

Department of Theoretical and Applied Biology

**PHYSICO-CHEMICAL QUALITY OF WATER
SOURCES IN THE GOLD MINING AREAS OF BIBIANI**

KNUST

Master of Science Thesis

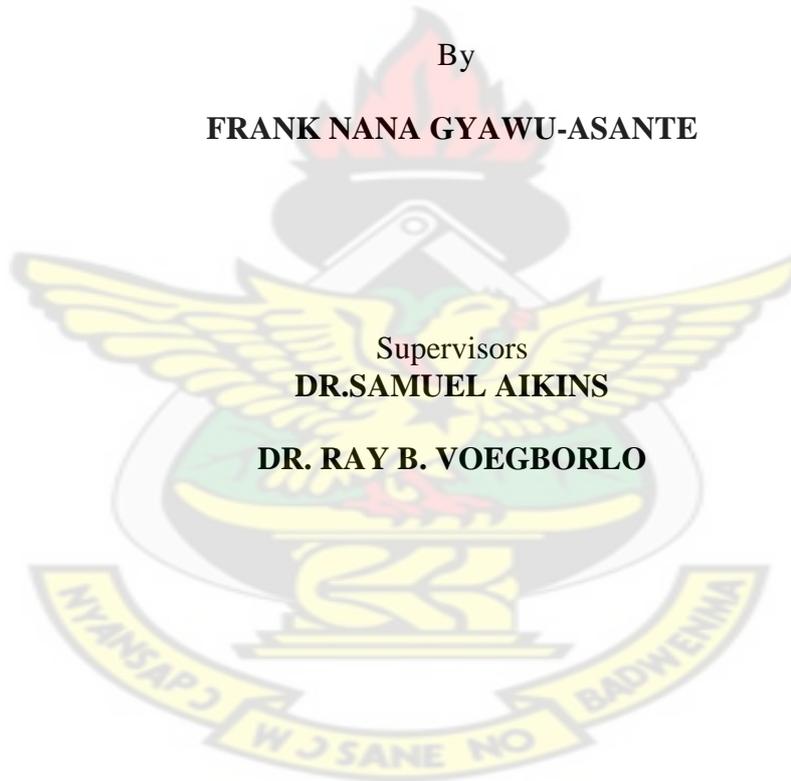
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JULY, 2012

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By

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KNUST

A Thesis submitted to
The Department of Theoretical and Applied Biology,
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In partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCE

College of Science

JULY, 2012

CERTIFICATION

I hereby declare that this submission is my own work towards the Master of Science and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Physico-chemical quality of ground and surface waters from Bibiani and its environs was conducted between November, 2009 and April, 2010. This study was undertaken to determine whether physical, chemical and trace metal contamination of water sources in Bibiani is as a result of mining or geochemical and biochemical processes within the environment. Levels of trace metals (Arsenic (As), Iron (Fe), Manganese (Mn), and Copper (Cu)), physical parameters (pH, Total Dissolved Solids (TDS), Electrical Conductivity (E.C) and Temperature) and chemical parameters (Alkalinity, Hardness, Phosphate and Cyanide (CN)) in water resources were determined. Water samples were collected from 10 sampling points including 2 streams, 2 rivers, 3 boreholes and 3 hand dug wells for trace metal analysis. The results showed that groundwater (pH range 5.77 – 6.56) was slightly acidic (low pH) compared to surface water (pH range 6.57 – 7.14 pH units). Groundwater electrical conductivity ranged from 360.17 to 957.12 $\mu\text{S}/\text{cm}$ whereas that of surface water ranged from 451.67 to 774.72 $\mu\text{S}/\text{cm}$. Mining related contaminants detected in water samples in this study were As (ranging from values <0.001 to 0.002 mg/l), CN (minimum and maximum concentrations of 0.002 and 0.036 mg/l respectively), Mn (ranging between 0.1 and 0.72 mg/l) and Fe (with 0.32 and 3.035 mg/l being the respective minimum and maximum values). Groundwater (GW1, GW2, GW3, GW4, GW5 and GW6) samples were found to contain more Mn (at GW3 and GW4 with concentrations of 0.72 and 0.5 mg/l respectively) and Fe (at all the sampling points with concentrations ranging from 0.32 to 1.47mg/l) contaminants. Surface water (SW1, SW2, SW3, and SW4) bodies were also found to have more As (at SW2 with a value of 0.02 mg/l) and Fe (also occurring at all the sampling points with values between 1.246 and 3.035 mg/l) contaminants.

Relationships between trace metals and chemical and physical parameters in groundwater showed that As had a strong negative correlation with alkalinity ($r = -0.866$) and Fe also had a strong positive correlation with electrical conductivity ($r = 0.906$). In surface water, Mn showed a strong positive correlation with phosphate ($r = 0.871$) but correlated negatively with alkalinity ($r = -0.93$). Fe also correlated negatively with electrical conductivity ($r = -0.864$) in surface water. Compared to WHO / EPA guideline, few of the ground and surface water supplies had one or more trace metal (Fe, As and Mn) levels outside acceptable limits set for drinking water. Most of them however have levels safe for human consumption.



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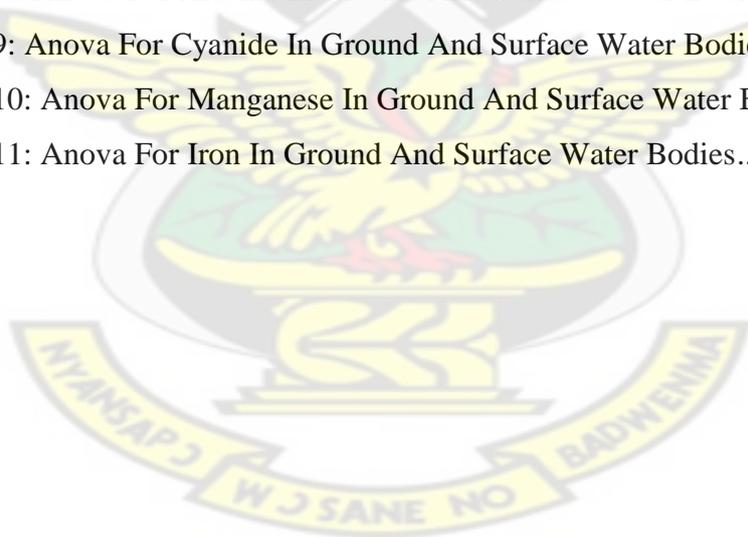
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List of Abbreviations and Acronyms

MDGs:	Millennium Development Goals
UNICEF:	United Nations Children’s Fund
WHO:	World Health Organisation
ICWE:	International Conference on Water and the Environment
CAG:	Central African Gold
CAGBL:	Central African Gold Bibiani Limited
CIL:	Cyanide In Leach
EPA:	Environmental Protection Agency
WRC:	Water Resources Commission
PNDC:	Provisional National Defence Council
ERP:	Economic Recovery Program
IMF:	International Monetary Fund
GLAMCO:	Ghana Libya Gold Mining Company
IGR:	International Gold Resource
AGCL:	Ashanti Goldfields Company Limited
AGBL:	Ashanti Goldfields Bibiani Limited
AMD:	Acid Mine Drainage
EC:	Electrical Conductivity
TDS:	Total Dissolved Solids
pH:	Potential of Hydrogen
GW:	Groundwater
SW:	Surface Water
HSE:	Health Safety and Environment

EU: European Union
USEPA: United States Environmental Protection Agency
EIS: Environmental Impact Statement

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CHAPTER ONE

INTRODUCTION

1.1 Background

In 2000, 189 nations adopted the United Nations Millennium Declaration, from which the Millennium Development Goals were established or determined. The Millennium Development Goals (MDGs), the blueprint for the world to accelerate development and measure progress, contain a set of time-bound measurable goals and targets for combating poverty, hunger, disease, illiteracy, environmental degradation and discrimination against women among others. Of paramount importance is the water supply sector which is Goal 7, and aims at ensuring environmental sustainability. According to the United Nations Mid-term Assessment reports, 80% of the world's population used an improved drinking water source in 2004, up from 71% in 1990 (UNICEF and WHO, 2004). Although these numbers indicate the world is on track to meet the goal, however there will be challenges as populations increase.

Two targets of goal 7 are:

1. To halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015
2. To have achieved a significant improvement in the lives of at least 100 million slum-dwellers by 2020 (United Nations, 2006).

According to WHO (2004a), 1.1 billion people did not have access to an improved water supply in 2002, and 2.3 billion people suffered from diseases caused by contaminated water. Each year 1.8 million people die from diarrhoeal diseases, and 90% of these deaths are of children under five (5) (WHO, 2004a).

Besides causing death, water-related diseases also prevent people from working and leaving active lives.

Good drinking water quality is essential for the well-being of all people. Unfortunately in many countries around the world, including Ghana, some drinking water supplies have become contaminated, which has impacted on the health and economic status of most people (Akoto and Adiyah, 2007). Potable water has become a scarce commodity due to over exploitation and pollution. Scarcity and misuse of potable water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food security, industrial development and ecosystems are all at risk, unless water and land resources are managed more effectively in the present decade and beyond than they have been in the past, (ICWE, 1992).

Potable water is a finite and precious resource that is essential for sustaining life. Water is needed in all aspects of life. A general goal is to make certain that adequate supply of water of good quality be made available for all people, present and future generations, while preserving required quantity and quality of water flow to sustain crucial functions of ecosystems (Bruntland, 1987). In many developing countries, availability of water has become a critical and urgent problem and it is a matter of concern to the communities that depend on non-public water supply system.

Conformation with drinking water quality standards is of special interest because of the capacity of water to spread diseases within a large population. Although the standards vary from place to place, the objective anywhere is to reduce the possibility of spreading water borne diseases to the barest minimum in addition to being pleasant

to drink, which implies that it must be wholesome and palatable in all respects (Edema *et al.*, 2001).

Surface waters include the lakes, ponds, reservoirs, rivers and streams and wetlands. The flow of water into and through these surface water bodies comes from rainfall, runoff from melting snow and ice and as base-flow from groundwater systems (Wolf *et al.*, 2002). While surface waters volumetrically hold only a small volume (0.3 percent) of the earth's total freshwater resources, they represent about 80 percent of the annually renewable surface and groundwater (Wolf *et al.*, 2002).

Water contained in the pores of soil or in aquifers is called groundwater (Appelo and Postma, 1993). The quality of groundwater, particularly shallow groundwater, is changing as a result of human activities. According to Appelo and Postma (1993), groundwater is less susceptible to bacterial pollution than surface water because the soil and rocks through which groundwater flows screen out most of the bacteria. But freedom from bacterial pollution alone does not mean that the water is suitable for drinking. Many unseen dissolved mineral and organic constituents are present in ground water in various concentrations. Most are harmless or even beneficial; though occurring infrequently, others are harmful, and a few may be highly toxic.

Groundwater pollution has become a major subject of public concern the world over (Bockris, 1978). Bockris (1978) stated that despite the large volume of water that covers the surface of the earth, only 1% is inland or fresh and easily available for human use.

The Ministry of Health in its medium term health strategy report in 1999 stated that only 30% of Ghanaians had access to safe drinking water; over 50% use

“unprotected” source of water (Ministry of Health, 1999). Rural communities in Ghana, which form about 70% of the total population, rely heavily on groundwater as the main source of drinking water and as such its quality is critical to the quality of the health of the people in these areas (Ministry of Health, 1999). Natural geochemical and biochemical, as well as anthropogenic impact on groundwater do not only threaten the quality of human health but also poses a threat to sustainable development and management of groundwater resources. This makes groundwater prone to chemical contamination. It is therefore imperative to carry out an extensive groundwater quality assessment, in order to understand the hydrochemistry of groundwater, and ensure its potable supply in Bibiani.

Man’s activities in his attempt to survive create environmental conditions that are detrimental to his very survival. These create imbalance in the natural cycle and the ecosystem. The physical factors of the ecosystem suffer from man’s various activities. Air (atmosphere), water and land (soil) are the recipients of the negative impact of man’s activities. Water is said to be contaminated when a foreign substance is introduced into it either through direct or indirect human intervention. When water is contaminated to a level such that it cannot be used for its intended purpose, it is said to be polluted (Kara *et al*, 2004). Pollution is also defined by Kara *et al*, (2004) as the undesirable state of the natural environment being contaminated with harmful substances as a consequence of human activities. Pollutant material is of any kind: solid, liquid or gas. It is predominantly of inorganic composition, though organic materials may produce undesirable effects on ecosystems.

The most important problem in protecting water resources is pollution (Kara *et al*, 2004). Pollution parameters have been classified as physical, chemical and biological on the basis of analytical tests. Physical pollution can be determined by parameters such as pH, temperature, colour, turbidity, electrical conductivity, light permeability, suspended matter and dissolved matter (Tuzen, 2002). Chemical pollution is determined by values which are derived from parameters such as total hardness, total alkalinity, phosphate content, and different heavy metal ions present in water (Tuzen, 2002). Biological pollution may be determined by the presence of microorganisms such as faecal coliform bacteria (*E. Coli*), *Cryptosporidium parvum* and *Giardia lamblia*. The accurate determinations of trace element concentrations and other physical, chemical and biological parameters of ground and surface waters are important for controlling their pollution (Tuzen, 2002).

Water is affected by mining through heavy use of water in processing the ore, and through water pollution from discharged mine effluent and seepage from tailings and waste rock impoundments. Water has been called “mining’s most common casualty” (Banks *et al*, 1997). Bibiani is a town in Ghana where the indigenous population in the town as well as surrounding communities use groundwater, rivers and streams as their sources of drinking water (Mensah, 2004). The qualities of these water supplies vary naturally and widely dependent on climate, season, and the geology of the bedrock, as well as anthropogenic activities. This study is thus focused on the water sources of Bibiani where gold mining activities occur. There are fears among residents that the operations of the mining company (Central African Gold) in the area are causing serious contamination of the water sources.

Arsenic, copper, iron, manganese, and cyanide are among the contaminants likely to be released from mining operations (Akabzaa and Darimani, 2001). It has been anticipated that metal levels in ground and surface water may exceed WHO guidelines for drinking water in many mining areas in Ghana. This has been confirmed by earlier studies in areas like Obuasi, Tarkwa and Prestea (Akabzaa and Darimani, 2001).

For instance, a study conducted by Friends of the Earth-Ghana in Obuasi and its surrounding settlements in 1996, showed that the Kwabrafo River at Obuasi in the Ashanti region, had 38 times more arsenic than World Health Organization (WHO) permissible levels whilst the Jimi River at Akrofrom also in the Ashanti region had 36 times more arsenic (Agyapong, 1998). Agyapong, (1998) further stated that small scale mining operations also contribute significantly to the pollution of water bodies in mining communities.

1.2 Justification

The environment is the most important asset for man. It is therefore prudent to protect it from pollution. The development of every nation depends largely on its well-managed environment. In Ghana surface gold mining operations generate substantial revenue for the nation. However, if its activities are not well monitored and proper measures put in place, it will be a major cause of environmental degradation (e.g. loss of farm land, air pollution, water resource contamination etc.). Many of the residents in the Sefwi-Bibiani belt, within which Bibiani falls, depend on ground and surface waters for drinking and domestic purposes (Mensah, 2004). However, effluents from the mining industry may pollute some of these water bodies and make them unsafe.

Gold mining has been the most important industry in Ghana for a long time and the country is one of the major gold producing countries in the world today. Surface gold mining involves the extraction and exploitation of gold minerals from the ore in the earth's crust by surface (strip) mining operation. Surface gold mining operations basically involves the clearing of vegetation cover from the area to be mined, stripping off topsoil, creating pit with ramps, waste rock dumps and / or stock piles and haul roads. Gold extraction process depends on the ore mineralogy of the area being mined. The major chemical used in extracting gold in CAG is mainly sodium cyanide solution in the Cyanide In Leach (CIL) plants. This chemical used in the gold extraction and the leachate from the waste and / or ore dumps turns to affect the hydrology, physical and chemical nature of the environment. Besides, spillage from the tailing may have adverse effect on man and the ecological life due to poisoning (e.g. Cyanide poisoning). It is thus essential to identify the water sources within the Bibiani gold mining area and determine the actual sources of impact on the quality of water in relation to the geochemistry or mining activity. The study seeks to assess and compare the physico-chemical qualities of water sources in Bibiani and its environs in order to evaluate their suitability for drinking and domestic uses whiles sustaining them for future generations.

1.3 Aim and Objectives

The study aims to determine the quality of water in the Bibiani area in order to evaluate their suitability for drinking and domestic use.

The Specific Objectives are to:

1. determine the levels of heavy metals (As, Mn, Fe and Cu),
2. determine the physical (pH, temperature, electrical conductivity and TDS) and chemical (phosphate, total alkalinity, total hardness and cyanide) parameters of the water sources under study,
3. determine whether metal concentrations in water in the area are within World Health Organization (WHO) guidelines and thus meet Environmental Protection Agency (EPA)-Ghana standards.



CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The term 'water quality' is a widely used expression which has an extremely broad spectrum of meanings. Each individual has vested interest in water for his particular use, which may include commercial and industrial uses or recreational pursuits. Since the desired characteristics of water vary with its intended use, there is frequently unsatisfactory communication among the users of water where quality is concerned.

Thus in discussing a public water supply, a housewife may declare the water to be of good quality, while a brewer considers the water quality to be poor. All other water uses must be subordinated to man's need for a helpful fluid for his consumption.

Water for drinking and food preparation must be free from minerals and organic substances that can produce adverse physiological effects. To encourage man to drink this health-promoting liquid, the water must be aesthetically acceptable. For example, it should be free from apparent turbidity, colour and odour and any objectionable taste. Drinking water should also have a reasonable temperature. Such water is termed "potable," meaning that it could be consumed in any desired amount without concern for adverse health effects. Potable water is thus defined as water that is free from disease producing microorganisms and chemical substances deleterious to health (Tebutt, 1983). The provision of potable water to the rural and urban population is necessary to prevent health hazards. Before water can be described as potable, it has to comply with certain physical, chemical and microbiological standards, which are designed to ensure that the water is palatable and safe for drinking (Tebutt, 1983).

2.2 Water resources of Ghana

Ghana is well endowed with perennial rivers and groundwater, although seasonal shortages are quite common. The mean annual rainfall ranges from 2,150 mm in the extreme southwest of the country, reducing progressively eastwards and northwards to 800 mm in the southeast and about 1,000 mm in the northeast of the country (WRC, 2000).

Ghana is drained by three main river systems; the Volta, the south-western and the coastal basins river systems, which respectively cover 70, 22 and 8 percent of the total area of Ghana (Water Resources Commission, 2000). The Volta River system is shared with Côte d'Ivoire, Burkina Faso, Togo, Benin and Mali. Two river basins in the south-western system are also transboundary – the Bia River is shared with Côte d'Ivoire, while the lower reaches of the Tano River form part of the boundary with Côte d'Ivoire. Data available at the Water Resources Commission, (2000), reports that the total annual runoff of the river basins is 56.4 billion m³. The Volta, south-western and coastal systems contribute 73.7, 29.2 and 6.1 percent, respectively, of the annual runoff originating from Ghana (Ministry of Works and Housing, Ghana, 1998). The quality of groundwater resources in Ghana is generally good except for some cases of localized pollution with high levels of iron and arsenic, as well as high mineralization with total dissolved solids, especially in some coastal aquifers (Water Resources Commission, 2000).

2.2.1 Surface Water Resource

Surface waters include the lakes (as well as ponds), reservoirs, rivers and streams and wetlands our societies have depended upon and benefited from throughout history. Rivers are the most important freshwater resource for man (WHO, 2004b).

The WHO (2004b) reported that water quality problems intensified through the ages in response to the increased growth and concentration of populations and industrial centres. Polluted water is an important vehicle for the spread of diseases. In developing countries 1.8 million people, mostly children, die every year as a result of water-related diseases (WHO, 2004b).

Ghana's water resources have been under increasing threat of pollution in recent years due to rapid demographic changes, which have coincided with the establishment of human settlements lacking appropriate sanitary infrastructure. Many such settlements have developed with no proper water supply and sanitation services. People living in these areas, as well as downstream users, often utilise the contaminated surface water for drinking, recreation and irrigation, which creates a situation that poses a serious health risk to the people (Verma and Srivastava, 1990).

A number of factors influence water chemistry. Gibbs, (1970) proposed that rock weathering, atmospheric precipitation, evaporation and crystallisation control the chemistry of surface water. The influence of geology on chemical water quality is widely recognised (Gibbs, 1970; Langmuir, 1997; Lester and Birkett, 1999). The influence of soils on water quality is very complex and can be ascribed to the processes controlling the exchange of chemicals between the soil and water (Hesterberg, 1998). Apart from natural factors influencing water quality, human activities such as domestic and agricultural practices impact negatively on river water quality. It is therefore, important to carry out water quality assessments for sustainable management of water bodies.

2.2.2 Groundwater Resource

Water contained in the pores of soil or in aquifers is called groundwater (Appelo and Postma, 1993). Groundwater as defined by Falkenmark (2005) is the water contained beneath the earth surface in rocks and soil, and is the water that accumulates underground in aquifers. Groundwater constitutes 97 percent of global freshwater and is an important source of drinking water in many regions of the world (Falkenmark, 2005). In many parts of the world groundwater sources are the single most important supply for the production of drinking-water, particularly in areas with limited or polluted surface water sources. For many communities it may be the only economically viable option. This according to Falkenmark (2005) is in part because groundwater is typically of more stable quality and better microbial quality than surface waters.

The quality of ground water, particularly shallow ground water, is changing as a result of human activities. According to Appelo and Postma (1993), ground water is less susceptible to bacterial pollution than surface water because the soil and rocks through which ground water flows screen out most of the bacteria. Furthermore aquifers are often well protected by layers of soil and sediment, which effectively filter rainwater as it percolates through them, thus removing particles, pathogenic microorganisms and many chemical constituents. Many unseen dissolved mineral and organic constituents are present in ground water in various concentrations. Most are harmless or even beneficial; though occurring infrequently, others are harmful, and a few may be highly toxic.

Groundwater has been termed the 'hidden sea' – *sea* because of the large amount of it, and *hidden* because it is not visible, thus pollution pathways and processes are not readily perceived (Chapelle, 1997). This highlights a key issue in the use of aquifers as drinking water source, showing that particular attention is needed to ascertain whether the general assumption of groundwater being safe to drink is valid in individual settings. Groundwater often requires little or no treatment to be suitable for drinking whereas surface waters generally need to be treated, often extensively. It is vital therefore that the quality of groundwater is protected if public health is not to be compromised. Whilst there is a large volume of groundwater in this 'hidden sea', its replenishment occurs slowly – at rates varying between locations. Over-exploitation therefore readily occurs, bringing with it additional quality concerns.

2.3 Gold mining in Ghana – Historical background

West Africa has for centuries been one of the world's most important gold mining regions. Today the most significant gold producing country in this area is Ghana. Prospective gold regions are located in the western part of the country. Numerous hard rock deposits can be found and significant quantities have also been re-deposited in local water-bodies, alluvial gold. These gold deposits enhanced the development of many successful ancient West African civilizations, and attracted both Arabic and European merchants. The country of Ghana took its name from the ancient Kingdom of Ghana, which was located about 800 km north of present Accra.

The earliest European attempts to extract gold on a large scale were concentrated in Tarkwa and Prestea in the late 19th century and the first official European gold mining company was the African Gold Coast Company, registered on February 18th 1878. A number of other companies were established in Tarkwa at this time. The

majority of these companies failed due to various reasons and it was not until 1895, when a series of gold mines opened in Obuasi, increases in gold production occurred.

A gold rush in the early 20th century was followed by a mass increase in gold production. After this the gold production decreased, but experienced a gold rush after the First World War. Because of the unwillingness of Ghanaians to work for Europeans in late 1920s the British passed the Mercury Ordinance, which made it illegal for Ghanaians to own Mercury. After Ghana gained independence in 1957 the industry collapsed. The drastic decrease in gold production was due to the many problems resulting from the economic, financial, institutional and legal framework within which the sector operated (Aryee, 2001).

By 1966 all but one of the Ghanaian gold mines were nationalized. The industry experienced a continuous decrease in production and the rapid deterioration was the result of excessive state control. In the 1960s and 1970s Ghana developed one of the most centrally controlled economies outside Eastern Europe (Hilson, 2002a). This resulted in a rise of illegal and uncontrolled artisanal mineral production and smuggling as well as declining mineral sector performance (Addy, 1998).

In 1983, the Provisional National Defence Council (PNDC) government started the Economic Recovery Program (ERP) under the guidance of IMF (Hilson, 2002a).

The objective of the program was to quickly attract investors to the mining sector and other key sectors, which had export potential, to turn around the general economy of the country (Aryee, 2001).

After the implementation of the ERP the mining industry has seen a phenomenal growth, which mainly can be attributed to the adoption of World Bank recommendations in a new national mineral policy through the 1986 Minerals and Mining Law. This law basically means that the government leaves the mine operation, management and ownership to the private sector (Addy, 1998). In 1989 the Small Scale Gold Mining Law legalized small-scale gold mining as an industry in Ghana (Hilson, 2002b). Both large and small-scale projects have developed during the 1990s and a wide range of companies from Australia, Canada, the Netherlands, South Africa, the United Kingdom and the United States now hold controlling interest in most of the gold mines currently in operation (Addy, 1998).

2.3.1 History of Gold mining in Bibiani

Gold mining in Bibiani was first recorded between 1902 and 1903 but was closed down in 1913. In 1927 the Bibiani Gold limited restarted an underground mine, which provided a total of 2.2 million ounces of gold. The property was sold to State Gold Mining Corporation in 1961 but was shut down in 1968. Ghana Libya Gold Mining Company (GLAMCO) and International Gold Resource (IGR) each also took over the property between 1987 and 1996. Ashanti Goldfields Company Limited (AGCL), acquired the Bibiani Gold project in June, 1996 and took over its management and development which resulted in Ashanti Goldfields Bibiani limited (AGBL). In December, 2006 Central African Gold Limited (CAGL) took over the operations and management of the Bibiani mines and has remained so till date.

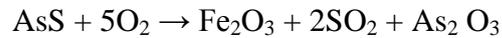
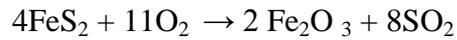
2.3.2 Gold mining operations

Surface gold mining is the extraction and exploitation of gold minerals from the earth's crust by surface mining operations. Surface mining operations basically involves clearing of vegetation cover from the area to be mined, stripping of topsoil, creating pits with ramps, waste rocks dumps and / or stockpiles, haul roads and gold extraction. Rocks are extracted into dump trucks. The ore and waste material are hauled into stockpiles and waste dumps respectively. This creates pits and renders the excavated materials loose enough to be carried away into water bodies. Gold extraction process depends on the ore mineralogy of the material being mined. Bibiani gold contains mainly sulphides (Pyrites, FeS_2 and arsenopyrites, FeAsS) in associate with graphite, laminated quartz and minor fine free gold (Hilson, 2002b). The essential processes involved in the extraction of gold at CAG are from gold ore to gold bullion (fig. 2.1). The gold ore stock pile is close to the processing plant. The ore is crushed and ground into fine powder. Free gold is removed by gravitation for smelting. For sulphide material this involves pre-treatment with lime, followed by cyanidation in CIL (Carbon in leach) tanks. The gold is leached into solution using excess dilute sodium cyanide solution as shown in the reaction:



The gold in the cyanide solution is then adsorbed onto carbon particles. It is then desorbed from the carbon and after calcination, borax, silica and sodium nitrate is used for fluxing. And finally smelting giving gold bullion.

Fe, As, and sulphate are released during the combustion of pyrites, FeS₂, arsenopyrites and Fe₂AsS as shown by the reaction below:



In addition to the conventional treatment process, the following are potential pollution sources associated with the CAG gold mining process: dust particles, chemical reagents used in the gold extraction, gaseous emissions and tailing materials. The major mining related environmental problems include air pollution and dust, water pollution, noise and land degradation.

2.3.3 Impact of mining and environmental degradation

Mining cause somewhat different environmental concerns. The major concerns observed in this area include land degradation which results from removal of vegetative cover and destruction of flora and fauna. Another concern is the contamination of water bodies and soil resulting from the release of cyanide, arsenic, sulphates, and heavy metals such as Cu and Fe during ore processing (Akosa *et al.*, 2002). Cyanide spillage may also occur. For instance there have been a number of accidental cyanide spillages in Ghana. The major spillages occurred in 1989, 1991, 1994, 1996, 1999 and 2001, (Akosa *et al.*, 2002). The most recent occurred in 2009 within the Ahafo concession of Newmont Ghana Limited. Roasting of ore containing pyrite gives rise to the production of SO₂ in the atmosphere which produces acid rain. The acid water then releases high levels of toxic ions from the rock matrix in the groundwater (Kortatsi, 2004). Other impacts associated with mining includes, noise, vibration and dust from blasting operations; AMD from solid waste from sulphidic ore leaching heavy metal and acidity into water and soil.

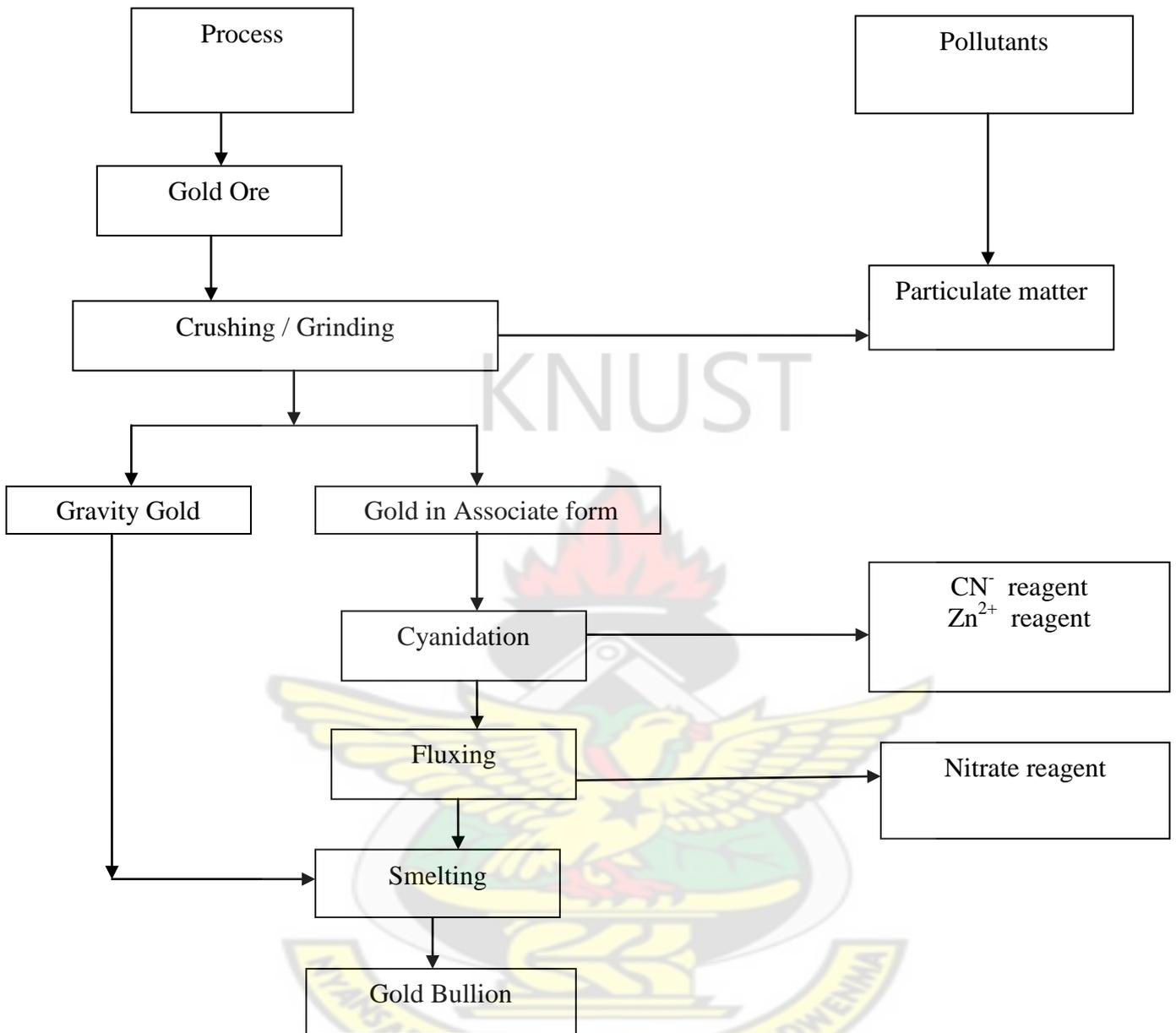


Fig. 2.1: Flow chart of Gold extraction process and possible pollutants.

2.3.4 Mining Impact on Water

There are four main means by which mining impacts on water quality. In the first scenario AMD occurs when large quantities of rock containing sulphide minerals are excavated from an open pit or opened up in an underground mine and it reacts with water and oxygen to create sulphuric acid. When the water reaches a certain level of

acidity, a naturally occurring type of bacteria called *Thiobacillus ferrooxidans* enters the process, accelerates the oxidation and acidification processes, leaching more trace metals from the wastes. Acid is carried off the mine site by rainwater or surface drainage and deposited into nearby streams, rivers, lakes and groundwater.

The next involves heavy metal pollution from mining and it occurs when such metals as arsenic, manganese, iron, copper, and zinc contained in excavated rock or exposed in an underground mine come in contact with the resource. Metals are leached out and carried downstream and underground as water washes over the rock surface. The third is when, chemical agents such as cyanide or sulphuric acid used by mining companies to separate the target mineral from the ore spills, leaks, or leaches from the mine site into nearby water bodies.

Finally, mineral development disturbs soil and rock in the course of constructing and maintaining roads, open pits, and waste impoundments. In the absence of adequate prevention and control strategies, erosion of the exposed earth may carry substantial amounts of sediment into streams, rivers and lakes. When these sediments are in excess, they can clog riverbeds and smother or suppress watershed, vegetation, wildlife habitat and aquatic organisms.

2.4 Some Metallic Contaminants Related To Mining

Several of the metals are essential to the human body. The metals are mainly utilised in enzymes to make them function properly. But we only need the metals in small quantities (WHO, 2004a). Some of them we need as trace elements and some are non-essential for us. Calcium, sodium and magnesium are essential metals and cobalt, molybdenum, selenium, chromium, nickel, vanadium and silicon are added as trace

metals. Mercury and cadmium are examples of non-essential metals (Walker and Sibly, 2001).

2.5 Some Trace / Heavy Metals

The term heavy metal is used for metals with a density more than 5 g/cm³ (Walker and Sibly, 2001). Heavy metals important in environmental and health issues include arsenic, lead, cadmium, copper, chromium, mercury, zinc, cobalt, nickel, tin and vanadium (WHO, 1996). Those are not normally a part of the human body and are more poisonous to us than other metals.

2.5.1 Arsenic (As)

Arsenic is a naturally occurring, common element found in the earth's crust. Arsenic occurs naturally in the mineral mispickel or arsenopyrites. Very low levels of arsenic are also present in plants and foods such as fish as well as in the air. Arsenic is typically found in combination with other elements – arsenic compounds – and has no distinctive taste or smell. Many of these compounds occur naturally but some are man-made. At very low levels, there is relatively little concern. Most people consume small amounts of arsenic in the food they eat, but drinking water with even low to moderate levels of arsenic can provide more than is safe. The most toxic form of arsenic, known as inorganic arsenic, is the form typically found in groundwater. Inorganic As compounds are classified as carcinogenic to humans (Asklund and Eldvall, 2005).

Studies have shown that people drinking well water with elevated levels of arsenic have higher risks of some diseases. Drinking well water with low to moderately elevated levels of arsenic over a long period of time may lead to chronic health

effects. Chronic health effects, such as cancer, develop over a number of years and can be difficult to detect, especially in the early stages. Higher levels of arsenic can also lead to more immediate or acute health effects that usually have more noticeable symptoms.

The level of As in natural waters generally varies between 1 and 2 mg/l, (Asklund and Eldvall, 2005). Concentrations may be elevated, however, in areas containing natural sources; values as high as 12 mg/l have been reported. As is a component in the manufacture of bronze materials, fireworks, agricultural chemicals, laser materials, glass, semiconductor materials, wood preservatives, copper and lead alloys and insecticides, (Hardy *et al*, 2008).

Clinical symptoms of acute intoxication of As include abdominal pain, vomiting, diarrhoea, muscular pain, and weakness, with flushing of the skin, (Asklund and Eldvall, 2005). Within a month, one may show progressive deterioration in motor and sensory responses. Signs of chronic arsenicalism, including dermal lesions, skin cancer, and peripheral vascular disease, have been observed in populations ingesting arsenic-contaminated drinking-water. In view of reducing the concentration of As in drinking-water, a provisional guideline value of 0.01 mg/l is recommended. The guideline value is derived based on the estimated lifetime cancer risk (WHO, 1996). The amount of arsenic in water is measured in micrograms of arsenic per liter of water, abbreviated as $\mu\text{g/l}$, or as milligrams per liter, abbreviated as mg/l.

2.5.2 Copper (Cu)

Cu occurs in rocks, soil, water, air, plants and animals. It is a component in metal alloys, electrical wiring, some water pipes, preservatives for wood, leather and

fabrics, and some agricultural fungicides, (Hardy *et al*, 2008). Cu is an essential plant micronutrient. However, at high levels, it may be toxic to plants.

It can also bind to soil organic matter and become unavailable to plants. Higher availability is usually associated with low pH. Copper is an essential nutrient that the body requires in very small amounts. However, drinking very high levels of copper can cause nausea, vomiting and diarrhoea, and can damage your liver and kidneys. People with Wilsons disease (a rare inherited disease that causes the body to accumulate copper) may be more sensitive to the harmful effects of copper. The stipulated Cu level in drinking water according to the WHO, (2004a) is 1.0 mg/l.

2.5.3 Iron (Fe)

Fe is an essential element in human nutrition. The most common sources of iron in groundwater are naturally occurring, for example from weathering of iron bearing minerals and rocks. Industrial effluent, acid-mine drainage, sewage and landfill leachate may also contribute iron to local groundwater. Estimates of the minimum daily requirement for iron depend on age, sex, physiological status and iron bioavailability and range from about 10 to 50 mg/day (Asklund and Eldvall, 2005). In drinking-water supplies, Fe (II) salts are unstable and are precipitated as insoluble Fe (III) hydroxide, which settles out as a rust-coloured silt.

Anaerobic groundwater may contain Fe (II) at concentrations of up to several milligrams per litre without discolouration or turbidity in the water when directly pumped from a well. Turbidity and discolouration may develop in piped systems at Fe levels above 0.05-0.1 mg/l, whereas levels of 0.3-3 mg/l are usually found acceptable.

As a precaution against storage of excessive iron in the body a provisional maximum tolerable daily intake was calculated to about 2 mg/l drinking water, (WHO,1996).

That level does not present a hazard to health. The taste and appearance of drinking water will usually be affected below this level, although iron concentrations of 1-3 mg/l can be acceptable for people drinking anaerobic well-water (WHO, 1996). The WHO (2004a) and the Ghana EPA, (1997) prescribes 0.3 mg/l as the limited Fe level allowable in water for drinking and domestic purposes.

2.5.4 Manganese (Mn)

Manganese like iron is a metallic element present in many types of rock. Mn is commonly found in water and is an essential element required in small amounts by all living organisms. Concentration of manganese in groundwater is often higher than that measured in surface waters.

The most common sources of manganese like iron in groundwater are naturally occurring, for example from weathering of manganese bearing minerals and rocks. Industrial effluent, acid-mine drainage, sewage and landfill leachate may also contribute manganese to local groundwater. Mn concentrations above 0.1 mg/l impart an undesirable taste to drinking water. Even at about 0.02 mg/l, Mn will form coatings on piping that may later tear off as a black precipitate. Humans can consume as much as 20 mg/day without apparent ill effects. Mn is believed to have a neurotoxic effect; a provisional health-based guideline value of 0.5 mg/l is proposed to protect public health (WHO, 1996).

2.6 Physical Parameters

Physical parameters of pollution include but not limited to pH, temperature, colour, turbidity, electrical conductivity, light permeability, suspended matter and dissolved matter.

2.6.1 Electrical Conductivity (EC)

The electrical conductance of water is a measure of the ability of the water to conduct electricity. It is also an indirect measure of the presence of ions, such as nitrate, sulfate, phosphate, sodium, magnesium, calcium, and iron. These substances conduct electricity because they are negatively or positively charged when dissolved in water.

The concentration of dissolved solids, or the conductivity, is affected by the bedrock and soil in the watershed. It is also affected by human influences. For example, agricultural runoff can raise conductivity because of the presence of phosphate and nitrate. It is important to measure the conductivity of water because aquatic organisms require a relatively constant concentration of the major dissolved ions in the water. Levels too high or too low may limit survival, growth or reproduction.

Electrical conductivity is affected by temperature, it is thus important to report temperature data along with conductivity values. In unpolluted waters, conductance increases by 2 to 3% per °C. The international standard temperature to which conductivity measurements are corrected is 25°C. This measurement is expressed in microsiemens per centimeter (uS/cm) at 25 degrees Celsius. Conductivity values can be used to estimate the total concentration of dissolved solids (commonly referred to as total dissolved solids, or TDS). The desired level of conductivity in drinking water according to the WHO (2004a) is 1,000 uS/cm and that of the Ghana EPA, (1997) is 750 uS/cm.

2.6.2 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) is the term used to describe the inorganic salts and small amounts of organic matter present in solution in water. The principal constituents are

usually calcium, magnesium, sodium, and potassium cations and carbonate, hydrogen carbonate, chloride, sulfate, and nitrate anions. The presence of dissolved solids in water may affect its taste (1). The palatability of drinking water has been rated by panels of tasters in relation to its TDS level as follows:

Table 2.1- Palatability of drinking water in relation to its TDS level (WHO, 2003)

TDS category	Concentration of TDS
Excellent	less than 300mg/l
Good/ fresh	300 to 600 mg/l
Fair	600 to 900 mg/l
Poor	900 to 1200 mg/l
Unpalatable / unacceptable	above 1200 mg/l

Water with extremely low concentrations of TDS may also be unacceptable because of its flat, insipid taste. Increases in conductivity indicate increased concentrations of TDS and may be attributed to development activities, leaking septic systems, salt runoff from highways, fertilizers, or other pollutants. Rainwater has less than 100 mg/l TDS, while streams may contain 100 to 2,000 mg/l TDS. The desired level of TDS for public drinking water is 500 mg/l (EPA, 1997) and 1,000 mg/l (WHO, 2004a)

2.6.3 pH

pH is the term indicating the hydrogen ion (positively charged hydrogen atom) concentration of a solution, a measure of the solution's acidity. It is a measure of the acidic or alkaline content of water. The pH level of drinking water reflects how acidic it is. pH is measured on a scale that runs from 0 to 14. Seven (7) is neutral, meaning

there is a balance between acidity and alkalinity. A measurement below 7 means acid is present and a measurement above 7 is basic (or alkaline). It is classified as a secondary drinking water contaminant whose impact is considered aesthetic. However, the WHO, (2004a) and the EPA, (1997) recommend that public water systems maintain pH levels of between 6.5 and 8.5, a good guide for individual well owners.

Water with a low pH is acidic, naturally soft and corrosive. Acidic water can leach metals from pipes and fixtures, such as copper, lead and zinc. It can also damage metal pipes and cause aesthetic problems, such as a metallic or sour taste, laundry staining or blue-green stains in sinks and drains. Water with a low pH may contain metals in addition to copper, lead and zinc. Drinking water with a pH level above 8.5 indicates high levels of alkalinity. High alkalinity may not pose a health risk, but can cause aesthetic problems, such as an alkaline taste to the water; scale build-up in plumbing; and lowered efficiency of electric water heaters.

2.6.4 Temperature

Temperature has both direct and indirect effects on aquatic ecosystems. Variations in water temperature occur both seasonally and daily. Maximum daily temperatures usually occur in the afternoon; minimum temperatures are recorded in the early morning hours.

Variations in daily temperature are attributed to radiation into and out of the water. Short-term variations are greatest in unshaded, shallow streams and less in deep-water streams and near the source of spring-fed streams. In large rivers or streams away from their source, the water temperature nearly equals the mean monthly air temperature. Temperature is a critical water quality parameter, since it directly

influences the amount of dissolved oxygen that is available to aquatic organisms. Water temperature is a major factor in determining which species are present in the stream. Different species have different temperature requirements and optimal temperatures may change for fish and invertebrate life stages.

As the temperature of water changes, chemical and physical properties of the stream are affected. Specific conductivity and pH are temperature dependent. Increase in temperature of water also increases the velocity of salt ions and, in turn, the conductivity of the water. Changes in chemical nature of the stream can have significant impacts on biological processes. Temperature of water for drinking and domestic use should not exceed 30°C (EPA, 1997).

2.7 Chemical Parameters

Chemical parameters of pollution include but not limited to total hardness, total alkalinity, phosphate content, and different heavy metal ions present in water.

2.7.1 Total Alkalinity

Alkalinity is a measure of the presence of bicarbonate, carbonate or hydroxide constituents. Concentrations less than 100 ppm are desirable for domestic water supplies. The recommended range for drinking water is 300 to 400 mgCaCO₃/l (Anon., 2006). A minimum level of alkalinity is desirable because it is considered a “buffer” that prevents large variations in pH. Alkalinity is not detrimental to humans. Moderately alkaline water (less than 350 mgCaCO₃/l), in combination with hardness, forms a layer of calcium or magnesium carbonate that tends to inhibit corrosion of metal piping. Many public water utilities employ this practice to reduce pipe corrosion and to increase the useful life of the water distribution (Anon., 2006).

High alkalinity (above 500 mgCaCO₃/l) is usually associated with high pH values, hardness and high dissolved solids and has adverse effects on plumbing systems, especially on hot water systems (water heaters, boilers, heat exchangers, etc.) where excessive, scale reduces the transfer of heat to the water, thereby resulting in greater power consumption and increased costs. Water with low alkalinity (less than 75 mgCaCO₃/l), especially some surface waters and rainfall, is subject to changes in pH due to dissolved gasses that may be corrosive to metallic fittings. Due to the presence of bicarbonate (HCO₃⁻), carbonate (CO₃²⁻) or hydroxide (OH⁻). Most of the natural alkalinity in water is due to HCO₃⁻ produced by the action of groundwater on limestone or chalk. $\text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{Ca}(\text{HCO}_3)_2$.

Alkalinity is usually divided into caustic alkalinity above pH 8.2 and total alkalinity above pH 4.5. Alkalinity can exist down to pH of 4.5 because of the fact that HCO₃⁻ is not completely neutralised until this pH is reached. The amount of alkalinity present is expressed in terms of CaCO₃.

2.7.2 Total Hardness

The hardness of water is a measure of the amount of minerals, primarily calcium and magnesium, it contains. The hardness criterion is used exclusively for determining the usability of the water resources under study for domestic and drinking purposes. Hardness of water for domestic use relates mainly to its reaction with soap. Since soap is precipitated principally by Ca²⁺ and Mg²⁺ salts, hardness is defined as the sum of the concentrations of these ions expressed as mg/l of CaCO₃.

Table 2.2 - Hardness range for drinking water

Hardness Category	Equivalent Concentration of CaCO₃
Soft	less than 60 mg/l
Medium/moderately hard	60 mg/l – 120 mg/l
Hard	120 mg/l – 180 mg/l
Very hard	above 180 mg/l

Source: Hem, 1970; The British Columbia Groundwater Association, 2007

This property of water prevents lather formation with soap and produces scale in hot-water systems. It is due mainly to the metallic ion Ca^{2+} and Mg^{2+} although Fe^{2+} and Sr^{2+} are also responsible. There is no health hazard but the economic disadvantage of hard water includes increased soap consumption and higher fuel costs. Hardness is expressed in terms of CaCO_3 and is divided into two forms:

- (a) Carbonate hardness – metals associated with HCO_3^- .
- (b) Non-carbonate hardness – metals associated with SO_4^{2-} , Cl^- , NO_3^- .

If high concentrations of Na and K salts are present, the non-carbonate hardness may be negative since such salts could form alkalinity without producing hardness.

2.7.3 Cyanide

Cyanide is not a metal. Cyanide compounds include both naturally occurring and human-made (anthropogenic) chemicals. There are more than 2,000 natural sources of cyanide, including various species of arthropods, insects, bacteria, algae, fungi and higher plants (Gray *et al.*, 1997).

A natural source of hydrogen cyanide (HCN) is a sugar-like compound called amygdalin, which exists in many fruits, vegetables, seeds and nuts, including apricots,

bean sprouts, cashews, chestnuts, corn, peaches, peanuts, potatoes, soybeans and walnuts (Gray *et al.*, 1997). In the kernel of bitter almond, there is about 1 mg of HCN as amygdalin (Gray *et al.*, 1997). The principal human-made cyanide forms are gaseous hydrogen cyanide and solid sodium and potassium cyanide. Thus cyanide compounds are present in such everyday anthropogenic sources as automobile exhaust, cigarette smoke, and even road and table salt (Gray *et al.*, 1997).

One of the major health and environmental concerns with some synthetic chemicals is that they do not decompose readily and so can accumulate in the food chain. Cyanide, however, is transformed by natural, physical, chemical and biological processes into other, less toxic chemicals. Since cyanide oxidizes when exposed to air or other oxidants, it decomposes and does not persist.

While it is a deadly poison when ingested in a sufficiently high dose, it does not give rise to chronic health or environmental problems when present in low concentrations (Gray *et al.*, 1997).

Mining is one industrial activity that uses a significant amount of cyanide—about 20% of total production (Mudder and Smith, 1994). Since 1887, cyanide solutions have been used primarily to extract gold and silver from ores that otherwise could not be mined effectively. In addition, cyanide is used in low concentrations as a flotation reagent to aid in the recovery of base metals such as lead, copper and zinc (Mudder and Smith, 1994). Gold mining operations use very dilute solutions of sodium cyanide, typically in the range of 0.01% and 0.05% cyanide (100 to 500 parts per million).

CHAPTER THREE

MATERIALS AND METHODS

3.1 STUDY AREA

3.1.1 Selection of study area

The study area, Bibiani was selected for this study because of the fact that the surface and ground water sources are extensively used for drinking and domestic purposes. Most of the water is easily accessible and there is a mine operation in the area.

3.1.2 Location and access

Bibiani is located in the Western Region of Ghana. It has a population of about 19,076 (Mensah, 2004). Bibiani is located at latitude 6.47°N and longitude -2.33°W at an altitude of 250 meters. The Bibiani gold mine is located in the Western region of Ghana. The mine lies within the Sefwi-Bibiani belt, host to over 17 million ounces of gold mineral resources, and the second-most significant gold-bearing belt in Ghana after the Ashanti belt to the east (Mensah, 2004). The mining concession area of approximately 49km² is closely adjoined to the town of Bibiani, approximately 80km southwest of the Ashanti capital, Kumasi. The most practicable access to the area is from the east on the Kumasi road.

3.1.3 Relief, drainage and topography

The area is very well drained with rivers and streams of dendrite pattern. The notable ones are the streams Mesin and Kyirayaa and Pamunu River. Most of these water bodies flow into the Tano River at Tano Odumasi and finally ends up in the Atlantic Ocean. Tano, Kyirayaa and Pamunu are some of the water bodies which are used by the surrounding communities extensively for drinking and domestic purposes.



Map not to scale

Figure 3.1 - Map of Ghana showing the location of Bibiani.

In general the area consists of two (2) main land types. These are the mountainous area reaching a height of about 340m above sea level. They are of upper Birimian geological formation and consist of very steep sided hills of narrow valleys separating

them. The rest of the area consists of low peneplains with elongated ridges of about 260m in height.

3.1.4 Climate

The study area is part of the wet semi-equatorial climate zone of Ghana. It is characterised by an annual double maxima rainfall pattern occurring in the months of May and July and September to October. The wet semi-equatorial climate with weather influenced by the cool and moist South – western monsoon wind from the South Atlantic Ocean and hot, dry and dust laden north east trade winds (locally known as Harmattan) which blows over the Sahara desert from the northern Subtropical high pressure zone (AGBL, 1996). The double maxima rainfall has a mean rainfall of 1,566.3mm. Annual mean temperature is 26.9 °C with maximum and minimum air temperatures observed in March (mean 28.3°C) and August (mean 28.3°C) respectively. Daily temperature variations are very small ranging from 1.5 °C to 3 °C (AGBL, 1996; 2001). The mean monthly relative humidity increases from a minimum value of 64% in January to a maximum of 85% in July or August (AGBL, 1996; 2001).

3.1.5 Soil and Vegetation

Soil type ranges from good, moderate to very poor agriculture lands. The north eastern, eastern and southern parts of the CAG concession have good agriculture soil whiles soil in the CAG concession is moderate to very poor agriculture lands (AGBL, 1996). The study area has been well known for its cocoa producing by migrant farmers. Bibiani is located in the major food crop producing zone in the forest belt

(AGBL, 1996). In recent times it is made up of secondary forest, upland regrowth and swamp. There are still farm lands producing mainly cocoa and food crops.

3.1.6 Geology of Study Area

The Bibiani area is underlain mainly by Precambrian metamorphic rocks of the Birimian system. This forms part of the basement complex rock of Ghana. The rocks are represented by varying thickness of folded, steeply dipping; alternating slates, phyllites, schists graywacke and argillaceous beds with tuffs and lavas. The CAG concession is located on the gold reef belt of the sewum-Antubia Bibiani Gold belt. The geology of the area is dominated by Birimian system where auriferous quartz veins occur firstly at the contact of meta-volcanic sediments of lower Birimianage and well defined meta-volcanic of upper Birimianage and secondly as reefs with the Birimianage rocks. The rock types of the Bibiani District consist of the following.

- Tarkwaian which includes sandstone, quartzite, greywacke and conglomerate.
- Upper Birimian made up of volcanic and pyroclastic rocks with some phyllites.
- Lower Birimian also made up of phyllites, tuffs, graywacke with some volcanic rocks
- Intrusive rocks such as Biotite and muscovite- biotite, granite and gneiss, hornblende granite, porphyry, pegmatite and aplite.

3.1.7 Land use

The major categories of land use identified are agriculture, industry, forestry, mining and settlement. Agricultural practice is predominately cocoa, food and tree crop farm. Mining activities may affect the ecological balance in the concession in the sense that

some of the farmlands have been converted to pits, haulage roads, waste and ore dumps.

3.2 FIELD WORK

3.2.1 Sampling points and location

Sampling points were carefully chosen in order to assess the general characteristics of ground and surface water quality in Bibiani and its environs. Ten (10) sampling points: four surface water bodies (SW1, SW2, SW3 and SW4) and six groundwater samples (GW1, GW2, GW3, GW4, GW5 and GW6) were chosen to investigate the potential source of pollution and establish the possible impact of the mining activities on the water quality.

The following factors were considered in choosing the sampling points:

- **Proximity:** This has to do with the location of the sampling points in relation to the mines (whether it is within or outside the concession of the mines). By this SW2, GW3, and GW6 were determined to be within the vicinity of the mines while SW1, SW3, SW4, GW1, GW2, GW4 and GW5 are outside mining concession.
- **Purpose:** What the water source is used for; drinking, domestic, agricultural or industrial purposes. The water bodies selected for the study are mainly used for drinking and/or domestic purposes.
- **Population:** The size of the population that depends on water from that sample point (size of the population served by the water source). Pipeline had the least population of about 70 people.

Table 3.1 – Sampling points from ten locations in Bibiani and its environs.

SAMPLING POINT	LOCATION
SW1	This is the Mesin stream at the outskirts of Bibiani town. It is about 500m away from the mines.
SW2	Kyrayaa stream at the old pumping station at Pipeline. This is within the mines.
SW3	This is the Pamunu River at Abofrem. It is outside mine concession of mining activity and processing facility. The river is about 6km away from the mines.
SW4	Tano River at Tano Odumasi. It is far from the mines about 12km from the mines.
GW1	Hand dug well at Abofrem (about 5km).
GW2	Bore hole at Abofrem (5km).
GW3	Ground water (hand dug well) at Pipeline. This is within the mines.
GW4	Groundwater (bore hole) at Tano Odumasi (12km away from the mines).
GW5	A hand dug well located at Tano Odumasi (12km away).
GW6	This is a bore hole located at the CAG Community School and is within the mines.

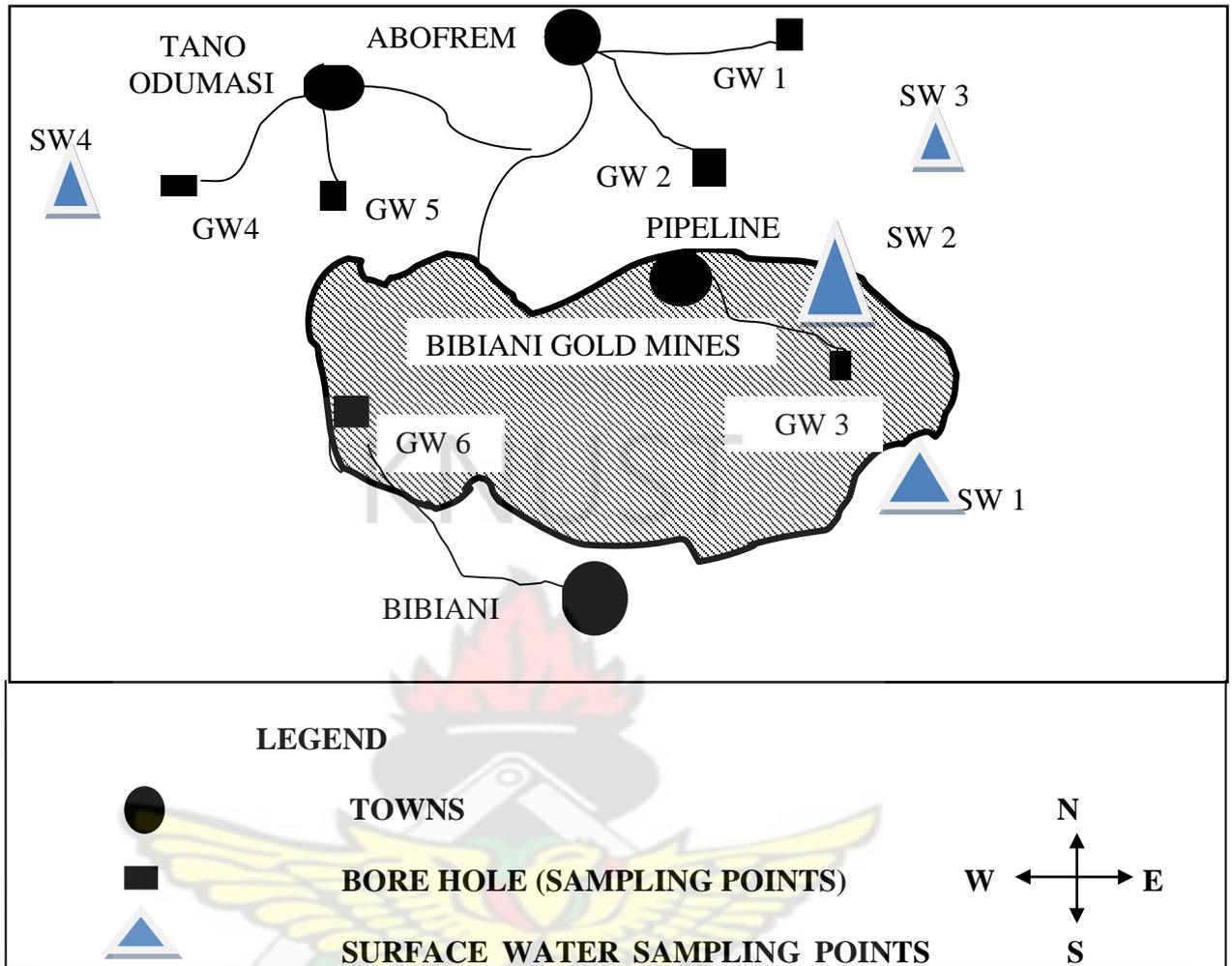


Diagram not to scale

Figure 3.2 - Diagram of the sampling area showing the sampling points.

3.2.2 Sampling and Sample preparation

Sampling was done between November, 2009 and April, 2010. Samples were collected at one month interval from ten (10) sampling points. Sampling was done for six (6) months. Six (6) samples were taken from each sampling point and a total of sixty (60) samples were collected during the study. To obtain reliable results, sampling procedures which eliminate or minimise potential contaminants were adopted. This was achieved by soaking sample containers in nitric acid solution overnight and thoroughly flushing the container with distilled water and finally

rinsing them with de-ionized water. Water sample for physico-chemical analysis were collected into 500ml plastic containers. Samples were transported (stored in an ice chest containing ice) to the laboratory and analysed within 12 hours. Samples for trace metal analysis were also collected into 500ml container but were acidified with concentrated nitric acid. This was done to preserve sample for six months if the need arose (low pH keeps the metals in solution).

In sampling surface water, bottles were held near the base and its neck was plunged downward below the surface of the water body. Bottle was turned until the neck pointed slightly upwards, the mouth being directed towards the current of the water body. Bottles were filled directly from the water body. In the case of SW 1 sampling was done with the aid of a bailer. Groundwater was sampled only after waiting for about thirty (30) minutes by which period the nearby community would have pumped much water to ensure that the water sample collected was not that contained in the column of the bore-hole but from the ground. Temperature, pH, TDS and electrical conductivity were measured on site.

3.3.1 DETERMINATION OF PHYSICAL AND CHEMICAL PARAMETERS

Physical Parameters

pH

Calibration of pH meter (3-Point Calibration - 7.00 pH, 4.00 pH and 10.01 pH)

Turn the meter on using the power key. The **CAL** key was first pressed to enter the Calibration mode. The meter's display showed a blinking 'C1'. The probe was then rinsed in distilled water, allowed to dry, and submerged into a pH **7.00** buffer solution. The solution was stirred briefly and allowed to stay in the buffer solution until a stable reading was reached. The **CAL** key was pressed again and the display

showed a blinking '7.00'. This portion of the calibration procedure was completed when the display stopped blinking and showed the 'C2' icon. The unit automatically switched to the second point of calibration. The probe was rinsed in distilled water again, allowed to dry, and submerged into a pH 4.00 buffer solution. The solution was stirred briefly and allowed to stay in the buffer solution until a stable reading was reached. The CAL key was again pressed and the display showed a blinking '4.00'. This portion of the calibration procedure was completed when the display stopped blinking and showed the 'C3' icon. The unit automatically switched to the third point of the calibration. Probe was rinsed in distilled water again, allowed to dry, and submerged into a pH 10.01 buffer solution. Stir the solution briefly and allow it to stay in the buffer solution until a stable reading was reached. CAL key was pressed and the display showed a blinking '10.01'. After the display stabilized the 3-point calibration icon appeared for the lowest, medium and highest points of calibration.

Measuring pH

Calibration of the pH meter was undertaken as described above. The pH probe was rinsed, dried and submerged in sample water. The solution was stirred briefly with the probe and allowed to stand until the display stabilized and value read.

Calibrating the Conductivity meter

The meter was first turned on using the power key. The CAL key was pressed and 'CAL' appeared flashing on the LCD. The conductivity electrode was cleaned and dried (distilled water was used for the cleaning). The electrode was then immersed in the 1413 μ S/cm calibration solution. The solution was stirred with the electrode and allow it to rest in the solution until the stabilize icon appeared. The CAL key again

was pressed and the display flashed '1413 μ S/cm'. After several seconds the 'END' icon appeared and the meter returned to the measuring mode. The LCD displayed the icon 'M', to indicate that the calibration was completed.

Measuring Total dissolved solids, conductivity and temperature

The three parameters were measured using the Sension 16 Portable Conductivity Meter. The electrode was rinsed in deionised water and placed in the sample to record TDS, conductivity and temperature values. The electrode was removed from the sample, rinsed with deionised water and placed in the next sample to also take TDS, conductivity and temperature values.

Chemical Parameters

Phosphate

A 10-ml sample cell was filled with sample. Contents of one phos Ver 3 phosphate reagent were added to the sample cell. The cell was capped and shaken gently to mix (Prepared sample). Three minutes wait period was then allowed. A second sample cell was filled with 10 ml of sample as blank. The cell was wiped of any liquid or fingerprints. The blank was placed in the cell holder and covered with the cap to "zero" it. The blank was then removed from the cell holder. Within 3 minutes after the reaction period ends, the prepared sample was placed in the cell holder, covered with the cap and the result recorded in mg/l phosphate.

Total Alkalinity

Sample cell was filled with 50ml of sample. Alkalinity test pellets were added one at a time and shaken. Pellets were added until colour changed to pink. The number of pellets added was noted. Total alkalinity was calculated using the formula:

$$\text{Total alkalinity} = (\text{Number of pellets} \times 40) - 20.$$

The value obtained was recorded as total alkalinity of the sample.

Total Hardness

Sample cell was filled with 50ml of sample. Hardness test pellets were added one at a time and shaken. Pellets were added until colour changed from violet to purple. The numbers of pellets added were noted. Total hardness was calculated using the formula below:

$$\text{Total hardness} = (\text{Number of pellets} \times 40) - 20.$$

The value obtained was recorded as total hardness of the sample.

Cyanide

A 10 –ml cell was filled to the 10ml mark with sample. The contents of one Cyani Ver3 Cyanide Reagent Powder Pillow were added and sample cell capped. Sample cell was shaken for 30 seconds. An additional 30 seconds wait period was allowed, leaving the sample cell undisturbed. The contents of Cyani Ver4 Cyanide Reagent Powder were added and sample cell capped. Sample cell was shaken for 10 seconds. This was immediately followed with the next step where the contents of one Cyani Ver 5 Cyanide Reagent Powder Pillow were immediately added. The sample cell was then capped. The sampled cell was shaken vigorously to completely dissolve the Cyani Ver Reagent Powder (if cyanide is present, a pink colour will develop which

turns blue after a few minutes) and allowed to stand for about 30 minutes. A 10-ml cell was filled to the 10ml mark with sample as the blank and placed in the cell holder to “zero” it. The prepared sample was placed in the cell holder and the results recorded in mg/l cyanide after 30 minutes.

3.3.2 DETERMINATION OF TRACE METALS

Trace metals were determined using the HACH Water Meter Model.

Copper

Copper was selected on the meter. The colour viewing tubes were rinsed several times with the water to be tested. Both tubes were filled to the bottom (5 ml) mark with the water sample. The cover of the comparator box was opened and the colour disc inserted. The cover was closed and tube placed in the top left opening of the comparator. One free Copper Reagent Powder Pillow was added into one of the tubes. The tube was stoppered and inverted several times to mix. About two minutes was allowed for the colour to develop. Development of a purple colour indicates presence of free copper. The prepared sample was inserted into the top right opening of the colour comparator. The comparator was held to a light source such as window, the sky or a lamp. The disc was rotated until a colour match was obtained. The mg/l free copper was read through the scale window and the value recorded.

Manganese

A 10-ml sample cell was filled with sample. The contents of one buffer Reagent Powder pillow, citrate type, were added to the sample cell. The cell was capped and shaken gently to mix. About two minutes wait period was allowed. A second sample cell was filled with 10 ml of sample as the blank. The blank was placed in the cell

holder and covered with the cap to “zero” the instrument. The cell was first wiped to remove any liquid or fingerprints on it before placing it into the cell holder. The blank was then removed from the cell holder. Within 2 minutes after the reaction period ended, the prepared sample was placed in the cell holder. The sample cell was covered with the cap and the resulting value recorded in mg/l manganese.

Total Iron

A 10-ml sample cell was filled with sample. The contents of one Ferro Ver Reagent Powder pillow were added to the sample cell. The cell was capped and shaken gently to mix (Prepared sample). About three minutes wait period was then allowed. A second sample cell was filled with 10 ml of sample as blank. The cell was wiped of any liquid or fingerprints. The blank was placed in the cell holder and covered with the instrument cap to “zero” it. The blank was then removed from the cell holder. Within 3 minutes after the reaction period ended, the prepared sample was placed in the cell holder. The sample cell was covered with the cap and the resulting value recorded in mg/l iron.

Arsenic

Arsenic was determined using the HACH Chart Comparator. The reaction vessel was filled with sample to the 50 ml mark. The contents of one of the reagent number 1 and reagent number 2 powder pillows were added to the reaction vessel. Cap was immediately attached with the test strip inserted to the reaction vessel and swirled to mix. Mixture was allowed to react for 20 minutes and the reaction vessel swirled twice during the reaction period. Test strip was removed and immediately the developed colour compared with the chart on the strip bottle.

3.3 STATISTICAL ANALYSIS

Microsoft excel and sigmaplot were the statistical packages used for analysing the data obtained. Analysis of variance (ANOVA) was used in comparing the means between the various parameters.

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CHAPTER FOUR

RESULTS

4.1 WATER QUALITY RESULTS

A summary of results recorded for physico-chemical parameters and trace metals analyses have been presented in figures 4.1 to 4.23. Where possible, these values have been placed alongside WHO and/or EPA (Ghana) guidelines for surface and ground waters.

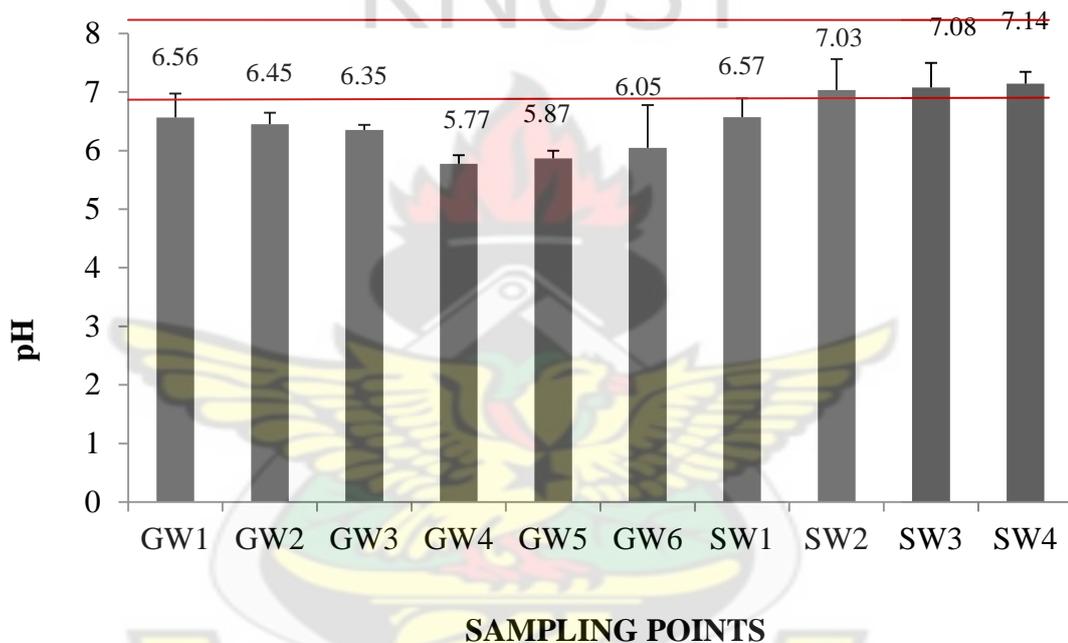


Figure 4.1 - Mean pH values recorded for ground and surface water bodies. Bars indicate standard deviation. The lines indicate the pH range stipulated by the WHO, (2004).

pH

pH values ranged from 5.77 to 7.14 pH units (Fig.4.1). This gives the general indication that the water bodies under study ranges from being weakly acidic to neutral. The highest desirable level for pH stipulated for drinking and domestic purposes is within the range of 6.5 to 8.5 (EPA, 1997; WHO, 2004) (Fig. 4.1). The pH values of surface water varied from a minimum of 6.57 to maximum of 7.14 whereas

ground water pH was from 5.77 to 6.56 (Fig.4.1). Minimum and maximum surface water pH values were recorded at SW1 (within mine concession) and SW4 (outside mine concession) and those of ground water were obtained at GW1 and GW4 both of which were outside mine concession and processing facilities. There was a significant difference between the pH values for ground and surface water bodies ($P = 0.00418$) (Table D-1) (Appendix D).

TOTAL DISSOLVED SOLIDS (TDS)

TDS concentrations for water samples ranged from 162.45 to 552.38 mg/l (mg/l). Surface water TDS concentration ranged from a minimum of 208.12 to a maximum of 552.38 mg/l (Fig.4.2).

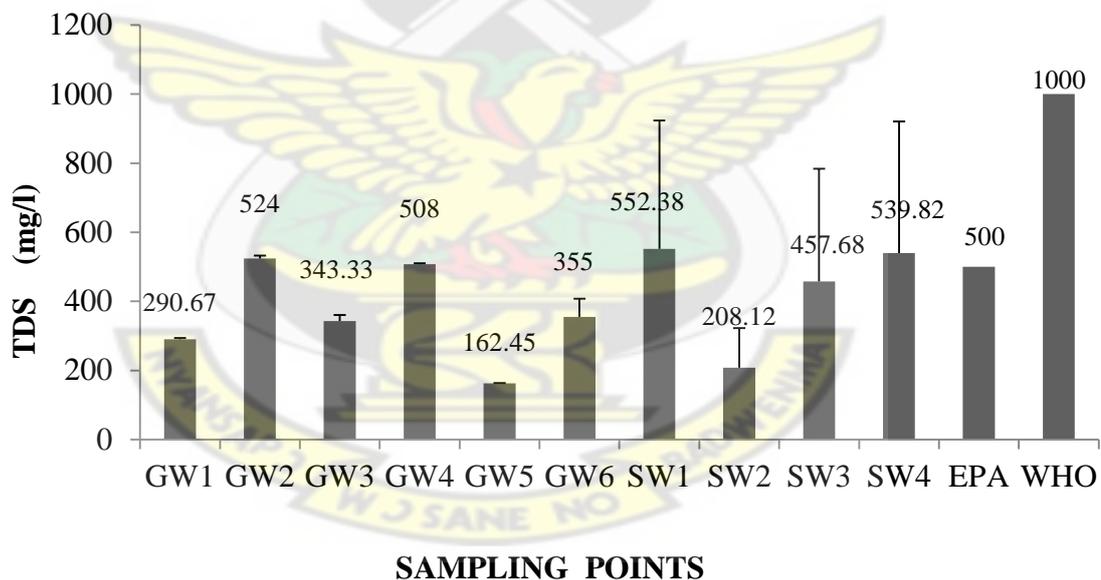


Figure 4.2 - Mean TDS values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

These TDS values were obtained at SW2 and SW1 respectively and were both within the Bibiani mines. Ground water concentration values ranged from 162.45 to 524 mg/l

(Fig.4.2). These minimum and maximum values were recorded at GW5 and GW2 which were located outside the mines. These values were within WHO guideline value of 1000 mg/l. Groundwater TDS varies significantly ($P = 0.4$) from that of surface water (Table D-2) (Appendix D).

TEMPERATURE

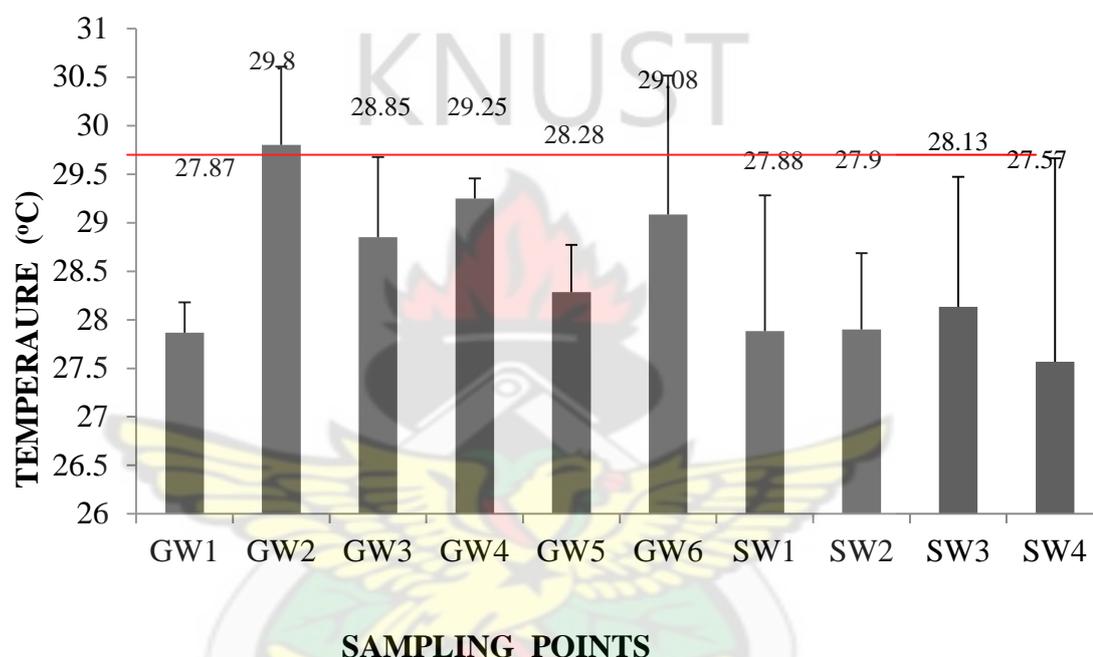


Figure 4. 3 - Mean temperature values (°C) recorded for ground and surface water bodies. Bars indicate standard deviation. The line indicates the temperature limit stipulated by EPA, Ghana (1997).

The mean temperature value of all the water samples analysed ranged from 27.57 to 29.8°C (Fig.4.3). There was no WHO guideline value to be compared with. Surface water temperature ranged from the minimum value of 27.57 to a maximum of 28.13°C (Fig. 4.3) occurring at SW4 and SW3 respectively. SW3 and SW4 were both located outside the mines. Groundwater recorded values ranging from 27.87 to 29.08°C (Fig.4.3) which occurred at GW1 and GW2 respectively.

ELECTRICAL CONDUCTIVITY (E.C)

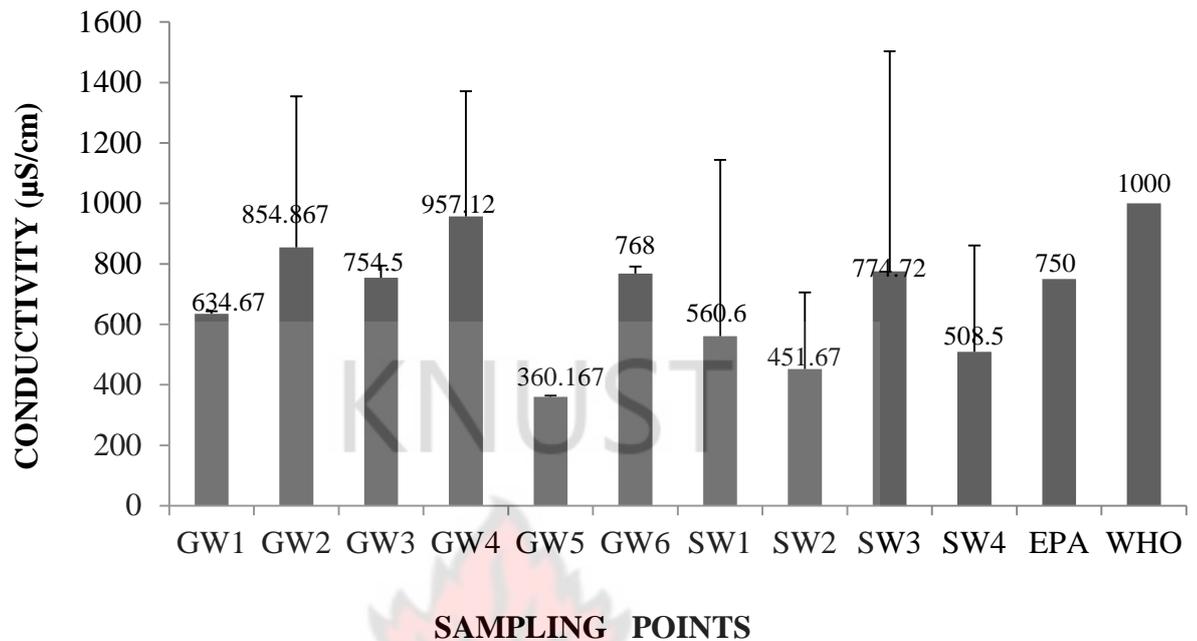


Figure 4.4 - Mean conductivity values ($\mu\text{S}/\text{cm}$) recorded for ground and surface water bodies. Bars indicate standard deviation.

Recorded E.C. values for water in the study area varied between 360.167 to 957.12 $\mu\text{S}/\text{cm}$ (Fig.4.4). These values were within the WHO guideline limit of 1000 $\mu\text{S}/\text{cm}$ (WHO, 2004) stipulated for drinking and domestic water. The conductivity values for groundwater ranged between 360.167 to 957.12 $\mu\text{S}/\text{cm}$ and were recorded at GW5 and GW4 (both outside areas of mining and mining activities) whereas surface water values were from 451.67 $\mu\text{S}/\text{cm}$ to 774.72 $\mu\text{S}/\text{cm}$ occurring at SW2 (within mines) and SW3 (outside mines) (Fig.4.4). The conductivity variations (Table D-4) (Appendix D) between ground and surface water bodies were statistically insignificant ($P = 0.25$).

PHOSPHATE

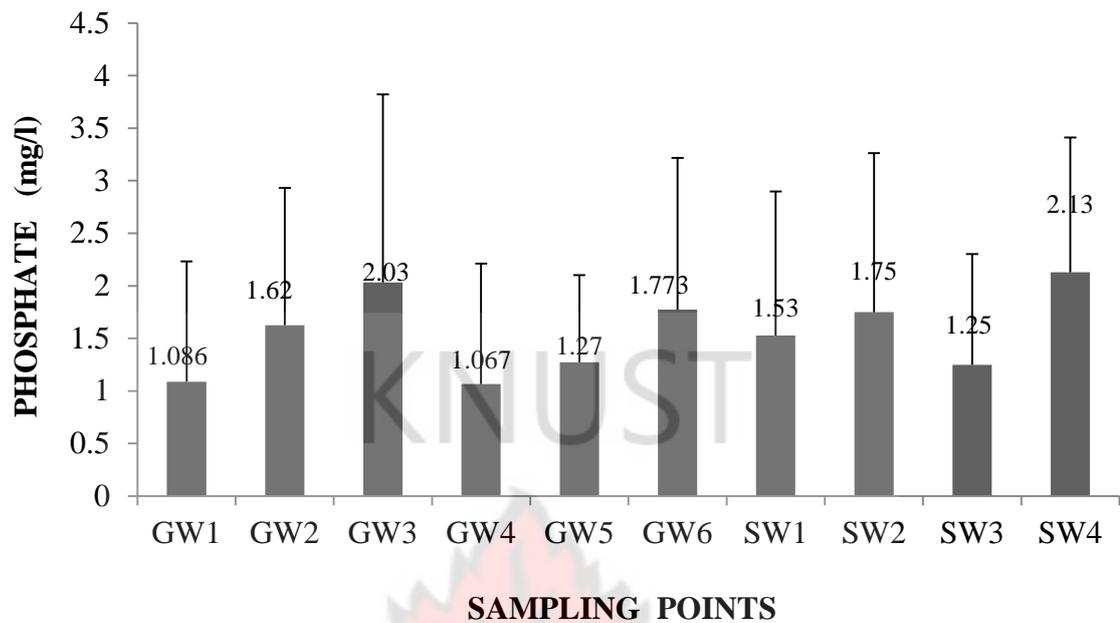


Figure 4.5 - Mean phosphate values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

Phosphate concentrations for the water samples varied between 1.067 and 2.13 mg/l (Fig.4.5). Phosphate concentrations for groundwater ranged from 1.067 to 2.03 mg/l (Fig.4.5). Surface water concentrations from the study area ranged from 1.25 to 2.13 mg/l (Fig.4.5). The recorded phosphate concentrations (Table D – 5 of Appendix D) for ground and surface water bodies were not significantly different ($P = 0.47$).

TOTAL ALKALINITY

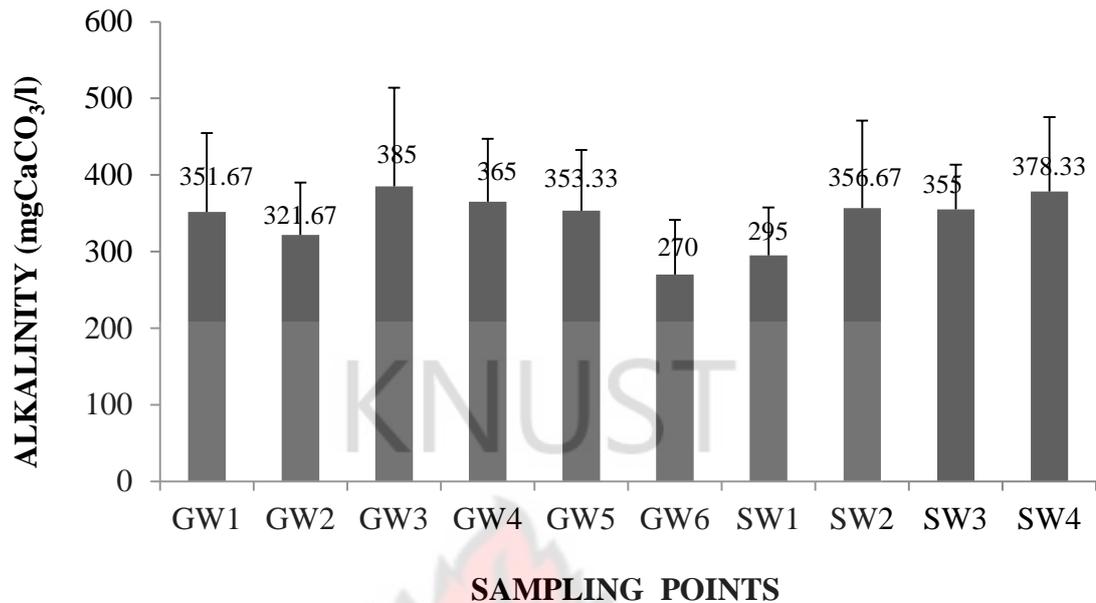


Figure 4.6 - Mean alkalinity values (mgCaCO₃/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

Alkalinity concentration ranged from 270 to 385 mgCaCO₃/l (Fig.4.6) for both water sources. Recorded alkalinity values for surface water bodies ranged from 295 to 378.33 mgCaCO₃/l (Fig.4.6). Groundwater concentrations were from 270 to 385 mgCaCO₃/l (Fig.4.6). There was no guideline limit to be compared with.

Surface water minimum and maximum alkaline concentrations occurred at SW1 (within Bibiani Gold mines) and SW4 (outside the mines) whereas those of groundwater were recorded at GW6 and GW3 (both located within mine concession and processing facilities). Groundwater alkalinity values did not differ significantly from that of surface water sources ($P = 0.84$) (Table D-6) (Appendix D).

TOTAL HARDNESS

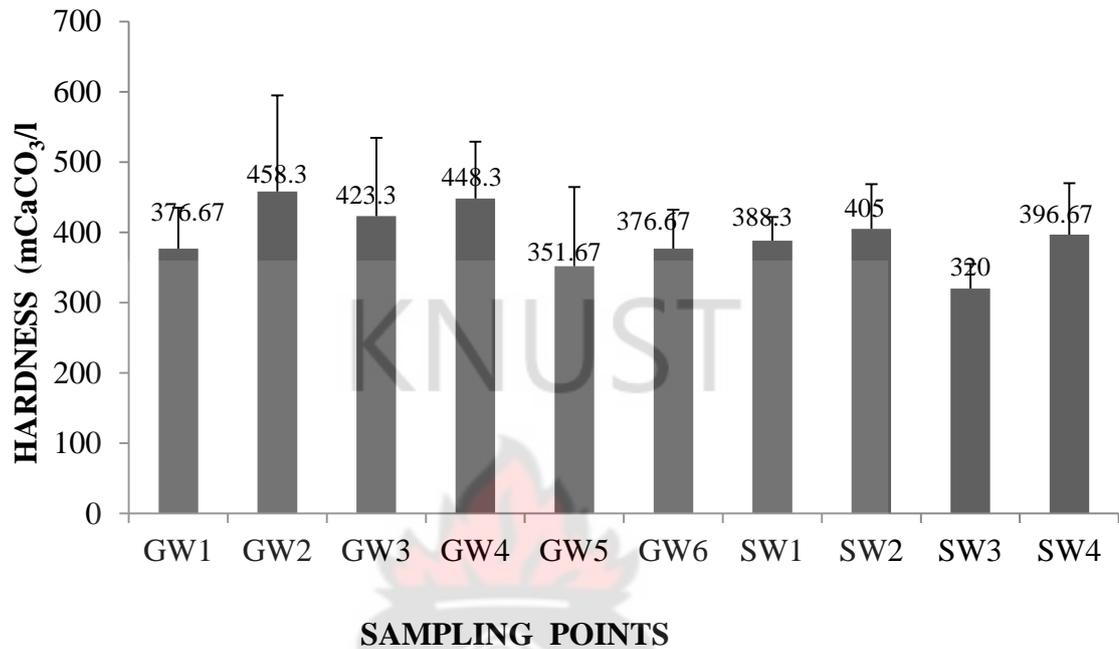


Figure 4.7 - Mean hardness values (mgCaCO₃/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

Total hardness concentrations recorded during the study ranged from 320 to 458.3 mgCaCO₃/l (Fig.4.7). The hardness value for groundwater ranged between 351.67 to 458.3 mgCaCO₃/l whereas surface water values were from 320 to 405 mgCaCO₃/l (Fig. 4.7)

ARSENIC

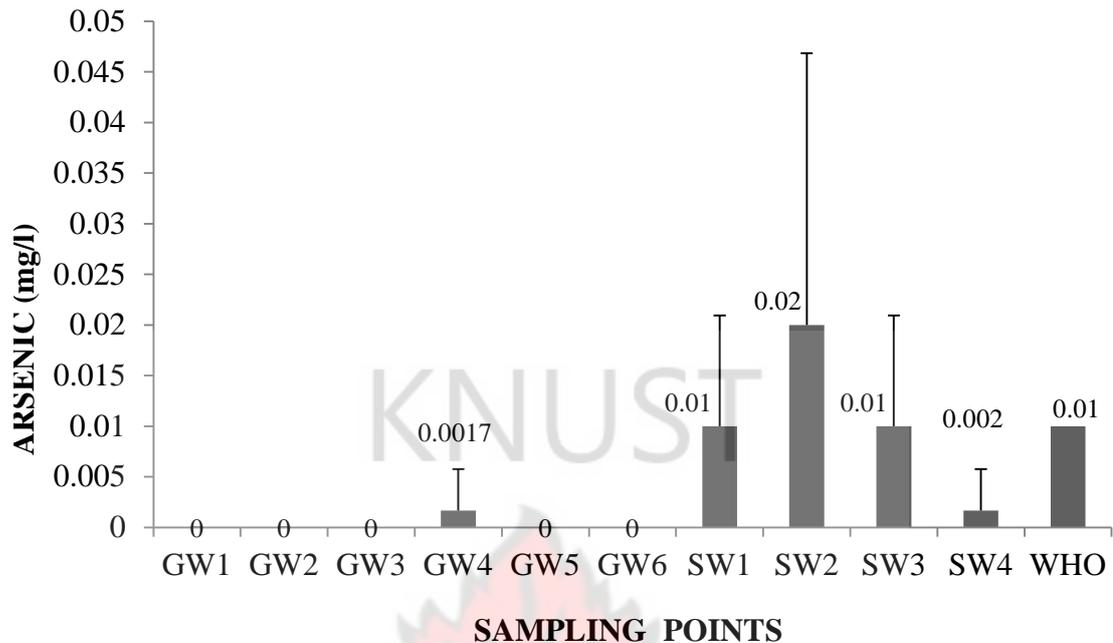


Figure 4.8 - Mean arsenic values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

As concentration for the water samples in Bibiani ranges from values < 0.001 to 0.02 mg/l (Fig. 4.8). Surface water As concentration ranged from 0.002 to 0.02 mg/l whereas ground water recorded concentrations from values < 0.001 to 0.0017 mg/l (Fig. 4.8). Minimum and maximum surface water As concentrations were recorded at SW4 (outside the mines) and SW2 (within the mines) while the highest groundwater As concentration was recorded at GW4 which was not within concession of the mines. The concentration of As is generally very low (below detection limit) almost throughout the study. However at SW2 (located within mine concession and processing facilities), As concentrations exceeded the WHO guideline limit of 0.01 mg/l (Fig. 4.8). The concentration of As in groundwater varied significantly from that of surface water ($P = 0.009$) (Table D-8) (Appendix D).

TOTAL CYANIDE

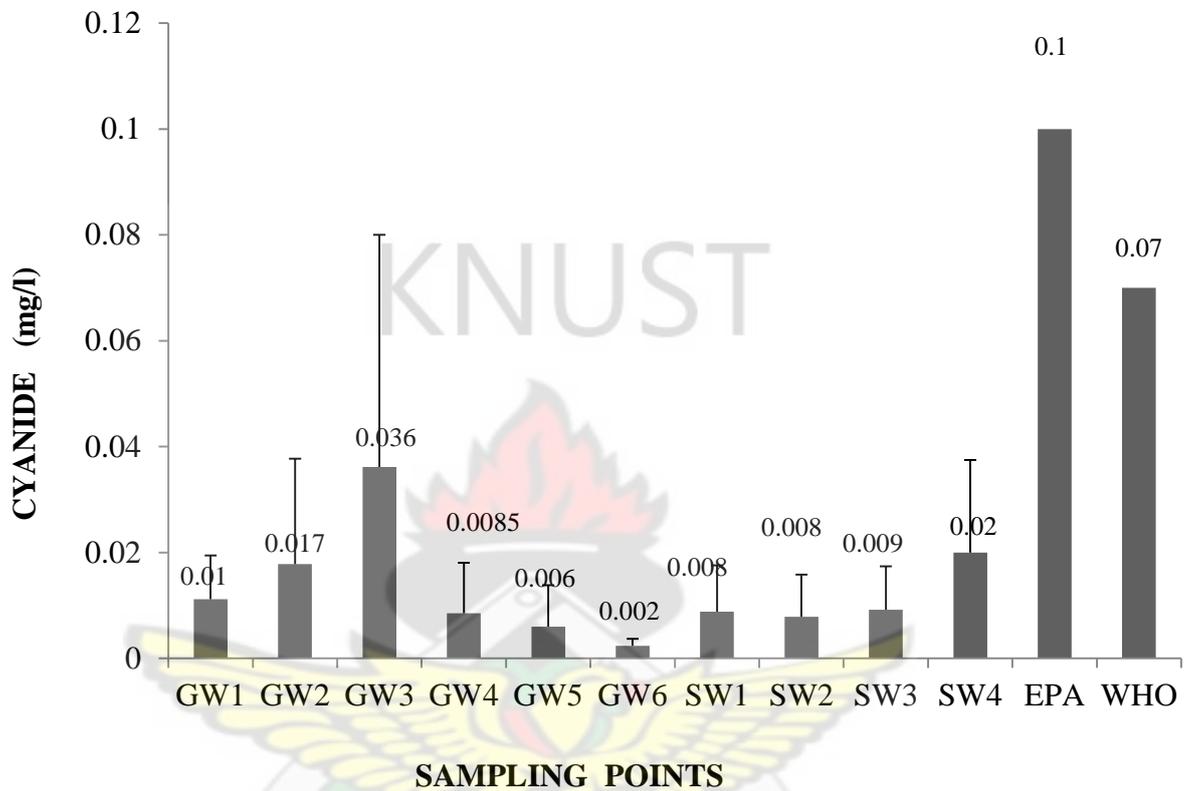


Figure 4.9 - Mean cyanide values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

CN concentrations for the water samples under study varied between 0.002 and 0.036 mg/l (Fig.4.9). This falls within the WHO and EPA guideline limit of 0.07 and 0.1 mg/l (WHO, 2004; EPA, 1997) (Fig.4.9). The level of concentration of CN in groundwater ranged from 0.002 to 0.036 mg/l while surface water recorded values from 0.008 to 0.02 mg/l. These values were recorded at GW6 and GW3 for groundwater; SW1, SW2 and SW4 for surface water. The sampling points GW6, GW3, SW1, and SW2 are located within the mines whereas SW4 is not. Cyanide levels in surface water

bodies showed significant variations ($P = 0.7$) from that of groundwater (Table D-9) (Appendix D).

MANGANESE

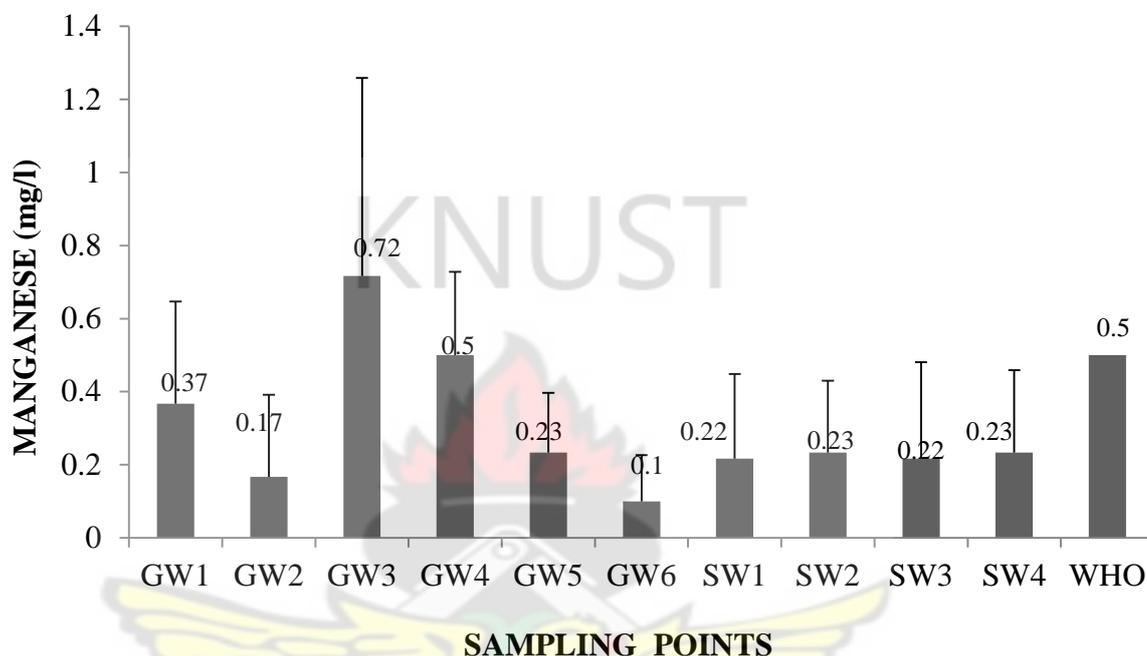


Figure 4.10 - Mean manganese values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

Values recorded for water samples were between 0.1 and 0.72 mg/l. Groundwater Mn concentration ranged from 0.1 to 0.72 mg/l at GW6 and GW3 (Fig.4.10). Mn concentrations for surface water were between 0.22 and 0.23 mg/l occurring at the sampling points SW1 and SW3 for the minimum and SW2 and SW4 for maximum (Fig.4.10). These concentrations fall within the WHO guideline limit of 0.5mg/l. However at GW3 which is located within the Bibiani mines Mn concentration exceeded the WHO guideline limit of 0.5 mg/l stipulated for drinking and domestic purposes. Variations between Mn concentrations in surface and ground water samples were statistically insignificant ($P = 0.3$) (Table D-10) (Appendix D).

TOTAL IRON

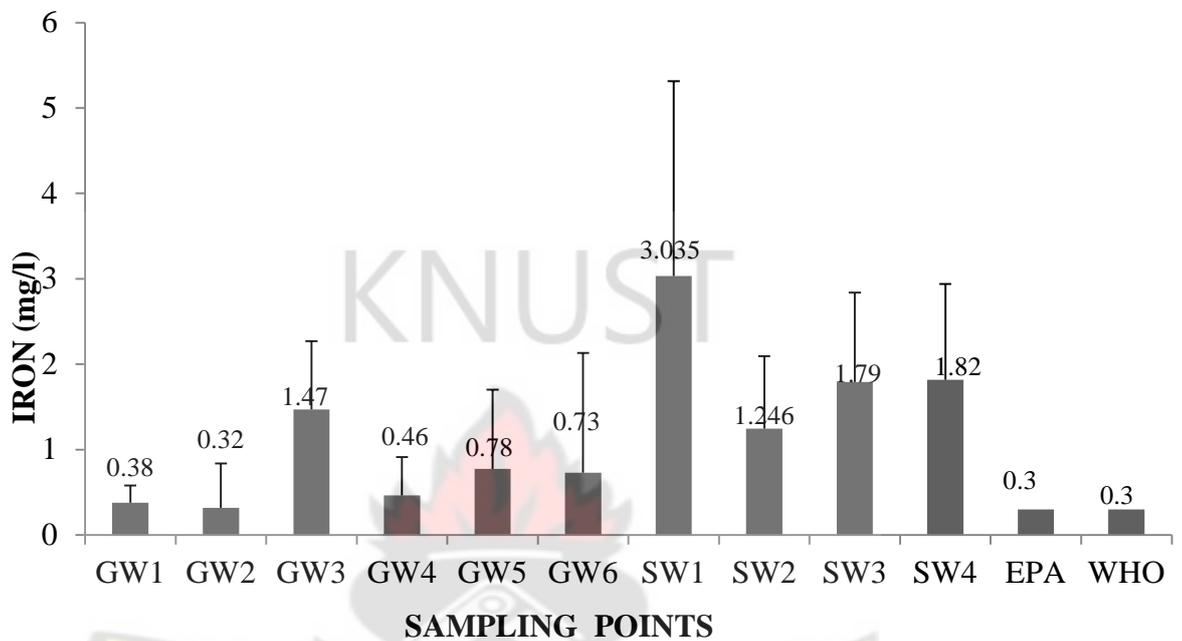


Figure 4.11 - Mean iron values (mg/l) recorded for ground and surface water bodies. Bars indicate standard deviation.

Iron (Fe) values for both ground and surface waters ranged from 0.32 to 3.04 mg/l (Fig.4.11). Concentrations obtained for groundwater varied between 0.32 and 1.47 mg/l occurring at GW2 (located outside the mines) and GW3 (located within the mines) (Fig.4.11)). Fe concentrations recorded for surface water sources ranges from 1.246 to 3.035 mg/l at the sampling points SW2 and SW1 both of which are located within the Bibiani mines (Fig.4.11). Fe concentrations recorded at all the sampling points are clearly in excess of the WHO and EPA guideline limit of 0.3mg/l (WHO, 2004; EPA, 1997) (Fig4.11). From Table D -11 (Appendix D), the variations of Fe concentrations between ground and surface water bodies were statistically significant ($P = 0.008$).

COPPER

Throughout the sampling period Cu levels were below the detectable limit (i.e. < 0.001) of the equipment used.

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4.3 DESCRIPTION OF CORRELATION MATRIX

There was a strong negative correlation ($r = -0.899$) with significance between TDS concentration and temperature in groundwater samples (Table 4.1). A weak positive correlation ($r = 0.124$) was however observed between these variables in surface water samples (Table 4.2). Alkalinity and phosphate concentrations exhibited a strong negative correlation with significance ($r = -0.962$) in surface water samples (Table 4.2). In groundwater samples the two variables exhibited a weak negative correlation ($r = -0.277$) (Table 4.1).

The correlation matrix (Table 4.1) showed a significant correlation ($r = -0.866$) for arsenic and alkalinity concentrations in groundwater samples. Arsenic and alkalinity concentrations in surface water exhibited a moderate positive correlation with no significance ($r = 0.333$) (Table 4.2).

Mn and phosphate concentration in surface water correlated positively with significance ($r = 0.871$) (Table 4.2) implying both variables increased together. The two variables also exhibited a strong positive correlation ($r = 0.729$) in groundwater (Table 4.1). Mn and alkalinity had a strong negative correlation also with significance ($r = -0.93$) in surface water samples (Table 4.2). They however showed a weak positive correlation ($r = 0.207$) in groundwater (Table 4.1).

The correlation matrix (Table 4.1) showed that Fe concentration in groundwater had a significantly positive correlation ($r = 0.906$) with electrical conductivity. The opposite was however observed in surface water samples where conductivity and Fe concentration had a strong negative correlation with significance ($r = -0.864$).

CHAPTER FIVE

DISCUSSION

5.1 WATER QUALITY

pH: Surface water pH values fell within the 6 – 9 pH range of natural waters (Stumm and Morgan, 1981). With the exception of SW1, all the surface water bodies can be described as being neutral (pH range 7.03-7.14). These pH values also fell within the range of 6.5 to 8.5 stipulated for drinking and domestic purposes by the WHO, (2004a). The EU also sets protection limits of pH from 6 to 9 for fisheries and aquatic life (Chapman, 1996). The pH obtained in the surface water bodies were within these ranges. Based on these guidelines, the pH of surface water sources from Bibiani would not adversely affect its suitability for drinking, domestic and recreational purposes as well as aquatic ecosystem.

Groundwater pH recordings were generally low except at GW 1 which recorded a pH value of 6.56 (Fig.4.1), and which is within the WHO limit of 6.5 to 8.5 (WHO, 2004a). The highest desirable level for pH stipulated for drinking and domestic purposes is within the range of 6.5 to 8.5 (EPA, 1997; WHO, 2004a). Groundwater pH was below this limit suggesting possible acidity. The low pH in groundwater may be due to natural geochemical and biochemical processes within the aquifers (Edwards, 1981). This is due to the fact that, the presence of sulphides and carbonaceous matter in the ore formations means that natural geochemical and biochemical degradation (oxidation) of these rocks may occur, when in contact with oxygen gas containing water, leading to increased hydrogen ion activity in the waters with which they are in contact.

Bio-oxidation of sulphur-containing materials may also take place in tailing dumps in abandoned mine areas and hydrogen ions migrate into the aqueous environment and, thereby, increase the acidity of groundwater.

Acidity in some groundwater sources in Bibiani may therefore be attributed either to mining activity (seepage of effluent discharge or old tailing dams or to natural geochemical and biochemical processes within the aquifers especially at sampling points outside mining concession, activities and processing facilities (GW 1, GW 2, GW 4, and GW 5). Acidity gives sour taste to water. It is for this reason of taste that the EPA, (1997) and WHO, (2004a) limit the pH range for water potability from 6.5 to 8.5. Consequently, from Fig.4.1, pH values for most of the groundwater sources in the study area were lower than the WHO and EPA limits which suggests a potential taste problem. There is a significant difference between the pH values for ground and surface water bodies ($P = 0.00418$). The differences in pH between ground and surface waters may be attributed to the influence of aquifer materials on the chemistry of the ground waters. This is due to the fact that the presence of sulphides and carbonaceous matter in the ore formations means natural geochemical and biochemical degradation (oxidation) of these rocks may occur.

Total Dissolved Solids (TDS): TDS variations between ground and surface water bodies were statistically different from each other ($P = 0.4$) (Table D-2). TDS values recorded for ground and surface water sources were within the WHO limit of 1,000 mg/l. This indicates that the water bodies in the study area are generally fresh (WHO, 2003). Davis and DeWiest, (1966), regard water as fresh if the TDS value is less than 1,000 mg/l. According to Karikari and Ansa-Asare (2006), the palatability of water with TDS level less than 600 mg/l is generally considered to be good whereas water

with TDS above 1,200 mg/l becomes increasingly unpalatable. The highest groundwater TDS concentration was recorded at GW2. Since the sampling point GW2 is outside the mining and processing facilities, it is possible seepage of effluent discharges, as well as agriculture and domestic waste substances might have contributed to the high TDS values recorded. There was a strong negative correlation ($r = - 0.899$) with significance between TDS concentration and temperature in groundwater samples (Table 4.1). This implies as TDS concentration increased temperature decreased and vice versa. A weak positive correlation ($r = 0.124$) was however observed between these variables in surface water samples (Table 4.2).

Temperature: There was a significant difference in temperature variation between water bodies in the study. Minimum and maximum temperature values for ground and surface water bodies were both recorded at sampling points outside concession of the mines and processing activities and facilities. The EPA, Ghana (1997), stipulates that water for drinking and domestic purposes should have a temperature not exceeding 30 °C. The temperature values recorded for water in the study area were within the EPA limit of 30°C. Thus suggesting the quality of water in Bibiani with respect to temperature may be suitable for drinking as well as for domestic uses.

Electrical Conductivity: The level of ion concentrations in groundwater does not differ from that of surface water. This was exhibited in Table D-4 (Appendix D) where the variations of conductivity between ground and surface water bodies were statistically insignificant ($P = 0.25$). Conductivity values fell within the WHO, (2004) guideline limit of 1,000 $\mu\text{S}/\text{cm}$ for drinking water. Compared to the other sampling points, groundwater from GW2 and GW4 (Fig.4.4) recorded high conductivity values.

Since these sampling points are outside the mining and processing facilities, it is possible seepage of effluent discharges, as well as agriculture and domestic waste substances might have contributed to the high conductivity values recorded. It could also be due to the weathering of sulphide-bearing rocks greatly facilitated by mining, accounting for the elevated ion concentrations in GW2 and GW4 (Fig.4.4) which is located outside mining concession and processing facilities.

At sampling point SW3, a high conductivity value was recorded. The location of SW3 is far from the mines (outside mine facilities) and so the high value recorded might be due to domestic effluent discharges. Surface and agricultural run-offs might have contributed to the increased concentration of ions in the surface water. Since all the conductivity values fell within the WHO, (2004a) guideline limit of 1,000 $\mu\text{S}/\text{cm}$ for drinking water, it could be concluded that no adverse health effects associated with the electrical conductivity of water bodies in Bibiani and its environs were expected. Thus, the parameter does not give cause for concern and it makes the water sources suitable for direct domestic use.

Phosphate: There was no WHO guideline value to compare with the recorded values. However, comparing these values with the natural phosphate range of 0.005 to 0.020 mg/l (Chapman, 1992), it could be concluded that groundwater phosphate concentrations were high. This might be as a result of eroded materials from waste rock dumpsites and old tailings coming in contact with the water table via seepage. For sampling points not close to mining activities and processing facilities, the high phosphate concentrations might be as a result of detergents from domestic activities that infiltrate the topsoil. Phosphate is the limiting nutrient for algal growth and therefore controls the primary productivity of a surface water body. In most natural

waters, phosphate ranges from 0.005 to 0.020 mg/l (Chapman, 1992). In some pristine waters concentrations as low as 0.001 mg/l may be found. High concentrations of phosphate could indicate the presence of pollution and are largely responsible for eutrophic conditions.

The high phosphate loads that occurred in surface water at the sampling points could be attributed to industrial (inflows from eroded materials carried from waste rock dumpsite and old tailing dams) and domestic activities (e.g. detergents from washing and bathing and refuse). It could thus be inferred with respect to this parameter that the water sources in Bibiani might not be suitable for drinking and domestic purposes. The recorded phosphate concentrations for ground and surface water bodies were not significantly different ($P = 0.4723$). This suggests that the levels of nutrient loadings (surface runoff) received by surface water bodies do not differ from that received by ground water bodies (infiltration and seepage).

Total Alkalinity: Groundwater alkalinity values did not differ significantly ($P = 0.84$) from that of surface water sources (Table D-6). Alkalinity is a measure of the presence of bicarbonate, carbonate or hydroxide constituents. Concentrations less than 1,000 mgCaCO₃/l are desirable for domestic water supplies (Anon., 2006). There was no WHO/EPA guideline to compare with the recorded values from the study area. However, the range of 300 to 400 mgCaCO₃/l has been recommended for drinking water (Anon., 2006). Alkaline concentration recorded from the study area for most of the ground and surface waters fell within the 300 to 400 mgCaCO₃/l range. It can thus be inferred that the water sources in Bibiani per this parameter are suitable for drinking purposes. A minimum level of alkalinity is however desirable because it is considered a “buffer” that prevents large variations in pH. Alkalinity is not

detrimental to humans. Moderately alkaline water (less than 350 mgCaCO₃/l) in combination with hardness forms a layer of calcium or magnesium carbonate that tends to inhibit corrosion of metal piping. Many public water utilities employ this practice to reduce pipe corrosion and to increase the useful life of the water distribution system. High alkalinity has adverse effects on plumbing systems, especially on hot water systems (water heaters, boilers, heat exchangers, etc.) where excessive scale reduces the transfer of heat to the water, thereby resulting in greater power consumption and increased costs (Anon., 2006). Alkalinity and phosphate concentrations exhibited a strong negative correlation with significance ($r = - 0.962$) in surface water samples (Table 4.2). In groundwater samples the two variables exhibited a weak negative correlation ($r = - 0.277$) (Table 4.1).

Total Hardness: Hardness is an important criterion for ascertaining the suitability of water for domestic, drinking and many industrial uses (Karanth, 1994). In this study the hardness criterion was used for determining the usability of the water supplies under study for domestic and drinking purposes. Hardness of water for domestic use relates mainly to its reaction with soap. Since soap is precipitated principally by Ca²⁺ and Mg²⁺, hardness is defined as the sum of the concentrations of these ions expressed as mg/l of CaCO₃. Water with hardness in the range 0–60 mgCaCO₃/l, 61 – 120 mgCaCO₃/l, 121 – 180mgCaCO₃/l and > 180 mgCaCO₃/l are regarded as soft, moderately hard, hard and very hard, respectively (Hem, 1970; The British Columbia Groundwater Association, 2007).

Surface water from the study recorded varying levels of hardness between 320 to 465 mgCaCO₃/l (Fig.4.7). The WHO (2004a) recommends 500 mgCaCO₃/l as the guideline value for surface water. Comparing the recorded values with the WHO (2004a) value of 500 mgCaCO₃/l surface water bodies in Bibiani could generally be described as safe. Thus surface waters in Bibiani and its environs can be used for domestic purposes without any human health concerns.

There was no WHO /EPA guideline to compare with groundwater values obtained from the study. However, comparing the recorded values with The British Columbia Groundwater Association, (2007) and Hem, (1970) guidelines it could be deduced that groundwater in Bibiani were generally very hard. This might have resulted from effluent discharges from the mines that seeped underground. It could also be attributed to weathering of limestone, sedimentary rock and calcium bearing minerals largely facilitated by mining activities. Other sources such as excessive application of lime to the soil in agricultural areas might have contributed to the high hardness values in this study. Contrary to the negative perception of domestic usage of hard water, studies have shown that coronary heart diseases are less common in areas of hard water than in areas of soft water (Crawford, 1972). Thus, although not detrimental to health; hard water reduces the ability of soap to produce a lather (retards the cleaning action of soaps and detergents), and causes scale (white deposit) formation in pipes and on plumbing fixtures. When hard water is heated, hard scales are deposited on heating coils and cooking utensils. Groundwater hardness level did not differ from those of surface water since no significant difference in hardness level between the water ($P = 0.3$) (Table D-7) was observed.

Arsenic (As): The variations of As concentrations between ground and surface waters were statistically significant ($P = 0.009$) (Table D-8). As was detected in all surface water bodies in the study at concentrations within the WHO (2004a) guideline of 0.01 mg/l. However at SW2, As concentrations were slightly in excess of the WHO (2004a) guideline of 0.01 mg/l (Fig. 4.8). This could be due to mineral dissolutions such as pyrite oxidation. The generally low As concentrations detected in surface water in Bibiani, suggests As could poses limited potential physiological problem to the use of these water bodies for drinking purposes. The very low concentrations in groundwater, in spite of the high presence of pyrite and arsenopyrite in association with the gold ore, suggests there might be a level of co-precipitation of As with ferric oxyhydroxide in the creeks before possible infiltration into the aquifer (Kortatsi, 2006). Since As levels in groundwater differed significantly from that of surface water, it could be deduced that surface water bodies were more affected by As contamination.

As is a known carcinogen (an agent producing and exciting cancer) and a toxin (Smedley *et al.*, 1995). Skin cancer has been associated with long-term, low-level exposure to arsenic through drinking water (Kortatsi, 2006). Thus, people living in communities where significant As concentrations were detected could, potentially, be at risk of diseases associated with long-term low-level As ingestion. However no morbidity cases would be expected where As concentration in drinking water remains less than 0.01 mg/l. It is important therefore to constantly monitor drinking water in the area in order to forestall any physiological problems that may arise due to unexpected increases in arsenic concentration. The correlation matrix (Table 4.1) showed a significant negative correlation ($r = - 0.866$) for arsenic and alkalinity

concentrations in groundwater samples (thus arsenic concentration increased with a decrease in alkaline concentration and vice versa) with high arsenic concentrations occurring at SW2 (located within mine concession) (Fig 4.8). Arsenic and alkalinity concentrations in surface water exhibited a positive correlation with no significance ($r = 0.333$) (Table 4.2).

Cyanide (CN): CN was detected in all the water bodies in Bibiani (Fig.4.9). The levels detected were however, less than the 0.1 and 0.07 mg/l guideline limits set by the WHO, (2004a) and EPA, (1997) respectively indicating low CN contamination levels (Fig.4.9). The low levels detected provide a useful early warning of potential problems. Chronic low exposure to hydrogen cyanide causes neurological, respiratory, cardiovascular and thyroid effects (Blanc *et al.*, 1985; Chandra *et al.*, 1980; El Ghawabi *et al.*, 1975). It is therefore important to constantly monitor CN levels in water bodies (drinking water in particular) in Bibiani and its environs. CN variations between ground and surface water bodies were statistically insignificant ($P = 0.7$) (Table D-9). This means the level of CN contamination in groundwater did not vary significantly from that of surface water.

Manganese (Mn): Mn was detected in all water samples. Variations in Mn concentrations between surface and ground water samples were statistically insignificant ($P = 0.3$) (Table D-10). This implies the rate at which Mn contaminates groundwater does not differ significantly from that of surface water. Surface water bodies investigated in this study had Mn concentrations below the WHO guideline value of 0.5 mg/l (WHO, 2004a) stipulated for drinking and domestic purposes (Fig.4.10).

Ground water sources sampled in the study area also recorded Mn concentrations within WHO guideline (Fig.4.10). GW3 was most affected by Mn contamination with a recorded value of 0.72 mg/l being in excess of the WHO guideline of 0.5 mg/l (Fig.4.10). The high Mn concentration level detected at GW3 located within concession of the mines could be attributed to anthropogenic sources such as effluent discharges and acid-mine drainage from mining activities. It could also be as a result of natural geochemical and biochemical processes such as weathering of manganese bearing minerals and rocks within the aquifers. Mn is very abundant in rocks and soil typically in the form of manganese oxides and hydroxides in association with other metallic cations. At low and neutral pH values, the predominant dissolved form of manganese is as the divalent cation, Mn^{2+} (Momade and Tay, 2006). Mn concentrations greater than 0.1 mg/l impart an undesirable taste to drinking water. At about 0.2 mg/l Mn concentration, Mn will form coatings on piping that may later tear off as a black precipitate. Concentrations of the order of 0.1 to 1.0 mg/l are common, although in low pH waters higher concentrations can occur (U.S. Environmental Protection Agency, 1980). It is important to state that the high or low Mn levels detected in the water samples does not pose human health problems. These concentrations have the ability of discolouring water, (i.e. high Mn concentrations results in black colouration, which leads to the staining of laundry and sanitary wares (WHO, 1996).

Mn and phosphate concentrations in surface water samples correlated positively with significance ($r = 0.871$) (Table 4.2) implying both variables increased together. The two variables also exhibited a strong positive correlation ($r = 0.729$) in groundwater samples (Table 4.1). Mn and alkalinity had a strong negative correlation also with

significance ($r = - 0.93$) in surface water samples (Table 4.2). Thus one variable tends to decrease while the other increases. They however showed a weak positive correlation ($r = 0.207$) in groundwater samples (Table 4.1).

Iron (Fe): From Table D -11, the variations of Fe concentrations between ground and surface water bodies were statistically significant at $P = 0.008$. Surface water bodies in Bibiani were more contamination by iron than groundwater bodies (Fig.4.11). Fe concentration in the water samples exceeded the 0.3 mg/l guideline set by the WHO, (2004a) and EPA, (1997). The major minerals found in igneous rocks; amphiboles, ferromagnesian micas, ferrous sulphide (FeS), ferric sulphide or iron pyrite (FeS₂), and magnetite (Fe₃O₄) form the natural sources of iron in ground water (Todd, 1980). According to the geology of the Bibiani area, rock mineral types present include arsenopyrites (FeAsS), magnetite, pyrite (FeS₂), (PbS) and iron-rich carbonates. The presence of these minerals in the study area is major natural sources of iron in water. The high Fe concentrations found in surface water samples compared to that of groundwater (Fig.4.11) might be suggestive of the mineral-water interactions and oxidation-reduction reactions taking place in such systems. Mine activity possibly resulting to effluent discharges as well as leachate from waste rock dump and tailing dams might also have contributed to the high Fe levels in surface water.

The high levels of Fe in the surface waters indicate possible contamination from inflows of waste rock dumpsites and old tailing dams. The presence of high Fe concentrations in water like Mn, does not pose human health problems. They however have the ability of discolouring water, i.e. high Fe concentrations results in reddish

brown colouration, which also result in the staining of laundry and sanitary wares (WHO, 1996).

The correlation matrix (Table 4.1) showed that Fe concentration in groundwater had a significantly positive correlation ($r = 0.906$) with electrical conductivity. This suggests both variables increased together. The opposite was however observed in surface water samples where conductivity and Fe concentration had a strong negative correlation with significance ($r = - 0.864$) (Table 4.2); implying one variable tends to decrease while the other increases. High Fe concentration occurred at SW1. Concentration of Fe at sampling points within the mines were higher than those outside the mine concession (Fig. 4.11).

Copper (cu): Levels of Cu in ground and surface water sources investigated in Bibiani and its surrounding communities were all below the WHO threshold of 1.00 mg/l (WHO, 2004a) (Table C– 12 and APPENDICE A and B). This suggests that any adverse health effects arising from domestic use of the water are not expected as far as this parameter is concerned.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

Groundwater had lower pH ranging from 5.77 to 6.56 pH units than surface water ranging from 6.57 to 7.14. The differences in pH between ground and surface waters may be due to natural geochemical and biochemical processes within the aquifers. Ground waters had higher concentrations of dissolved ions (ranging from 360.167 to 957.12 $\mu\text{S/cm}$) and so more mineralized than surface waters (ranging from 451.67 to 774.72 $\mu\text{S/cm}$).

Mining related contaminants detected were As, CN, Mn and Fe. Groundwater in the study area was established to be contaminated by Mn and Fe. Mn contamination may be due to natural geochemical and biochemical processes within the aquifer. Anthropogenic sources such as effluent discharge and acid-mine drainage from mining activities might also have contributed to the high Mn concentration in groundwater. High Fe concentrations may also be attributed to mineral water and oxidation – reduction reactions taking place in the system. Effluent discharges as well as leachate from waste rock dumpsite and tailing dams may also contribute to the excessive Fe level in groundwater.

Surface water bodies were found to be contaminated by As and Fe. As contamination may be due to the high presence of arsenopyrite in association with the gold ore. Fe levels in all the surface water bodies exceeded WHO/EPA guidelines. Fe contamination in the surface water like groundwater may also be attributed to mineral-water and oxidation – reduction reactions taking place in the system. Inflows

from waste rock dumpsites and old tailing dams might also have contributed to the increased Fe level.

Relationships between trace metals and chemical and physical parameters in groundwater showed that As had a strong negative correlation with alkalinity ($r = -0.866$) and Fe also had a strong positive correlation with electrical conductivity ($r = 0.906$). In surface water, Mn showed a strong positive correlation with phosphate ($r = 0.871$) but correlated negatively with alkalinity ($r = -0.93$). Fe also correlated negatively with electrical conductivity ($r = -0.864$) in surface water. Compared to WHO / EPA guideline, few of the ground and surface water supplies had one or more trace metal (Fe, As and Mn) levels outside acceptable limits set for drinking water. Most of them however have levels safe for human consumption.

6.2 RECOMMENDATIONS

Water resources in Bibiani and its environs are used for a variety of purposes such as domestic, drinking, fishing and irrigation without prior treatment. For sustainable management of water resources, the Bibiani Anhwiaso Bekwai District Assembly should ensure that water resources are monitored constantly (monthly monitoring) to prevent pollution and consequent transmission of water-related diseases.

Any future study on water sources in the area should look more closely at whether the quality is affected or influenced by seasonal variations; and location in relation to the mines (i.e. within and outside concession of the mines).

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APPENDIX A: FIELD MEASURED PARAMETERS

Table A-1: FIELD MEASURED PARAMETERS IN NOVEMBER, 2009

PARAMETER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	6.77	6.48	6.48	5.88	5.93	5.31	6.58	7.09	7.00	7.45
TDS (mg/l)	292	512	326	511	163.1	351	107.7	107.7	695	964
Temp. (°C)	28.3	30.7	28.6	29.1	29.0	27.8	27.1	29.1	27.5	27.6
E.C. (µS/cm)	643	1163	720	1126	366	789	235	221	1530	212
Phos. (mg/l)	3.30	2.85		1.14	0.41	2.52	0.29	0.38	0.30	0.88
Alkalinity (mgCaCO ₃ /l)	440	380	540	400	380	220	380	360	340	560
Hardness (mgCaCO ₃ /l)	320	380	560	420	280	380	420	400	320	460
As (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CN (mg/l)	0.009	<0.001	0.008	0.003	0.001	0.003	0.003	0.003	0.006	0.019
Mn (mg/l)	0.40	0.00	1.8	0.3	0.2	0.3	0.1	<0.001	<0.001	<0.001
Fe (mg/l)	0.37	0.37	2.11	0.44	0.26	0.02	5.37	1.44	1.72	1.38
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table A-2: FIELD MEASURED PARAMETERS IN DECEMBER, 2009

PARAMETER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	6.82	6.5	6.43	5.97	5.97	5.7	6.47	7.13	6.80	7.1
TDS (mg/l)	290.0	516	324	506	161.5	337	112.5	117.0	728	104.4
Temp. (°C)	27.5	30.4	30.4	29.1	27.8	28.1	25.6	26.8	26.5	23.5
E.C. (µS/cm)	629	118.2	709	111.7	355	75.4	238	254	157.3	230
Phos. (mg/l)	1.2	0.43	3.3	3.3	1.19	0.21	3.3	3.3	1.20	3.3
Alkalinity (mgCaCO ₃ /l)	230	210	230	240	270	220	250	270	270	290
Hardness (mgCaCO ₃ /l)	320	620	280	580	220	420	380	380	330	420
As (mg/l)	<0.001	<0.001	<0.001	0.01	<0.001	<0.001	0.01	0.01	<0.001	<0.001
CN (mg/l)	0.011	0.027	0.049	0.008	0.003	0.004	0.020	0.015	0.003	0.05
Mn (mg/l)	0.1	<0.001	0.5	0.8	0.2	0.1	0.5	0.5	0.7	0.2
Fe (mg/l)	0.45	0.01	1.79	0.15	0.13	<0.001	4.03	1.49	2.05	1.15
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table A-3: FIELD MEASURED PARAMETERS IN JANUARY, 2010

PARA-METER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	6.82	6.8	6.35	5.79	6.03	6.11	7.12	7.83	7.50	7.02
TDS (mg/l)	297	526	340	506	1628	334	543	416	833	942
Temp. (°C)	27.7	30.4	28.7	29.5	27.9	30.7	29.1	28.3	28.3	28.7
E.C. (µS/cm)	647	1185	745	1129	359	792	846	912	1865	1120
Phos. (mg/l)	0.96	3.05	4.0	0.91	2.85	3.30	3.20	3.9	0.93	3.80
Alkalinity (mgCaCO ₃ /l)	220	360	380	380	270	240	220	250	360	380
Hardness (mgCaCO ₃ /l)	420	540	380	460	380	300	400	420	380	380
As (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CN (mg/l)	0.010	0.054	0.012	0.006	0.021	0.002	0.005	0.002	0.006	0.005
Mn (mg/l)	0.7	0.4	0.6	0.6	0/3	0.2	0.2	0.3	0.1	0.6
Fe (mg/l)	0.42	0.004	2.05	0.02	1.53	0.40	0.2	0.27	1.63	1.73
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table A-4: FIELD MEASURED PARAMETERS IN FEBRUARY, 2010

PARAMETER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	5.75	6.33	6.24	5.56	5.75	7.43	6.15	6.28	6.52	7.32
TDS (mg/l)	289	533	345	507	161.7	457	857.1	226	197.4	643
Temp. (°C)	27.7	28.7	27.9	29.0	27.9	28.3	27.6	27.4	27.2	28.9
E.C. (µS/cm)	629	1168	752	1117	356	754	188.6	478	429	642
Phos. (mg/l)	0.41	0.37	0.64	0.33	0.98	3.30	1.14	1.6	3.30	0.57
Alkalinity (mgCaCO ₃ /l)	380	330	270	440	340	380	280	300	420	380
Hardness (mgCaCO ₃ /l)	400	390	540	380	460	440	420	330	280	360
As (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.1	0.03	0.10	<0.001
CN (mg/l)	0.027	0.011	0.008	0.00	0.002	0.003	0.02	0.02	0.02	0.03
Mn (mg/l)	0.1	0.5	0.6	0.3	0.2	<0.001	<0.001	0.3	0.2	0.3
Fe (mg/l)	0.44	0.02	1.95	0.22	0.12	0.10	2.28	1.77	1.78	0.91
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table A-5: FIELD MEASURED PARAMETERS IN MARCH, 2010

PARAMETER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	6.59	6.30	6.29	5.65	5.70	5.93	6.68	7.04	7.63	6.93
TDS (mg/l)	290	523	357	511	161.5	30.6	971	229	140.2	118.5
Temp. (°C)	27.8	28.8	28.8	29.4	28.6	31.1	29.2	27.8	30.1	29.1
E.C. (µS/cm)	630	31.2	790	1133	360	73.50	221	507	323	269
Phos. (mg/l)	0.25	2.52	0.30	0.38	1.26	0.29	0.86	0.92	1.07	1.94
Alkalinity (mgCaCO ₃ /l)	380	270	360	440	380	220	360	400	320	360
Hardness (mgCaCO ₃ /l)	460	260	340	360	500	320	380	380	320	280
As (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.03	0.10	0.10	0.01
CN (mg/l)	0.003	0.010	0.020	0.027	0.001	<0.001	0.001	<0.001	0.001	0.011
Mn (mg/l)	0.20	0.10	0.50	0.30	<0.001	<0.001	<0.001	<0.001	0.30	0.30
Fe (mg/l)	<0.001	0.17	0.25	1.23	0.30	0.30	5.50	2.32	0.15	1.73
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table A-6: FIELD MEASURED PARAMETERS IN APRIL, 2010

PARA-METER	SAMPLING POINTS									
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	SW 1	SW 2	SW 3	SW 4
pH	6.63	6.29	6.31	5.78	5.82	5.81	6.41	6.65	7.01	7.03
TDS (mg/l)	286	534	368	507	164.1	34.5	72.3	1530	152.5	467
Temp. (°C)	28.2	29.4	28.7	29.4	28.5	28.5	28.7	28.0	29.2	27.6
E.C. (µS/cm)	630	1183	811	1126	365	784	1635	338	344	578
Phos. (mg/l)	0.40	0.52	0.30	0.34	0.94	1.02	0.38	0.39	0.69	2.29
Alkalinity (mgCaCO ₃ /l)	460	380	530	290	480	340	280	560	420	300
Hardness (mgCaCO ₃ /l)	340	560	440	490	270	400	330	520	290	480
As (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.10	0.07	0.03	<0.001
CN (mg/l)	0.007	0.004	0.12	0.007	0.008	0.002	0.004	0.007	0.019	0.005
Mn (mg/l)	0.7	0.0	0.3	0.7	0.5	0.00	0.5	0.3	0.0	0.0
Fe (mg/l)	0.6	1.34	0.67	0.72	2.32	3.57	0.83	0.19	3.43	4.01
Cu (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

APPENDIX B: WHO/ EPA DRINKING WATER GUIDELINE LIMITS

Table B-1: EPA and WHO Guideline Values for Portable Water

PARAMETER	EPA, (1997)	WHO, (2004)
pH	6.5 – 8.5	6.5-8.5
TDS	500	1000
TEMP.	< 30	—
E.C.	750	1000
Phos.	—	—
Alkalinity	—	—
Hard.	—	—
As	—	0.01
CN	0.1	0.07
Mn	—	0.5
Fe	0.3	0.3
Cu	—	1.0

**APPENDIX C: PARAMETER RANGE, MEAN AND STANDARD
DEVIATION (SD) VALUES**

Table C-1: WATER SAMPLES – pH RANGE, MEAN AND STANDARD DEVIATION
VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	5.75	6.82	6.56	0.410
GW 2	6.29	6.8	6.45	0.194
GW 3	6.24	6.48	6.35	0.090
GW 4	5.56	5.97	5.77	0.149
GW 5	5.7	6.03	5.87	0.130
GW 6	5.31	6.05	6.05	0.728
SW 1	6.15	7.12	6.57	0.324
SW 2	6.28	7.83	7.03	0.530
SW 3	6.52	7.63	7.08	0.420
SW 4	6.93	7.45	7.14	0.2003

Table C- 2: WATER SAMPLES– TDS RANGE, MEAN AND STANDARD DEVIATION
VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	286	297	290.67	3.669
GW 2	512	534	524	8.877
GW 3	324	368	343.33	17.224
GW 4	506	511	508	2.366
GW 5	161.5	164.1	162.45	1.062
GW 6	306	457	355	52.318
SW 1	107.7	971	552.38	371.088
SW 2	107.7	416	208.12	114.363
SW 3	140.2	833	457.68	326.17
SW 4	104.4	964	539.82	380.717

Table C-3: WATER SAMPLES – TEMPERATURE RANGE, MEAN AND STANDARD DEVIATION VALUES

WATER SAMPLE	MIN.	MAX	MEAN	STANDARD DEVIATION
GW 1	27.5	28.3	27.87	0.314
GW 2	28.7	30.7	29.8	0.807
GW 3	27.9	30.4	28.85	0.826
GW 4	29.0	29.5	29.25	0.207
GW 5	27.8	29.0	28.28	0.488
GW 6	27.8	31.1	29.08	1.432
SW 1	25.6	29.2	27.88	1.399
SW 2	26.8	29.1	27.9	0.785
SW 3	26.5	30.1	28.13	1.339
SW 4	23.5	29.1	27.57	2.095

Table C-4: WATER SAMPLES – CONDUCTIVITY RANGE, MEAN AND STANDARD DEVIATION VALUES.

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	629	647	634.67	8.116
GW 2	118.2	1185	854.867	499.408
GW 3	709	811	754.5	39.521
GW 4	111.7	1133	957.12	414.201
GW 5	355	366	360.167	4.535
GW 6	735	792	768	23.469
SW 1	188.6	1635	560.6	583.024
SW 2	221	912	451.67	253.322
SW 3	157.3	1865	774.72	727.937
SW 4	212	1120	508.5	351.971

Table C-5: WATER SAMPLES – PHOSPHATE RANGE, MEAN AND STANDARD DEVIATION VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	0.25	3.3	1.086	1.145
GW 2	0.37	3.05	1.62	1.308
GW 3	0.3	4.0	2.03	1.791
GW 4	0.33	3.3	1.067	1.145
GW 5	0.41	2.85	1.27	0.829
GW 6	0.21	3.3	1.773	1.444
SW 1	0.29	3.3	1.53	1.369
SW 2	0.38	3.9	1.75	1.514
SW 3	0.3	3.3	1.25	1.054
SW 4	0.57	3.8	2.13	1.282

Table C-6: WATER SAMPLES – TOTAL ALKALINITY RANGE, MEAN AND STANDARD DEVIATION VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	220	460	351.67	103.667
GW 2	210	380	321.67	68.532
GW 3	230	540	385	128.802
GW 4	240	440	365	82.402
GW 5	270	480	353.33	79.414
GW 6	220	380	270	71.274
SW 1	220	380	295	62.53
SW 2	250	560	356.67	114.31
SW 3	270	420	355	58.566
SW 4	290	560	378.33	97.245

Table C-7: WATER SAMPLES – TOTAL HARDNESS RANGE, MEAN AND STANDARD DEVIATION VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	320	460	376.67	58.537
GW 2	260	620	458.33	136.589
GW 3	280	560	423.33	111.295
GW 4	360	580	448.33	80.602
GW 5	220	500	351.17	112.857
GW 6	300	440	376.67	55.738
SW 1	330	420	388.33	33.715
SW 2	330	520	465	63.797
SW 3	280	380	320	35.214
SW 4	280	480	396.67	73.121

Table C-8: WATER SAMPLES — CYANIDE RANGE, MEAN AND STANDARD DEVIATION VALUES.

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	0.03	0.027	0.01	0.008
GW 2	0.001	0.054	0.017	0.019
GW 3	0.008	0.12	0.036	0.009
GW 4	<0.001	0.021	0.0085	0.008
GW 5	0.001	0.021	0.006	0.001
GW 6	<0.001	0.04	0.002	0.009
SW 1	0.001	0.02	0.008	0.008
SW 2	<0.001	0.02	0.008	0.008
SW 3	0.001	0.02	0.009	0.018
SW 4	0.005	0.05	0.002	0.001

Table C-9: WATER SAMPLES – ARSENIC RANGE, MEAN AND STANDARD DEVIATION VALUES

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	<0.001	<0.001	<0.001	-
GW 2	<0.001	<0.001	<0.001	-
GW 3	<0.001	<0.001	<0.001	-
GW 4	<0.001	0.01	0.0017	0.004
GW 5	<0.001	<0.001	<0.001	-
GW 6	<0.001	<0.001	<0.001	-
SW 1	<0.001	0.03	0.01	0.011
SW 2	<0.001	0.07	0.02	0.027
SW 3	<0.001	0.03	0.01	0.011
SW 4	<0.001	0.01	0.02	0.004

Table C-10: WATER SAMPLES – IRON RANGE, MEAN AND STANDARD DEVIATION VALUES

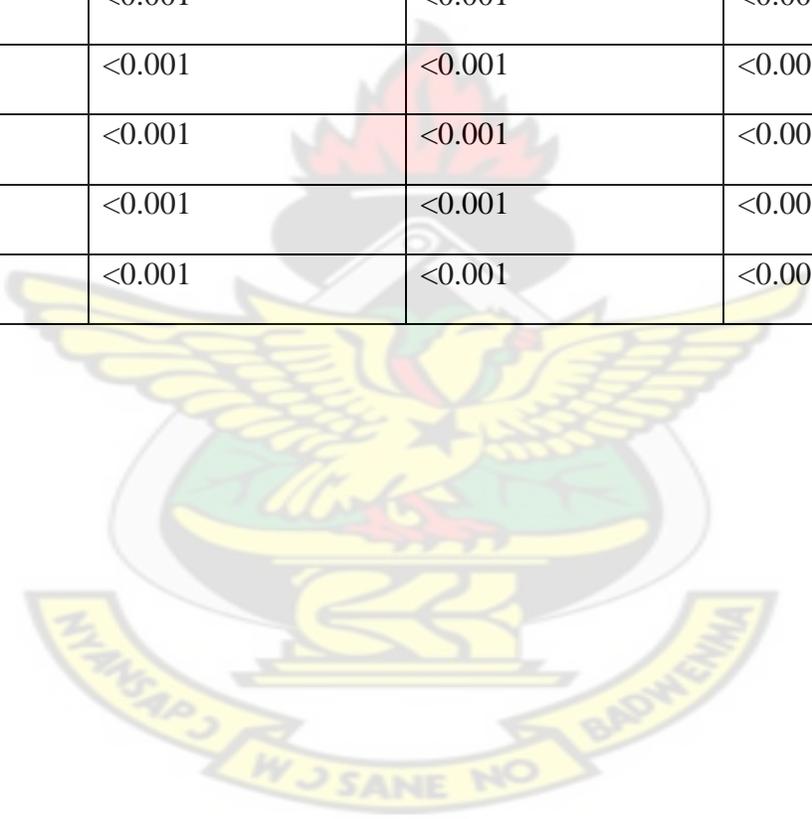
WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	<0.001	0.6	0.38	0.201
GW 2	0.004	1.34	0.32	0.519
GW 3	0.25	2.11	1.47	0.801
GW 4	0.02	1.23	0.46	0.449
GW 5	0.12	2.32	0.78	0.927
GW 6	<0.001	3.57	0.73	1.399
SW 1	0.2	5.5	3.035	2.279
SW 2	0.19	2.32	1.246	0.848
SW 3	0.15	3.43	1.79	1.047
SW 4	0.91	4.01	1.91	1.12

Table C-11: WATER SAMPLES — MANGANESE RANGE, MEAN AND STANDARD DEVIATION VALUES.

WATER SAMPLE	MIN	MAX	MEAN	STANDARD DEVIATION
GW 1	0.1	0.7	0.37	0.280
GW 2		0.5	0.17	0.225
GW 3	0.3	1.8	0.72	0.541
GW 4	0.3	0.8	0.5	0.228
GW 5	<0.001	0.5	0.23	0.163
GW 6	<0.001	0.3	0.1	0.126
SW 1	<0.001	0.5	0.22	0.232
SW 2	<0.001	0.5	0.23	0.197
SW 3	<0.001	0.7	0.22	0.264
SW 4	<0.001	0.6	0.23	0.225

Table C-12: WATER SAMPLES –RANGE AND MEAN COPPER VALUES

WATER SAMPLE	MIN	MAX	MEAN
GW 1	<0.001	<0.001	<0.001
GW 2	<0.001	<0.001	<0.001
GW 3	<0.001	<0.001	<0.001
GW 4	<0.001	<0.001	<0.001
GW 5	<0.001	<0.001	<0.001
GW 6	<0.001	<0.001	<0.001
SW 1	<0.001	<0.001	<0.001
SW 2	<0.001	<0.001	<0.001
SW 3	<0.001	<0.001	<0.001
SW 4	<0.001	<0.001	<0.001



**APPENDIX D: ANOVA TABLE FOR PHYSICO – CHEMICAL
PARAMETERS AND TRACE METALS.**

Table D-1: ANOVA FOR pH IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	1.447707	1	1.447707	15.67772	0.00418	5.317655
Within Groups	0.738733	8	0.092342			

Table D-2: ANOVA FOR TDS IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	13713.84	1	13713.84	0.647188	0.444367	5.317655
Within Groups	169519	8	21189.87			

Table D-3: ANOVA FOR TEMPERATURE IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	2.32724	1	2.32724	7.25233	0.027369	5.317655
Within Groups	2.567164	8	0.320895			

Table D-4: ANOVA FOR CONDUCTIVITY IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	52343.94	1	52343.94	1.526189	0.251732	5.317655
Within Groups	274377.3	8	34297.16			

Table D-5: ANOVA FOR PHOSPHATE IN GROUND AND SURFACE WATER BODIES.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	0.084998	1	0.084998	0.568922	0.472303	5.317655
Within Groups	1.195214	8	0.149402			

Table D-6: ANOVA FOR TOTAL ALKALINITY IN GROUND AND SURFACE WATER BODIES.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	63.37826	1	63.37826	0.042134	0.842491	5.317655
Within Groups	12033.54	8	1504.192			

Table D- 7: ANOVA FOR TOTAL HARDNESS IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	1926.667	1	1926.667	1.096937	0.325548	5.317655
Within Groups	14051.24	8	1756.406			

Table D- 8: ANOVA FOR ARSENIC IN GROUND AND SURFACE WATER BODIES.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	0.000247	1	0.000247	11.5417	0.009398	5.317655
Within Groups	0.000171	8	2.14E-05			

Table D-9: ANOVA FOR CYANIDE IN GROUND AND SURFACE WATER BODIES

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	1.17E-05	1	1.17E-05	0.111257	0.747292	5.317655
Within Groups	0.000842	8	0.000105			

Table D-10: ANOVA FOR MANGANESE IN GROUND AND SURFACE WATER BODIES.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	0.035853	1	0.035853	1.073517	0.330453	5.317655
Within Groups	0.267178	8	0.033397			

Table D-11: ANOVA FOR IRON IN GROUND AND SURFACE WATER BODIES.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	3.951974	1	3.951974	12.09308	0.00835	5.317655
Within Groups	2.614371	8	0.326796			