), and Pb (0.001-0.004 mg/L) were all below the WHO and EPA-Gh limits for drinking water. However, the levels of As (0.66-1.59 mg/L) and Cd (0.107-0.191 mg/L) were all above the WHO and EPA-Gh limits for drinking water. Also, the levels of Fe in samples from Nk-w1 (0.301 mg/L), Nk-w2

(0.303 mg/L), and Nk-site (0.304 mg/L) were marginally above the EPA-Gh limit for drinking water.

Table 4.4 Concentration of Trace Metals in Groundwater in Nkonya

	Site Code					Guideline Values	
Parameters	Nk-b1	Nk-b2	Nk-w1	Nk-w2	Nk-site	WHO[a]	EPA[b]
Zinc (mg/L)	0.053	0.054	0.055	0.055	0.056	N.A	5
Arsenic (mg/L)	1.56	1.59	0.66	0.66	0.67	0.01	0.01
Cadmium (mg/L)	0.191	0.189	0.107	0.109	0.111	0.003	0.1
Copper (mg/L)	0.22	0.22	0.234	0.24	0.236	2	5
Iron (mg/L)	0.148	0.15	0.301	0.303	0.304	N.A	0.3
Manganese (mg/L)	0.005	0.004	0.005	0.005	0.006	0.4	N.A
Lead (mg/L)	0.003	0.004	0.001	0.001	0.002	0.01	0.1

[a](WHO 2017); [b](EPA-Gh, Environmental Protection Agency).

4.3.4 Physicochemical Properties of Groundwater in Nkonya

The results of the physicochemical properties of groundwater in Nkonya have been presented in Table 4.5. All the water samples from Nkonya were acidic and outside the WHO/EPA-Gh range for portable water. The pH of samples from the sites was in the range of 4.0 to 4.23 and a mean pH of 4.126 was recorded. Also, the level of D.O from the samples ranged from 6.6 to 8.5 mg/L and were above the WHO guideline value of 5 mg/L. Additionally, the turbidity of samples from Nk-w1 (25.9 NTU), Nk-w2 (25.91 NTU), and Nk-site (25.89 NTU) were above the WHO/EP-Gh guideline values. However, the levels of T.S.S (0-27 mg/L), Ec (50-173 μS/cm), and T.D.S (31-106 mg/L) were all below the WHO/EPA-Gh guideline values.

Table 4.5 Physicochemical Properties of Groundwater in Nkonya

	Site Code					Guideline Values	
Parameters	Nk-b1	Nk-b2	Nk-w1	Nk-w2	Nk-site	WHO[a]	EPA[b]
pH	4	4	4.2	4.2	4.23	6.5-8.5	6-9
Turbidity (NTU)	0.95	0.95	25.9	25.91	25.89	5	5
T.S.S (mg/L)	0	0	26	26	27	50	50
E.C (µS/cm)	50	51	170	173	171	1,500	1,500
D.O (mg/L)	8.48	8.5	6.6	6.6	6.63	5	N.A
T.D.S (mg/L)	31	32	105	104	106	1000	1,000

[a](WHO 2017); [b](EPA-Gh, Environmental Protection Agency).

4.3.5 Concentration of Trace Metals in Groundwater in Ayanfuri

The levels of trace metals in groundwater samples from Ayanfuri have been summarized in Table 4.6. The results reveal that the levels of As (0.78-0.79 mg/L) and Cd (0.111-0.172 mg/L) were above the WHO/EPA-Gh limits for portable water. However, the levels of Zn (0.087-0.089 mg/L), Cu (0.21-0.219 mg/L), Fe (0.148-0.161 mg/L), Mn (0.005-0.009 mg/L), and Pb (0.002-0.003 mg/L) from all the sites were below the WHO/EPA-Gh limits.

Table 4.6 Concentration of Trace Metals in Groundwater in Ayanfuri

	Site Code					Guideline Values	
Parameters	Ay-b1	Ay-b2	Ay-w1	Ay-w2	Ay-site	WHO[a]	EPA[b]
Zinc (mg/L)	0.087	0.087	0.087	0.087	0.089	N.A	5
Arsenic (mg/L)	0.78	0.78	0.78	0.78	0.79	0.01	0.01
Cadmium (mg/L)	0.131	0.134	0.164	0.17	0.172	0.003	0.1
Copper (mg/L)	0.21	0.214	0.219	0.214	0.216	2	5
Iron (mg/L)	0.148	0.157	0.149	0.152	0.161	N.A	0.3
Manganese (mg/L)	0.005	0.006	0.008	0.007	0.009	0.4	N.A
Lead (mg/L)	0.002	0.002	0.002	0.002	0.003	0.01	0.1

[a](WHO 2017); [b](EPA-Gh, Environmental Protection Agency).

4.3.6 Physicochemical Properties of Groundwater in Ayanfuri

The results of the physicochemical properties of groundwater in Ayanfuri have been presented in Table 4.7. The results revealed that the pH of the samples from all the sites were slightly acidic and fall outside the WHO/EPA-Gh range. The pH ranged from 5.17 to 5.42 and the mean pH was 5.304. Also, the levels of D.O from all the sites ranged from 8.67 to 9.24 and were above the WHO guideline value. However, the levels of turbidity (0.57-0.64 NTU), T.S.S (5-5.35 mg/L), Ec (130 to 142 µS/cm), and T.D.S (80-89 mg/L) were within the WHO/EP-Gh limits for portable water.

Table 4.7 Physicochemical Properties of Groundwater in Ayanfuri

	Site Code					Guideline Values	
Parameters	Ay-b1	Ay-b2	Ay-w1	Ay-w2	Ay-site	WHO[a]	EPA[b]
pH	5.17	5.2	5.34	5.42	5.39	6.5-8.5	6-9
Turbidity (NTU)	0.6	0.59	0.64	0.57	0.59	5	5
T.S.S (mg/L)	5.2	5.35	5.25	5	5.3	50	50
E.C (µS/cm)	132	130	138	139	142	1,500	1,500
D.O (mg/L)	8.76	8.67	8.89	9.24	9.18	5	N.A
T.D.S (mg/L)	80	81	84	87	89	1000	1,000

[a]*(W.H.O, 2017);* [b]*(EPA-Gh, Environmental Protection Agency, n.d.).*

4.3.7 Concentration of Trace Metals in Groundwater in Gyamang

The levels of trace metals in groundwater samples from Gyamang have been presented in Table 4.8. The levels of Cd (0.18-0.186 mg/L) from all the sites are above the WHO/EPA-Gh guideline values for portable water. Also, the levels of Fe from Gy-w1 (0.301 mgl) and Gy-site (0.31 mg/L) are marginally above the EPA-Gh acceptable limit for portable water. However, the levels of Zn (3-3.23 mg/L), As (0.001-0.001 mg/L), Cu

(0.002-0.008 mg/L), Mn (0.023-0.041 mg/L), and Pb (0.002-0.004 mg/L) were within the WHO/EPA-Gh acceptable limits for portable water.

Table 4.8 Concentration of Trace Metals in Groundwater in Gyamang

	Site Code					Guideline Values	
Parameters	Gy-b1	Gy-b2	Gy-w1	Gy-w2	Gy-site	WHO[a]	EPA[b]
Zinc (mg/L)	3.231	3.119	2.999	2.999	3.121	N.A	5
Arsenic (mg/L)	0.001	0.001	0.001	0.001	0.001	0.01	0.01
Cadmium (mg/L)	0.184	0.181	0.18	0.182	0.186	0.003	0.1
Copper (mg/L)	0.002	0.002	0.005	0.006	0.008	2	5
Iron (mg/L)	0.289	0.292	0.301	0.298	0.31	N.A	0.3
Manganese (mg/L)	0.023	0.025	0.037	0.041	0.039	0.4	N.A
Lead (mg/L)	0.002	0.002	0.002	0.003	0.004	0.01	0.1

[a](WHO 2017); [b](EPA-Gh, Environmental Protection Agency).

4.3.8 Physicochemical Properties of Groundwater in Gyamang

The results of the physicochemical properties of groundwater in Gyamang have been presented in Table 4.9. The pHs of the water samples ranged from 5.1 to 5.14 and were outside of the WHO/EPA-Gh acceptable range for drinking water. Also, the levels of D.O in all the samples ranged from 8.5 to 8.53 mg/L and were above the WHO guideline value for portable water. However, the turbidity (0.43-0.46 NTU), T.S.S (2-2.05 mg/L), EC (57.6-58 μS/cm), and T.D.S (28.1-28.3 mg/L) were within the WHO/EPA-Gh guideline values for portable water.

Table 4.9 Physicochemical Properties of Groundwater in Gyamang

	Site Code					Guideline Values	
Parameters	Gy-b1	Gy-b2	Gy-w1	Gy-w2	Gy-site	WHO[a]	EPA[b]
pH	5.1	5.12	5.1	5.14	5.11	6.5-8.5	6-9
Turbidity (NTU)	0.44	0.46	0.45	0.44	0.43	5	5
T.S.S (mg/L)	2	2	2.05	2.03	2.01	50	50
E.C (µS/cm)	57.6	57.8	57.79	58	57.65	1,500	1,500
D.O (mg/L)	8.51	8.51	8.52	8.5	8.53	5	N.A
T.D.S (mg/L)	28.1	28.3	28.2	28.1	28.15	1000	1,000

[a]*(WHO 2017);* [b]*(EPA-Gh, Environmental Protection Agency).*

4.3.9 Concentration of Trace Metals in Groundwater in Forbinso

The levels of trace metals in groundwater samples from Forbinso have been presented in Table 4.10. the results show that the levels of Cd from all the sites ranged from 0.155 to 0.272 mg/L and were above the WHO/EPA-Gh limits for portable water. Also, the levels of Fe at Fb-w1 (0.364 mg/L), Fb-w2 (0.361 mg/L), and Fb-site (0.375 mg/L) were above the guideline value of EPA-Gh. However, the levels of Zn (3.45-4 mg/L), As (0-0.001 mg/L), Cu (0.003-0.006 mg/L), Mn (0.019-0.039 mg/L), and Pb (0.002-0.003 mg/L) were within the WHO/EPA-Gh acceptable limits for portable water.

Table 4.10 Concentration of Trace Metals in Groundwater in Forbinso

	Site Code					Guideline Values	
Parameters	Fb-b1	Fb-b2	Fb-w1	Fb-w2	Fb-site	WHO[a]	EPA[b]
Zinc (mg/L)	3.499	3.546	3.448	3.848	3.999	N.A	5
Arsenic (mg/L)	0.0	0.0	0.0	0.0	0.001	0.01	0.01
Cadmium (mg/L)	0.155	0.163	0.258	0.267	0.272	0.003	0.1
Copper (mg/L)	0.003	0.003	0.005	0.005	0.006	2	5
Iron (mg/L)	0.138	0.142	0.364	0.361	0.375	N.A	0.3
Manganese (mg/L)	0.019	0.024	0.035	0.032	0.039	0.4	N.A
Lead (mg/L)	0.003	0.002	0.003	0.003	0.002	0.01	0.1

[a]*(WHO 2017);* [b]*(EPA-Gh, Environmental Protection Agency).*

4.3.10 Physicochemical Properties of Groundwater in Forbinso

The results of the physicochemical properties of groundwater in Abenabena have been presented in Table 4.11. The samples from all the sites were slightly acidic with pH values ranging from 5.18 to 5.2. These values were outside of the WHO/EPA-Gh range of pH for portable water. Also, the levels of D.O from all the sites ranged from 8.48 to 8.5 mg/L and were above the WHO guideline value for portable water. However, the turbidity (0.98-1 NTU), T.S.S (4-4 mg/L), EC (38.6-38.8 μS/cm), T.D.S (16.4 to 19.4 mg/L) were within the WHO/EPA-Gh limits for portable water.

Table 4.11 Physicochemical Properties of Groundwater in Forbinso

	Site Code					Guideline Values	
Parameters	Fb-b1	Fb-b2	Fb-w1	Fb-w2	Fb-site	WHO[a]	EPA[b]
pH	5.18	5.2	5.19	5.18	5.19	6.5-8.5	6-9
Turbidity (NTU)	0.98	1	0.99	0.98	0.98	5	5
T.S.S (mg/L)	4	4	4	4	4	50	50
E.C (μS/cm)	38.6	38.8	38.8	38.6	38.7	1,500	1,500
D.O (mg/L)	8.5	8.49	8.49	8.48	8.5	5	N.A
T.D.S (mg/L)	19.34	19.38	19.35	19.36	16.38	1000	1,000

[a]*(WHO 2017);* [b]*(EPA-Gh, Environmental Protection Agency).*

4.3.11 Comparisons of the Characteristics of Groundwater among the five Towns

The results of the One-Way ANOVA test have been presented on Table 4.12. Also, the descriptive results of the One-Way ANOVA and the Tukey Post Hoc comparisons can be found in Appendix A. The ANOVA comparisons on As and T.S.S returned undefined results since the minimum levels and standard deviations of As and T.S.S at Forbinso and Nkonya respectively were zero (0). Also, there was no evidence of a statistically significant difference in the mean Pb levels among the five towns ($p = 0.708$). However, there were statistically significant differences in the mean levels of all the remaining characteristics of groundwater among the five towns ($p < 0.001$). The descriptive results and the Post Hoc test showed that the mean levels of Zn at Gyamang and Forbinso were significantly higher than the mean levels in the remaining three towns ($p < 0.001$). Also, the mean level of Cd was significantly higher at Forbinso than Abenabena ($p < 0.01$), Nkonya ($p < 0.05$) and Ayanfuri ($p < 0.05$). Additionally, the mean levels of Cu at Abenabena, Nkonya and Ayanfuri were significantly higher than at Gyamang and Forbinso ($p < 0.001$). Moreover, the differences found in Fe levels among the towns was as a result of the difference between Abenabena (0.3408 mg/L) and Ayanfuri (0.1534 mg/L) with $p = 0.053$.

The mean level of Mn was found to be significantly higher at Abenabena than the remaining four towns ($p < 0.001$). The mean pH level at Nkonya was found to be significantly lower than those of all the other towns ($p < 0.001$). Also, the mean turbidity at Nkonya was found to be significantly higher than Ayanfuri, Gyamang and Forbinso ($p < 0.05$). The mean level of E.C was found to be significantly higher at Abenabena than the remainder of the towns ($p < 0.001$). Additionally, mean E.C levels at Nkonya and Ayanfuri were found to be significantly higher than at Gyamang and Forbinso. The mean levels of D.O at Ayanfuri, Gyamang and Forbinso were found to be significantly higher than at Abenabena and Nkonya. The T.D.S at Abenabena was significantly higher than in the remaining four towns ($p < 0.001$).

Table 4.12 One-Way ANOVA of the Properties of Groundwater in the Five Communities

Parameters	F	df1	df2	p
Zinc (mg/L)	2207.612	4	9.45	< .001
Arsenic (mg/L)	NaN	4	NaN	NaN
Cadmium (mg/L)	28.353	4	8.3	< .001
Copper (mg/L)	4172.436	4	9.09	< .001
Iron (mg/L)	219.951	4	8.97	< .001
Manganese (mg/L)	29.896	4	8.64	< .001
Lead (mg/L)	0.544	4	9.79	0.708
pH	149.17	4	8.74	< .001
Turbidity (NTU)	1486.694	4	9.24	< .001
T.S.S (mg/L)	NaN	4	NaN	NaN
E.C (µS/cm)	11296.8	4	8.92	< .001
D.O (mg/L)	273.511	4	9.03	< .001
T.D.S (mg/L)	411.605	4	8.02	< .001

NaN = Not a number (meaning an undefined result was obtained).

4.4 Water Quality Index (WQI) of Ground Water in the Study Areas

The results of the WQI estimation and sample classification have been presented in Table 4.13. From the results, the estimated WQI ranged from 53.3 to 127.7. Also, the water from the various samples was put under two classifications; good water and poor water. The samples from 22 out of the 25 samples (thus 88 % of the samples) were classified as good water based on their WQI estimates. However, samples from Nk-w1 (127.4), Nk-w2 (127.4) and Nk-site-w (127.7) were classified as poor water based on their WQI estimates. The average WQI estimate across all samples was also classified as good water.

Table 4.13 Water Quality Index (WQI) and Classification

Site	WQI	Classification	Site	WQI	Classification
Ab-b1	53.6	Good water	Ay-w2	63.0	Good water
Ab-b2	53.3	Good water	Ay-site-w	62.8	Good water
Ab-w1	95.1	Good water	Gy-b1	55.8	Good water
Ab-w2	95.7	Good water	Gy-b2	55.9	Good water
Ab-site-w	53.8	Good water	Gy-w1	55.9	Good water
Nk-b1	54.8	Good water	Gy-w2	55.8	Good water
Nk-b2	54.9	Good water	Gy-site-w	55.9	Good water
Nk-w1	127.4	Poor water	Fb-b1	57.4	Good water
Nk-w2	127.4	Poor water	Fb-b2	57.4	Good water
Nk-site-w	127.7	Poor water	Fb-w1	57.4	Good water
Ay-b1	59.9	Good water	Fb-w2	57.2	Good water
Ay-b2	59.5	Good water	Fb-sit-w	57.3	Good water
AY-b1	61.2	Good water			

CHAPTER FIVE

5.0 DISCUSSION OF THE RESULTS

5.1 Discussion of results

5.1.1 Consumer perceptions on the quality of groundwater

Consumer perceptions reflect the physical, chemical and biological problems associated with drinking water quality (Kulinkina *et al.*, 2017). The results of this study showed that majority of the residents in the study communities use groundwater for domestic activities sometimes. The major concerns raised were the presence of smell and salty taste in groundwater often times as expressed by the majority of the respondents (57.8 % and 52.5 % respectively) despite the majority (67 %) rating that groundwater in the area is acceptable. Concerns about salty taste could be caused by elevated levels of sodium. Sodium chloride or salt is a naturally occurring element that is highly soluble and commonly found in our groundwater (Harmon *et al.*, 2018).

Most rocks and soil naturally have soluble forms of minerals that could dissolve the water to release metals. As water passes through the various strata of rocks, soil, and sand, it acts as an effective solvent, and highly soluble sodium is added to the water (Ardakani & Razban, 2014). So, almost every groundwater supply will contain some level of sodium, but this is not usually detectable by taste (Taloor *et al.*, 2020). A sodium level below 200 mg/L will not impart a salty taste groundwater, and if water tastes salty, it is likely that there is a higher concentration of sodium present (Taloor *et al.*, 2020). This can be caused by an erosion of salt deposits, brackish water, salt water intrusion in coastal areas, road salt runoff, and leaching from landfills and industrial sites (Bempah *et al.*, 2016).

Also, the presence of odour in groundwater could be due to the presence of hydrogen sulfide gas (H_2S) which has a distinctive “rotten egg” odour (Scholes *et al.,* 2010). Iron bacteria and sulfur bacteria present in groundwater use iron and sulfur as an energy source and chemically change sulfates to produce H_2S gas (Kuma *et al.,* 2015). These bacteria use the sulfur available from decaying plants, rocks, or soil and often thrive in an iron-rich environment. The bacteria do not usually cause health problems but contribute to bad tastes and odour at low levels (Aly *et al.,* 2015). Moreover, the complaint of the presence of odour often times may be associated with the high concentration of iron in some water samples since a recent study in Ghana found that iron concentrations above 0.43 mg/L were associated with complaints of unfavorable scent (Kulinkina *et al.*, 2017).

5.2 Properties of groundwater in the study area

5.2.1 Concentration of trace metals in groundwater

The results on the levels of trace metals in groundwater in the study communities varied from town to town for the various metals. In most cases the concentrations of the trace metals were within WHO and EPA Ghana guideline limits for portable water. The range of levels of zinc (0.038 to 3.999 mg/L), copper (0.002 to 0.24 mg/L), manganese (0.004 to 0.17 mg/L), and lead (0.001 to 0.004 mg/L) were all below WHO and EPA Ghana the acceptable limits for drinking water. This situation is desirable given the potential health risks of exposure to these trace metals. For instance exposure to high levels of copper could lead to damage to essential body organs such as the kidneys and liver (Yolcubal *et al.,* 2016). Also, exposure to lead among children is associated with cognitive development problems such as learning disability (Cobbina *et al.,* 2015). The study found that levels of arsenic and iron from some sites were above WHO/EPA Ghana guideline values for portable water. The presence of high levels of arsenic in some sites could be due to the incessant use of arsenic-containing substances in the processing of ore (Umer *et al.,* 2018; Bempah *et al.,* 2016). Long term exposure to arsenic could cause skin disorders such as skin cancer, and short term effects are edema, gastrointestinal and upper respiratory symptoms (Hadzi *et al.,* 2018). The high presence of iron in groundwater from some of the sites could be due to weathering of the rock systems in the study area, discharge of mining waste and acid mine drainage. These sources of iron have been cited in the literature as common sources of iron in groundwater, especially in mining areas (Hirwa *et al.,* 2019; Adimalla *et al.,* 2018; Alshikh, 2011). Also, the study found that the levels of cadmium exceeded WHO (0.003) and EPA (0.1) Ghana guideline values for potable water in all samples. The high levels of cadmium in groundwater in the study area is worrying and requires urgent attention because the intake of high levels of cadmium could result in toxicity to the kidney and skeletal system and may be associated with an increased risk of hypertension and cardiovascular disease (Hamid *et al.,* 2019).

5.2.2 Physicochemical parameters in groundwater

On the physicochemical properties of groundwater in the study area, it was found that that the T.S.S ranged from 0 27 mg/L, E.C ranged from 38.6 276 μS/cm, and T.D.S ranged from 16.38 170 mg/L. The levels of all these parameters were within WHO/EPA Ghana acceptable limits for potable water. The generally low levels of these parameters are possible indication of the occurrence of young or recharging groundwater since high values of T.S.S, EC and TDS are mostly associated with old or discharging groundwater (Anim-Gyampo *et al.,* 2018). The possibility of the occurrence of adverse health effects on humans are therefore unexpected (Nishtha, 2012). The pH of all samples was slightly acidic ranging from 4.0 to 6.0 and in most cases fell outside of WHO and EPA Ghana guideline values for potable water. Lower values in pH are indicative of high acidity, which can be caused by the deposition of acid forming substances in precipitation. A high organic content will tend to decrease the pH because of the carbonate chemistry. As microorganisms break down organic material, the by product will be CO_2 that will dissolve and equilibrate with the soil forming carbonic acid (H_2CO_3) (Howladar *et al.*, 2017). Other organic acids such as humic and fluvic acids can also result from organic decomposition (Alshikh, 2011). The levels of turbidity ranged from 0.43 to 25.91 NTU. Turbidity levels exceeded the maximum allowable limits for portable water in five samples (Ab-w1, Ab-w2, NK-w1, Nk-w2, and Nk-site).

Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates. The more total suspended solids in the water, the murkier it seems and the higher the turbidity. Turbidity is considered as a good measure of the quality of water. Groundwater from Ab-w1, Ab-w2, NK-w1, Nk-w2, and Nk-site may present significant health implications for the health of people who use them for domestic activities since turbidity levels above 5 NTU is not safe for consumption (W.H.O, 2017). The levels of dissolved oxygen were high in all samples, ranging from 5.52 to 9.24 mg/L. A high dissolved oxygen (DO) level in a ground water source is good because it makes drinking water taste better (Mazhar & Ahmad, 2020). However, high DO levels speed up corrosion in water storage containers and pipes (Saleem *et al.*, 2016). For this reason, it is essential to use water with the least possible amount of dissolved oxygen.

5.3 Types of groundwater samples

The types of groundwater samples based on the WQI estimations from the study area were good and poor water with majority of them being good water (88 %). Only water from Nk-w1, Nk-w2 and Nk-site were classified poor water. The poor nature of water from the above sites, all in Nkonya, could be due to the high turbidity levels in groundwater in those areas. The turbidity of samples from Nk-w1 (25.9 NTU), Nk-w2 (25.91 NTU), and Nk-site (25.89 NTU) were above the WHO/EP-Gh guideline values. Such level of turbidity is a major public health concern which requires urgent remediation to prevent any possible adverse health effects from the use of groundwater for domestic activities. Mining activities in the study area could be a major cause of this problem since the changes in water quality resulting from mining activities include increase of water turbidity, concentrations of major ions and trace elements.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the results of the study, the following conclusions could be made:

- This study generally revealed that acceptable levels of trace metals such as zinc, copper, manganese, and lead existed in the groundwater in the study area. However, there was high arsenic, iron and cadmium pollution in the study area which requires urgent attention due to the potential adverse human health effects associated with exposure to high levels of these metals. The study also revealed that the physicochemical properties of groundwater from the study area were within acceptable limits for potable water with the exception of pH and turbidity. Groundwater samples were very acidic in some cases and in most cases, slightly acidic yet outside the recommended range of the WHO/EPA Ghana for potable water. There was high turbidity in some groundwater samples in the study area making these groundwater sources unhealthy for domestic consumption.

- The majority of groundwater sources in the study were found to be good for domestic consumption. However, three of the five samples from Nkonya (Nk-w1, Nk-w2 and Nk-site) were poor for domestic consumption due to high WQI values that are suggestive of high levels of pollution giving these samples a poor classification. The classification of these water sources was mainly attributed to the high levels of turbidity in these samples.

- There is a strong perception among the community members that odour and salty taste are often observed in groundwater in the area despite reporting that they only used groundwater for domestic activities sometimes. The concern of saltiness was attributed to high levels of sodium from natural and anthropogenic activities (e.g., erosion of salt deposits). Also, concerns of odour were attributed to the presence of hydrogen sulfide stemming from the activities of iron and sulfur bacteria. While these concerns make groundwater unpalatable, most community members rated the quality of groundwater as acceptable.

6.2 Recommendations

*6.2.1 Recommendations for Policy and Practice to go*vernment

From the conclusions of this study the following recommendations are necessary for policy and practice considerations.

1. There is the need for EPA Ghana to control the levels of arsenic, iron and cadmium levels in groundwater in the study area. Anthropogenic activities known in the literature to contribute to groundwater pollution such as illegal uncontrolled mining should be tackled with the necessary urgency to limit further pollution of groundwater sources.
2. There should be urgent steps by government to improve groundwater quality in Nkonya due to the high levels of pollution in the community by, for instance, building onsite low-cost treatment systems in the area due to the poor quality of groundwater.
3. There is also the need to educate the local residents by government on the potential health effects of groundwater pollution and available household level remediation practices before consumption of groundwater. This recommendation stems from the strong perception of odour and salty taste among community residents which could prevent them from using groundwater for domestic activities.

6.3 Recommendations for Research

The following recommendations are made for future research.

1. There is the need for seasonal monitoring of groundwater quality in the study area and Ghana as a whole given that the quality of groundwater remains an important issue in the country.
2. Future studies should consider assessing the microbial quality of groundwater in the study area for a better and much more informed insight into the quality of groundwater in the study area.

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APPENDICES

APPENDIX A

ANOVA DESCRIPTIVE RESULTS AND POST HOC TESTS

Table 1: ANOVA Descriptive Results

Parameter	Town	Mean	SD	SE
Zn mg/L	Abenabena	0.0402	0.00148	6.63E-04
	Nkonya	0.0546	0.00114	5.10E-04
	Ayanfuri	0.0874	8.94E-04	4.00E-04
	Gyamang	3.0938	0.09769	0.04369
	Forbinso	3.668	0.24177	0.10812
As mg/L	Abenabena	1.048	0.30963	0.13847
	Nkonya	1.028	0.49947	0.22337
	Ayanfuri	0.782	0.00447	0.002
	Gyamang	0.001	0	0
	Forbinso	2.00E-04	4.47E-04	2.00E-04
Cd mg/L	Abenabena	0.1352	0.00904	0.00404
	Nkonya	0.1414	0.04439	0.01985
	Ayanfuri	0.1502	0.02672	0.01195
	Gyamang	0.1826	0.00241	0.00108
	Forbinso	0.223	0.05871	0.02625
Cu mg/L	Abenabena	0.1816	0.06068	0.02714
	Nkonya	0.23	0.00938	0.0042
	Ayanfuri	0.2146	0.00329	0.00147
	Gyamang	0.0046	0.00261	0.00117
	Forbinso	0.0044	0.00134	6.00E-04
Fe mg/L	Abenabena	0.3408	0.16554	0.07403
	Nkonya	0.2412	0.08418	0.03764
	Ayanfuri	0.1534	0.0055	0.00246
	Gyamang	0.298	0.00822	0.00367
	Forbinso	0.276	0.12427	0.05557
Mn mg/L	Abenabena	0.1218	0.03995	0.01787

Parameter	Town	Mean	SD	SE
	Nkonya	0.005	7.07E-04	3.16E-04
	Ayanfuri	0.007	0.00158	7.07E-04
	Gyamang	0.033	0.00837	0.00374
	Forbinso	0.0298	0.00817	0.00365
Pb mg/L	Abenabena	0.0026	5.48E-04	2.45E-04
	Nkonya	0.0022	0.0013	5.83E-04
	Ayanfuri	0.0022	4.47E-04	2.00E-04
	Gyamang	0.0026	8.94E-04	4.00E-04
	Forbinso	0.0026	5.48E-04	2.45E-04
pH	Abenabena	5.926	0.109	0.04874
	Nkonya	4.126	0.11567	0.05173
	Ayanfuri	5.304	0.11283	0.05046
	Gyamang	5.114	0.01673	0.00748
	Forbinso	5.188	0.00837	0.00374
Turbidity (NTU)	Abenabena	7.476	7.21513	3.2267
	Nkonya	15.92	13.66568	6.11148
	Ayanfuri	0.598	0.02588	0.01158
	Gyamang	0.444	0.0114	0.0051
	Forbinso	0.986	0.00894	0.004
T.S.S(mg/L)	Abenabena	8.624	4.24339	1.8977
	Nkonya	15.8	14.42914	6.45291
	Ayanfuri	5.22	0.13509	0.06042
	Gyamang	2.018	0.02168	0.0097
	Forbinso	4	0	0
Ec uS/cm	Abenabena	260.8	17.79607	7.95864
	Nkonya	123	66.1929	29.60236
	Ayanfuri	136.2	5.01996	2.24499
	Gyamang	57.768	0.15611	0.06981
	Forbinso	38.7	0.1	0.04472
DO mg/L	Abenabena	5.732	0.17138	0.07664
	Nkonya	7.362	1.02982	0.46055

Parameter	Town	Mean	SD	SE
	Ayanfuri	8.948	0.25253	0.11293
	Gyamang	8.514	0.0114	0.0051
	Forbinso	8.492	0.00837	0.00374
T.D.S (mg/L)	Abenabena	160.4	10.92245	4.88467
	Nkonya	75.6	40.26537	18.00722
	Ayanfuri	84.2	3.83406	1.71464
	Gyamang	28.17	0.08367	0.03742
	Forbinso	18.762	1.33166	0.59554

Table 2: Tukey Post-hoc Test – Zinc (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	1	0.967	< .001	< .001
Nkonya	p-value		—	0.991	< .001	< .001
Ayanfuri	p-value			—	< .001	< .001
Gyamang	p-value				—	< .001
Forbinso	p-value					—

Table 3: Tukey Post-hoc Test – Cadmium (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	0.999	0.96	0.248	0.006
Nkonya	p-value		—	0.994	0.376	0.012
Ayanfuri	p-value			—	0.603	0.028
Gyamang	p-value				—	0.395
Forbinso	p-value					—

Table 4: Tukey Post-hoc Test – Cooper (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	0.077	0.352	< .001	< .001
Nkonya	p-value		—	0.899	< .001	< .001
Ayanfuri	p-value			—	< .001	< .001
Gyamang	p-value				—	1
Forbinso	p-value					—

Table 5: Tukey Post-hoc Test – Iron (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	0.53	0.053	0.959	0.841
Nkonya	p-value		—	0.642	0.894	0.981
Ayanfuri	p-value			—	0.191	0.331
Gyamang	p-value				—	0.997
Forbinso	p-value					—

Table 6: Tukey Post-hoc Test – Manganese (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	< .001	< .001	< .001	< .001
Nkonya	p-value		—	1	0.163	0.257
Ayanfuri	p-value			—	0.218	0.332
Gyamang	p-value				—	0.999
Forbinso	p-value					—

Table 7: Tukey Post-hoc Test – pH

		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	< .001	< .001	< .001	< .001
Nkonya	p-value		—	< .001	< .001	< .001
Ayanfuri	p-value			—	0.02	0.261
Gyamang	p-value				—	0.673
Forbinso	p-value					—

Table 8: Tukey Post-hoc Test – Turbidity (NTU)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	0.334	0.53	0.509	0.583
Nkonya	p-value		—	0.017	0.016	0.02
Ayanfuri	p-value			—	1	1
Gyamang	p-value				—	1
Forbinso	p-value					—

Table 9: Tukey Post-hoc Test – Electrical Conductivity (µS/cm)

		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	< .001	< .001	< .001	< .001
Nkonya	p-value		—	0.959	0.023	0.003
Ayanfuri	p-value			—	0.005	< .001
Gyamang	p-value				—	0.861
Forbinso	p-value					—

Table 10: Tukey Post-hoc Test – Dissolved Oxygen (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	< .001	< .001	< .001	< .001
Nkonya	p-value		—	< .001	0.009	0.011
Ayanfuri	p-value			—	0.617	0.574
Gyamang	p-value				—	1
Forbinso	p-value					—

Table 11: Tukey Post-hoc Test – Total Dissolved Solids (mg/L)

Town		Abenabena	Nkonya	Ayanfuri	Gyamang	Forbinso
Abenabena	p-value	—	< .001	< .001	< .001	< .001
Nkonya	p-value		—	0.948	0.006	< .001
Ayanfuri	p-value			—	0.001	< .001
Gyamang	p-value				—	0.929
Forbinso	p-value					—

APPENDIX B

GROUNDWATER QUALITY PERCEPTION SURVEY- QUESTIONNAIRE

I am a Master of Philosophy Environmental and Occupational Health Education student of the above-named university undertaking a study on the topic ***"ASSESSING GROUNDWATER QUALITY IN THE SURROUNDING COMMUNITIES OF PERSEUS MINING GHANA LIMITED (PMGL), AYANFURI".*** I would be very grateful if you could respond to this questionnaire as part of your contribution to the success of the study. Your responses shall be used strictly and exclusively for academic purposes and will be treated with utmost confidentiality. Thank you.

Serial number: ________ Date:
______/______/___________

Community name: ______________________________

SECTION A: BACKGROUND INFORMATION OF RESPONDENTS

No.	Questions	Responses/Coding Categories	Skip to No.
1	What is your age (as at last birthday)?	☐☐	
2	Gender	Male [1] Female [2]	
	What is your highest educational level?	No formal education [1] Basic education [2] Secondary education [3] Tertiary education [4]	
4	What is your employment status?	Unemployed [1] Employed [2]	

5	For how long have you been a resident of this community?	< 1 year [1] 1-5 years [2] 5-15 years [3] 15-25 years [4] > 25 years [3]	

SECTION B: WATER QUALITY PERCEPTIONS

No.	**Questions**	**Responses/Coding Categories**	**Skip to No.**
6.	How often do you use groundwater for domestic activities?	Never [1] Rarely [2] Sometimes [3] Often [4] Always [5]	
7.	How often do you see sediments/solid particles in groundwater?	Never [1] Rarely [2] Sometimes [3] Often [4] Always [5]	
8.	How often do you have salty taste or any other concern about the taste of groundwater?	Never [1] Rarely [2] Sometimes [3] Often [4] Always [5]	
9.	How often do you have bad smell or any other concern about the smell of groundwater?	Never [1] Rarely [2] Sometimes [3] Often [4] Always [5]	
10.	How often do you have any concern about the colour of groundwater?	Never [1] Rarely [2] Sometimes [3] Often [4] Always [5]	
11.	In your opinion, how will you rate the overall quality of groundwater in this community?	Very poor [1] Poor [2] Acceptable [3] Good [4] Excellent [5]	