GROUNDWATER CONTAMINATION WITH TOXIC METALS THROUGH SMALL SCALE MINING WITHIN THE LOWER PRA BASIN

BY

MICHAEL DORLEKU

(10363066)

BSc. (Hons) Laboratory Technology (UCC)

THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF M.PHIL. ENVIRONMENTAL SCIENCE DEGREE

JUNE, 2013

DECLARATION

I hereby declare that this research and all the experimental work described therein were solely carried out by me under the Institute of Environmental Science and Sanitation, University of Ghana, Legon, under the supervision of Prof. D. Carboo and Dr. D. Nukpezah.

No previous submission for a degree has been made here or elsewhere. References cited therein were duly acknowledged.

Student.. Date....................................

(Michael Dorleku)

SID: 10363066

Principal Supervisor..................................... Date...

(Prof.D. Carboo)

Supervisor... Date...

(Dr. D. Nukpezah)

DEDICATION

This thesis is dedicated to the Ancient of Days, the Lord Jesus Christ, whose I am. To my wife and my three lovely children Daisy, Elsie and Edlyn.

ACKNOWLEDGEMENTS

I am grateful to the almighty God through my Lord Jesus Christ for His abundant grace, love, protection and provision throughout this study.

I appreciate the tremendous assistance of my supervisors, Prof. D. Carboo of the Department of Chemistry and Dr. D. Nukpezah of Institute of Environmental Science and Sanitation for their guidance towards the completion of this thesis.

I wish to sincerely thank the Director, Dr Joseph A. Ampofo, the Administrator, Mrs. A. Sedziafa and Dr O. Ansa-Asare all of CSIR-Water Research Institute for their support in allowing me pursue this course. I also want to thank Mr Collins Tay of CSIR-WRI for his tremendous support and Dr. Isaac Hodgson also of the same institute for his encouragement and mentorship to make me a better person.

Last but not the least, my thanks goes to the technical staff of Environmental Chemistry Division of Water Research Institute especially Mr Lawrence Yawson and Mr Daniel Amoah for helping me do my work whilst I was away for the post graduate studies.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF APPENDICES

Page

ABSTRACT

Small-scale gold mining in Ghana is mainly an informal industry employing thousands of people. The generally undeveloped nature of the industry has resulted in lack of proper monitoring and supervision by relevant authorities. As a result, there is wanton destruction of farm lands and indiscriminate pollution of water bodies. These water bodies serve us recharge zones for groundwater, thereby polluting them. This study assessed the effects of small-scale gold mining on quality of groundwater in the Lower Pra Basin in terms of heavy metal and other physico-chemical pollution. The analysis shows that pH values are generally low in the Basin. More than 95 % of dry season and almost all the wet season values are acidic or slightly acidic. Approximately 35 % of boreholes in the wet season recorded values for Cadmium above W.H.O guideline value of 3.0 µg/l. Only two boreholes recorded values above W.H.O guideline value for the dry season. The higher wet season pollution suggests anthropogenic origin for Cd. Generally, high values were recorded for Iron, Manganese, Lead, Aluminium and Hg. Approximately 15% and 18 % of dry and wet season values respectively for Fe were above W.H.O recommended limit of 300 µg/l for drinking water with a mean of 218 µg/l and a median of 166 µg/l. Manganese concentration was in the range 2.5 - 1544 µg/l with a mean of 142 µg/l. Roughly 5 % and 11 % of the dry and wet season values respectively, were above the W.H.O recommended value of 500 µg/l. The concentration of Lead was higher than 10 µg/l (W.H.O guideline value) in 43% and 41% of the dry and wet season values respectively with a mean of 15.8 µg/l and 20.1 µg/l for dry and wet seasons respectively. About, 88% and 42% of the dry and wet season values, respectively, were above the W.H.O limit of 1.0µg/l for mercury. Dry season values ranged between 0.005 and 10.1µg/l with the wet season recording values between 0.005 to 16.4 µg/l. Approximately 17 % and 11 % of dry and wet seasons respectively recorded values above the W.H.O recommended limit of 200 µg/l for Aluminium. Other heavy metals present but were generally below W.H.O guideline values or were in insignificant concentrations include Copper, Arsenic, selenium and Zinc. Values recorded for Phosphate, Sulphate and Nitrate are within acceptable limits. In general, Lead, Copper, Cadmium, and Manganese showed higher wet season values than dry season suggesting anthropogenic influence.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Water is essential to the existence of man and all forms of life. However, this valued resource is increasingly being threatened as human populations increase and demand more water of high quality for domestic purposes and economic activities. Even though Ghana is well endowed with water resources, the amount of water available changes markedly from season to season as well as from year to year. The availability of water is also decreasing owing to climate variability and change, rapid population growth, increase in environmental degradation, pollution of rivers and draining of wetlands (WRC, 2008; Ackar et al., 2011).

Water abstraction for domestic use, agricultural production, mining (both large and small-scale), industrial production, power generation, and forestry practices can lead to deterioration in water quality and quantity that impact not only the aquatic ecosystem but also its availability for human consumption. Water is a cross-cutting element of the Growth and Poverty Reduction Strategy (GPRS II) of the Republic of Ghana and is linked to all Eight (8) of the Millennium Development Goals (MWRWH, 2007). The United Nations' Millennium Development Goal 7c, which seeks to ensure environmental sustainability enjoins countries where universal access to safe drinking water at an acceptable level of service has not been achieved, to halve by 2015, the proportion of people without access to safe drinking water and basic sanitation (UNESCO, 2010). According to (Prüss-Üstün *et. al.*, 2008), almost one tenth of the global disease burden could be prevented by improving water supply, sanitation, hygiene and management of water resources. The greatest impact of water pollution on human health comes from drinking water acting as an important vehicle for the transmission of a large variety of infectious diseases, leading the WHO to estimate that 70 per cent of disease episodes in developing countries are deeply related to polluted water and/or inappropriate excreta treatment (UN-Water/Africa, 2006, p. 90). The 2010 population and housing census have put Ghana’s population at about 24.7million people with a growth rate of about 2.6 % (Ghana Statistical Service, 2010). Although Ghana’s population growth rate is higher in the cities, majority of Ghana’s population still live in rural areas (Schäfer *et al.*, 2010). According to International Fact-finding Mission-(2000) access to treated water is available to 62-70 per cent in urban areas and 35-40 percent in rural areas. However, in urban areas, only 40 per cent of the population have access to tap water. According to the 2000 Population and housing census, 42.1 % have access to pipe borne water and tanker services, 33.0 % to wells and boreholes and 4.9 % to rivers, streams, rainwater etc (Ghana Statistical Service GSS, 2002).

Ghana has since the mid-1990S, been implementing a string of reforms in the water sector aimed at enhancing the efficiency of the production and utilisation of water. These reforms have culminated in the institutional re-alignment of key institutions in the sector.

The 2007 Water Policy document contains sections on integrated water resources management including water for energy, food security and transportation), urban and community/town water delivery. The policy also highlights the international legal framework for domestic and trans- boundary utilisation of water resources (National Water Policy, 2007). Rivers are said to be the most important freshwater resource for man. Social, economic and political development has been largely related to the availability and distribution of freshwaters contained in riverine systems (Karikari *et al.*, 2007). Weatherhead and Howden (2009) have described the relationship between land use[1] and water quality as a “Complex” relationship. This is because in any given catchment, a combination of processes controls the delivery of water into river channels. The resulting stream flows may “include components from different hydrological flow paths including direct runoff, shallow through-flow with a residence time of a few days, and groundwater base flow with a residence time of years or even decades” (Weatherhead & Howden, 2009).

The preference of groundwater to surface water as a source of drinking water was based on the fact that groundwater excluded from the atmosphere would be less susceptible to pollution. This is true to an extent. However, groundwater in hard-rock aquifers, particularly in mining areas, is known to be vulnerable to quality problems that may have serious impact on human health. The rocks are often carbonate-deficient and give rise to poorly buffered water (Smedley *et al.,* 1995). Secondly, in gold and base metal mining areas, sulphides oxidation resulting from chemical and biogeochemical processes leads to the production of low *p*H ground-water that encourages the dissolution of trace metals into the groundwater system in very high concentrations. The groundwater, thus, becomes dangerous for human consumption (Kortatsi, 2006).

Small scale gold mining is currently estimated to be responsible for 12 % of the world’s gold production or approximately 330 tons per year (Telma and Veiga, 2008).

---

[1]Lillesand and Kiefer (2000) have defined land use as the human activity or economic function associated with a specific piece of land whereas land cover relates to the type of features present on the surface of the earth.

Ghana has been known to be a gold producer since the fifteenth century and currently, Africa's second most important producer of gold after South Africa (Coakley, 1999). The sector is said to have attracted over US $3 billion of foreign direct investment by 1999 and now accounts for over 30 % of gross foreign earnings. Mining activities generally impact in various ways on the environment. A major impact is on water bodies through inadequate management of tailings and effluents from processing plants, exposure of mined surfaces leading to acid mine drainage and from the use of mercury by the small-scale alluvial workings (Ntibrey, 2001). Artisanal gold mining is said to be on the increase in the Pra Basin as reported extensively by (Donkor et al., 2006) and also in the Ankobra basin (Kortatsi, 2006) with its attendant potential environmental consequences as a result of the use of the amalgamation method of extraction of gold.

Generally, mining methods employed by small-scale miners of precious minerals vary according to the type of deposit being exploited and its location (Ntibrey, 2001). In view of the poor financial base of most of the small scale miners, they resort to the use of traditional/manual methods of mining, which are largely artisanal, featuring simple equipment like shovels, pick-axes, pans, chisels and hammers. There are generally two groups of the small scale miners, the licensed and the unlicensed which are popularly known as *galamsay* operators. Mining, irrespective of the scale of operation, has some degree of impact on the environment. Although legalised small scale mining may have some negative impacts on the environment, it can be minimised through environmental permitting and regular monitoring and supervision. Illegal miners, on the other hand, whose operations by their very furtive and clandestine nature are not amenable to being monitored, are responsible for the most significant share of environmental damages in the sector (Ntibrey, 2001). The use of earth moving equipment such as bulldozers and backhoe excavators are sometimes employed. In some cases underground tunnels are constructed which eventually results in land subsidence (Besseah, 2011).

Mining has a huge impact on the hydrosphere .The drainage system in many small-scale mining areas is adversely affected by their operations. Rivers and streams are polluted by solid suspensions and mercury, which are commonly discharged into resident water bodies during the sluicing process and amalgamation, respectively. This in turn leads to siltation and coloration of such waters. Improperly disposed tailings also find their way into streams and rivers during heavy rains, creating sedimentation problems and rendering streams unusable for both domestic and industrial purposes. Removal of vegetation for gold prospecting also causes soil erosion, which in turn increases the turbidity of runoff surface waters. The increasing mining operations in the Pra Basin and its environs has been a major source of both surface and groundwater pollution. This has led to chemical pollution of groundwater and streams, siltation through increased sediment load, increased faecal matter and dewatering effects (Akabzaa and Darimani, 2001).Amalgamation is said to be the most ideal method of gold recovery employed by most small scale gold miners because it is a simple technique. However, it is well known that the process is devastating to health, not only to users but also to those who are indirectly involved including the unborn, through peripheral contamination and the introduction into the food chain (Lombe, 2003).

Previous study by (Ahialey et al, 2010) shows significant concentration of Fe, Al and Cd in groundwaters in the Pra basin above WHO limit for drinking water. Other studies from Obuasi (Amonoo-Neizer and Amekor, 1993; Smedley, 1996) and from

Tarkwa another mining town in Ghana (Asante et al., 2007) show significant levels of As concentrations.

1.2 **Statement of the Problem**

Clean water is not merely a human need but a human right. Access to safe and adequate water supply is essential to man and all living things, and these form part of Ghana's Growth and Poverty Reduction Strategy and linked to all the eight Millennium Development Goals (MWRWH, 2007).

Most of the rivers and streams in the area of study, comprising the lower part of Pra basin have seen high level of pollution as a result of increased Small-scale mining operations and other anthropogenic activities as shown by Ansa-Asare and Asante (2000), Ampofo (1997) and Oduro et al(2012).The Government of Ghana, with the help of donor countries increasingly apprehensive of the extent of pollution of surface water resources, has been providing communities with drilled borehole and hand dug wells as alternative source of potable water supply.

However, activities of mining, either large or small-scale pose a threat to the groundwater resources in these basins. Natural geochemical and biochemical processes such as oxidation of pyrite and arsenopyrite in an aquifer do not only threaten the quality of human health but also poses a threat to sustainable development and management of groundwater resources. Groundwater may, thus, be prone to chemical contamination (Kortatsi,2006)

It is therefore, imperative to carry out an extensive groundwater quality assessment in terms of heavy metals associated with mining activities in the basin, in order to understand the hydrochemistry of groundwater and, therefore, ensure its potable supply in the area.

1.3 Aim and Objectives

The aim of the project is to assess the impact of anthropogenic (exploration and exploitation of gold) activities on the groundwater resources within the study area.

1.3.1Specific Objectives

1. To determine the physico-chemical quality of the groundwater resource in the selected area of study.
2. To assess the extent of heavy metal pollutions that is associated with mining.
3. To assess the impact of other socio-economic activities which may lead to pollution of ground water sources and how it affects water quality.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Water Resources

Pollution of water resources is on the ascendancy due to rapid population growth which is occurring simultaneously with the establishment of human settlements lacking appropriate sanitary infrastructure (Karikari *et. al.*, 2007). A precondition of sustainable growth must ensure water bodies are not contaminated (Olajire and Imeokparia, 2001). Providing safe and secure water to people around the world, and promoting sustainable use of water resources are elemental objectives of the Millennium Development Goals. The global community has established the important links between ecosystem and human health and well-being, particularly as human populations expand creating greater pressures on natural environments (UNEP GEM, 2006).The availability of water and its physical, chemical, and biological composition affect the aquatic life and its healthy ecosystems as lack of water leads to depletion of aquatic organisms which may lead to loss of ecosystem services. Moreover, an abundant supply of potable water is a basic requirement for human existence, including, but not limited to:

- water used for human consumption and public water supply;
- water used in agriculture and aquaculture;
- water used in industry;
- water used for recreation; and
- Water used for electrical power generation.

Increasing anthropogenic activities such as farming and mining could be a major threat to water resources on which most living organisms depend . Water has been called "mining's most common casualty" (McClaure and Schneider, 2001). Mining affects freshwater through effluent from processing of ore and seepage from tailings and waste rock impoundments. Rivers and streams are polluted by solid suspensions and mercury, which are commonly discharged into resident water bodies during the sluicing process and amalgamation, respectively. Small scale gold mining activities by its nature make use of a lot of water thereby seriously polluting water resources (Cunningham et al, 2005). Small scale gold mining all over the world is noted for its effects on water bodies through pollution of both ground and surface waters (Owen et al, 2005). This often deprived communities of access to water, which is a basic need for human survival.

According to a publication by Project underground (2000), lack of access to clean water in small scale gold mining communities has a relationship with the reduced health status of these communities, resulting in reported cases of water related diseases.

According to the National Water Policy (NWP, 2007) document, Ghana has a total annual runoff of 56.4 billion m^3 with the Volta River accounting for 41.6billion m^3. The Volta, South-Western and Coastal systems contribute 65 %, 29 % and 6 %, respectively, of this runoff. The runoffs are also characterized by wide disparities between the wet season and dry season flows. The total water available from surface water sources is 39.4 billion m^3 per annum. With respect to groundwater, most aquifers have a yield of between 6 to 180 m^3/h (NWP, 2007). The potential for increasing groundwater use is faced with challenges. There are intrusions in shallow aquifers along the coastal zone, while borehole yields in the Northern, Upper East, Upper West and parts of Brong-Ahafo regions are often insufficient. In reference to this, Ghana established the Water Resources Commission by an Act of Parliament (ACT 522 of 1996) with the mandate to regulate and manage the country‘s water resources and to co-ordinate government policies in relation to water.

Acquah (1995) recounted that, very early in the history of small scale gold mining in Ghana, water resource depletion increased marginal cost of providing potable water which increased burden on women‘s time and hastened climate change as a result of deforestation. Large and small scale mining industries looked at water (surface water) as ‘free good’ which was exploited with lack of effective regulatory framework which had deforested headwaters because there was no motivation to conserve water, as quoted by Besseah (2011).

2.2 Small Scale Gold Mining in Ghana

Small-scale (and artisanal) mining has been defined differently around the world. However, the United Nations (UN) and Intermediate Technology Development Group (ITDG) definition is given as any single unit mining operation having an annual production of unprocessed material of 50,000 tonnes, or less as measured at the entrance of the mine. It is also characterized by a labour force that is not formally trained in mining, prospecting, extracting, and processing of minerals. Working conditions are typically hazardous and unhealthy, and living conditions appalling. It is a critical livelihood activity, employing more than 13 million workers and sustaining 80 to 100 million people worldwide (ILO, 1999).

Ghana, known as the Gold Coast during colonial occupation, has a long history of mining going back over 1000 years (Annin, 1990; Dumett, 1998; Government of Ghana1989). Gold is the largest contributor to the economy, accounting for about 38% of total merchandise and 95% of total mineral exports (Aryee, 2001) as well as about 80% of all mineral revenue (Adadey, 1997).

In Ghana, small-scale (gold) mining is defined as"…mining (gold) by any method not involving substantial expenditure by an individual or group of persons not exceeding nine in number or by a co-operative society made up of ten or more persons" (Gov. Of Ghana,1989). Generally, it is a term used to describe gold mining activities that uses simple methods (e.g. pick-axes, chisels, sluices and pans) to extract and process gold on a small scale (Shoko and Love, 2005). Small scale gold mining in Ghana, as in most developing countries, was for decades treated as an informal industrial sector which employs thousands of people but uses largely rudimentary, unmonitored and unrestrained practices (Hilson, 2001).Until the1980s, small scale gold mining activities in Ghana remained largely unregulated and received little, if any, support from governmental bodies. After the implementation of the legal framework for registration of small scale gold and diamond mining, the sector has seen tremendous transformation (Hilson, 2001). In1989, a much-needed move was taken to legalize small-scale gold mining, which, from an economic perspective, is by far a more important sector of the economy. Three important laws were passed;

- The Small-scale Gold Mining Law (PNDCL 218) which provides for the registration of activity; the granting of gold-mining licences to individuals or groups; the licensing of buyers to purchase product; and the establishment of district-assistance centres.

- The Mercury Law (PNDCL 217): legalized the purchasing of mercury (for mineral processing purposes) from authorized dealers.

- The Precious Minerals Marketing Corporation Law (PNDC Law 219): transformed the Diamond Marketing Corporation into the Precious Minerals Marketing Corporation (PMMC), which was authorized to buy and sell gold.

Since the regulation exercise, two types of small scale miners have emerged, legal and illegal.

Legal small scale gold miners comprise of those who have acquired mining licenses from the Minerals Commission of Ghana to cover their concessions. An area of 25 acres is the maximum allowable area that is allocated to each person or group of persons as a concession (Appiah, 1998). The enactment of relevant legislation and effective legalization of small scale mining has had a positive impact on the economies of certain developing countries like Ghana. With operations formalised, illegal smuggling channels are being eliminated, thereby enabling the complete capture of internally mined product. The successful containment of the minerals mined on a small scale contributes enormously to sector revenues, and also contributes positively to foreign-exchange earnings (Hilson, 2001).

Illegal operators, on the other hand, work without licenses, have no concessions of their own and operate uncontrollably within the concessions of large scale mining companies or in areas prohibited for mining such as forest reserves and environmentally sensitive areas (Appiah, 1998).Their operations are furtive and clandestine in nature often initiating confrontations with both state law enforcement agencies and the security personnel of large scale mining companies. Several small scale mining areas are scattered throughout the country, specifically within the Tarkwaian and Birimian rock systems of Ghana since significant portions of these rocks have been re-deposited as placer formations in a number of streams and channels as a result of series of erosion (Kesse, 1985). Placer Gold Deposits, which are also referred to as alluvial gold, are found in the majority of rivers draining Birimian rocks. Large deposits of placer gold also occur along the terraces, floodplains, channels and river beds of the Offin, Pra, Ankobra, Birim and Tano rivers, where large Birimian and Tarkwaian gold deposits have experienced several episodes of erosion and subsequent deposition. Small scale gold mining is partly confined to these areas, since most operators lack the requisite mechanized equipment to mine hard rock deposits of the Birimian and Tarkwaian Belts (Hilson, 2001).

2.3 Methods of Mining

Mining methods employed by small scale gold miners vary according to the type of deposit being exploited and its location (Ntibrey, 2001). The poor financial status of most of the small scale gold miners constrain majority to rely solely on traditional/manual methods of mining, which use simple equipment like shovels, pick-axes, pans, chisels and hammers. One method is the shallow alluvial mining techniques, which are popularly called “dig and wash”, or the ‘Krowa’ method (wooden bowl carved out of tree stem to serve as a pan) are used to mine shallow alluvial deposits usually found in valleys or low lying areas. Such deposits have depths not exceeding three metres. The area is initially cleared and the soil excavated until the gold-rich layer is reached. The mineralized material is removed and transported to nearby streams for sluicing to recover the gold. Gold from sluices is concentrated by using a smaller 'krowa' or the gold pan. Women are said to be very effective in using the 'krowa' for the recovery of gold (Appiah, 1998).

Deep alluvial mining techniques or land dredges are another type used to mine deep alluvial deposits found along the banks of major rivers such as the Ankobra, Tano, and Offin and certain older river courses. These methods involve excavating a pit and digging until the gold bearing gravel horizon, which is typically located at depths of 7 to 12 metres, is reached. The gold bearing rocks are then removed and sluiced to recover the gold (Besseah, 2011). In recent times, the influx of Chinese who are relatively more resourced have introduced the use of large machinery to this method, bulldozing and back-hoeing pits to access layers of gold bearing gravels more quickly or those formerly inaccessible by manual methods alone.

In areas where hard rocks are encountered the ore is excavated manually and size reduction is carried out using a combination of jaw and rocker crushers and hammer (Amankwah and Anim-Sackey, 2003). In some cases, explosives are commonly used, despite being prohibited throughout Ghana (Ntribrey, 2001).

2.4 Methods of Processing

Small-scale gold miners invariably prefer free milling ores (not sulphidic ores), and therefore gravity concentration, using sluicing, as the main method for processing (Aryee et al, 2002).

The ore is first crushed into pebbles by physical or mechanical means. The pebbles undergo primary, secondary and tertiary grinding in preparation for washing. The ground ore are transferred to the riverside or pond in cloth bags to be refined (Amegbey and Eshun, 2003).The gold containing material is washed on sluices where the heavier gold particles are caught and concentrated on carpets or jute sacks placed in a box, due to gravity. The concentrate from the sluice box is re-assembled in rubber dishes or wooden pans (Krowa). Through panning, the undesirable sediments are separated from the gold particles until the latter clearly appear in the final concentrate.

Next, mercury is poured into the concentrate inside the pan. Mercury is usually mixed by hand with the concentrate, forming a lump or ball of mercury–gold amalgam. Water is added several times to discard tailings and remove lighter particles until only the amalgam remains. The amalgam is then squeezed in a piece of cloth to recover excess mercury (often re-bottled and used again). Some miners put the fabric with the amalgam into their mouth to suck out additional mercury (Hilson, 2001). Finally, the amalgam is heated to separate the gold.

2.5 Environmental, Health and Safety Impact of Small Scale Gold Mining

2.5.1 Environmental Impact

2.5.1.1 Land Degradation

Land degradation, is a common phenomenon at many uncontrolled, unmonitored small-scale mining sites. Miners leave behind “moonlike” landscapes consisting of unstable piles of waste, abandoned excavations and vast stretches of barren land (Aryee et al, 2002).This has crucial adverse impact on the people since land is the main source of livelihood of the people living in these areas. There is therefore deterioration in the viability of the land for agricultural purposes and loss of habitat for micro and macro organisms (Akabza and Daramani, 2001). Excavated pits are typically left unfilled and abandoned to become receptacles for water. Such areas become breeding grounds for mosquitoes and potential dangers to both humans and animals. Large tracts of agricultural lands are also destroyed as a result of excessive vegetation removal and disturbance of soil structure.

2.5.1.2 Deforestation

According to Lacerda, (1997) the hasty emergent of overnight settlements in newly discovered gold areas lead to rapid "urbanization" in the form of messy settlements which do not only end in rampant deforestation, but also social evils associated with urbanization which include alcohol and drug abuse, prostitution, land use conflicts with local communities, as well as water pollution, child labour and diseases. The need for shelter, underground support, panning dishes and firewood contributes to deforestation. The excessive dependence on wood as a source of energy results in the reduction of biodiversity and increasing rates of desertification. The major causes of deforestation have been fires, over logging, shifting cultivation, and an ever-increasing demand for fuel wood with shifting cultivation alone accounting for over 70 % of forest loss (IDRC,1999).

2.5.1.3 Water Pollution

Water pollution (surface and ground) may be considered as a naturally induced change in water quality or conditions induced directly by man‘s numerous activities which render it unbefitting for food, human health, industry, agriculture or leisure per suit (Cifuentes and Rodriguez, 2005).The natural processes and anthropogenic activities that generate pollutants/contaminants are many and varied, and so are their sources. These pollutants/contaminants in one way or the other via the hydrologic cycle reach the groundwater systems to pollute/contaminate them.

Rivers and streams are polluted by solid suspensions and mercury, which are commonly discharged into resident water bodies during the sluicing process and amalgamation, respectively. Polluted stream is an indication of its loss–based livelihoods, destruction of the recreational potential of rivers and the loss of all the valuable benefits that communities derive from rivers (Besseah, 2011). Crispin,(2003) reports that four key areas of impact that small scale gold mining may have on water systems are the release of metals, acid rock drainage (ARD), siltation and water use.

2.5.1.4 Acid Rock Drainage

Acid Rock drainage (ARD) is a potentially severe pollution hazard that can contaminate surrounding soil, groundwater, and surface water. The formation of acid rock drainage is a function of the geology, hydrology, and mining technology employed at mine sites. Acid rock drainage occurs when sulphide ores are exposed to the atmosphere, which can be enhanced through mining and milling processes where oxidation reactions are initiated (Besseah, 2011). Mining increases the exposed surface area of sulphur-bearing rocks allowing for excess acid generation beyond natural buffering capabilities found in host rock and water resources (RRG, 2008). Since large masses of sulphide minerals are exposed quickly during the mining and milling processes, the surrounding environment can often not attenuate the resulting low pH conditions. The primary sources for acid generation are sulphide minerals, such as pyrite (iron sulphide), which decompose in air and water (Skousen *et al*., 1990). Many of these sulphide minerals originate from waste rocks removed from the mine or from tailings. If water infiltrates pyrite-laden rocks in the presence of air, it becomes acidified, often at a pH level of two or three. A naturally occurring type of bacteria called *Thiobacillus ferroxidans* may kick in, accelerating the oxidation and acidification processes, leaching even more trace metals from the wastes (Rozkowski and Rozkowski, 1994). Metals that were once part of the host rock are solubilized and exacerbate the deleterious effect of low pH on terrestrial and aquatic receptors.

2.5.1.5 Mercury Pollution

Mercury is used during ore processing. It constitutes the major pollutants of surface and ground water in small scale gold mining areas (Ntengwe, 2006).

Mercury is one of the priority toxic elements of global concern. It is a liquid metal at ambient temperatures and pressures. Hg forms salts in two ionic states Hg (I) and Hg (II). Hg (II) or mercuric salts are more prevalent in the environment than Hg (I) or mercurous salts. These salts, when soluble in water, are bio-available and are thought to be toxic (Donkor et al, 2006). Elemental mercury (Hg) is quite volatile and only slightly soluble in water. It is dispersed very effectively through the atmosphere with long residence times of about 2 years, and is normally transported from likely sources of emission (Lodenius and Malm, 1998; Boening, 2000).

Thus, Hg in the various oxidation states is released into the environment from a variety of anthropogenic activities and natural sources. Wet and dry depositions are the only primary mechanisms for transporting this element from the atmosphere to the terrestrial and aquatic systems. Artisanal gold mining (AGM) is one such anthropogenic activity that has resulted in the use of an enormous amount of metallic mercury. The mercury used by the miners is usually discharged in an abusive manner into ecosystems (Pfeiffer and Larceda, 1988; Meech *et al.,* 1998).

Elemental Hg is now known to spread very effectively from diverse sources to both terrestrial and aquatic systems. Sediments function as sinks and potential sources of Hg and, once contaminated, pose a risk to aquatic life for many years. Depending on the environmental conditions present Hg compounds in aquatic systems could be transformed and liberated from sediments to water phase, ingested by aquatic biota, be lost to the atmosphere and dispersed; or be conveyed with sediment particulate matter to new previously uncontaminated locations (Ullrich *et al.,* 2001). Additionally, research indicates that the ecological and toxicological effects of Hg strongly depend on the various chemical species present (Donkor et al, 2006).

Inorganic Hg may be converted by microbial activity in an organic-rich environment to organic forms of Hg, e.g. methyl-Hg (MeHg), which are many times more toxic to organisms (Beijer and Jernelov, 1979). MeHg is a potent neurotoxin, damages the central nervous system and especially toxic to foetus. It is very soluble in lipids and therefore, crosses biological membranes with ease. Because of its protein binding properties, it readily bio-accumulates and bio-magnifies in aquatic food chains. As a result, it poses a threat to humans and other fish-eating animals (Lodenius&Malm, 1998).

2.5.1.6 Airborne Particulate Matter.

The effect of small-scale precious minerals mining on the atmosphere has generally been considered to be insignificant since operations are carried out in ambient air. Nevertheless, emissions of gaseous pollutants do occur (Aryee, 2001). Sulphide dioxide (SO_2), nitrogen dioxide (NO_2) and carbon monoxide (CO) are of major concern in mining areas. The activities that generate this particulate matter include grinding equipment, vehicular movement, ore and waste rock heaps and site clearance (Baird, 1995). Small-scale mining operations that involve size reduction of ore generate some dust that could be hazardous to human health since the particles generated from such sources fall within the respirable dust range and are capable of causing dust-related diseases. Furthermore, a common practice of small-scale gold miners in Ghana is the burning of gold amalgam in the open air. This practice produces mercury fumes, which are released into the atmosphere.

2.5.2 Safety and Health Impacts

Small scale gold mine operators dig only to a limited depth, supported by wooden logs. Hand dug tunnels and shafts created by these miners are shallower and smaller than those of commercial mining companies, and have no logistical support (Ashton *et al*., 2001) making them prone to dangers of pit collapse and landslides. It is reported that the risks of fatal and disabling accidents are high, particularly in underground mines (Hilson, 2001). In China, Pakistan and many other countries more than 6,000 fatalities are estimated to occur in small scale gold mines each year (ILO, 1999).

In Ghana it was reported that over 124 people were trapped underground in a *galamsey* site at Dunkwa –on –Offin in the Central Region (Daily Graphic, 2010). Similarly, a mining pit caved in at Subrisu, near Tepa in the Ashanti Region, trapping five illegal miners to death. It was also reported that rescuers worked for about one hour to bring out the trapped illegal miners but only three out of the eight miners who had been trapped survived (Daily Guide, 2012). In another development, 12 small scale gold miners were trapped in a collapsed pit at Attaso in the Ashanti Region (Daily Graphic, 2010).

It is said that *galamsey* operators believe the superstition that anytime lives are lost in the mines, they are able to secure more minerals, for which reason when the accidents occur, the operators are rather spurred on to engage in their illegal activities (Daily Guide,2012).

The activities of the miners promote environmental modifications that support malaria vector growth by creating open pits, divert watercourses and subsequently result in pools of stagnant water (Akabzaa and Dramani, 2001).According to the Takwa District Medical Officer of Health Dr.Avorti, the common, mining-related diseases observed in the area over the years include vector-borne diseases such as malaria, schistomiasis and onchocerciasis.Respiratory tract diseases, especially pulmonary tuberculosis and silicosis are also common. A report by the District Medical Officer revealed that the Wassa West District has the highest incidence of malaria in the Western Region (Akabzaa and Darimani, 2001). Malaria is the primary cause of child mortality in the country and the Wassa West District is the worst affected area with an infant mortality rate as high as 85/1000 compared with the national average of 80/1000.

CHAPTER THREE

3.0 MATERIAL AND METHODS

3.1 Study Area

3.1.1 Location

The study area is made of about 45 communities spanning the Western and Central regions of Ghana. It lies between latitudes 5'50N and 5'00N and longitudes 1'10W and 1'80W. It spans a total area of about 3607km^2 (WRC,2012) and consists of six (6) districts, namely, Lower Denkyira, Assin North, Assin South, Mpohor Wassa East, Shama Ahanta East and Komenda Edna. It spans a total area of about 3607km^2(WRC, 2012).

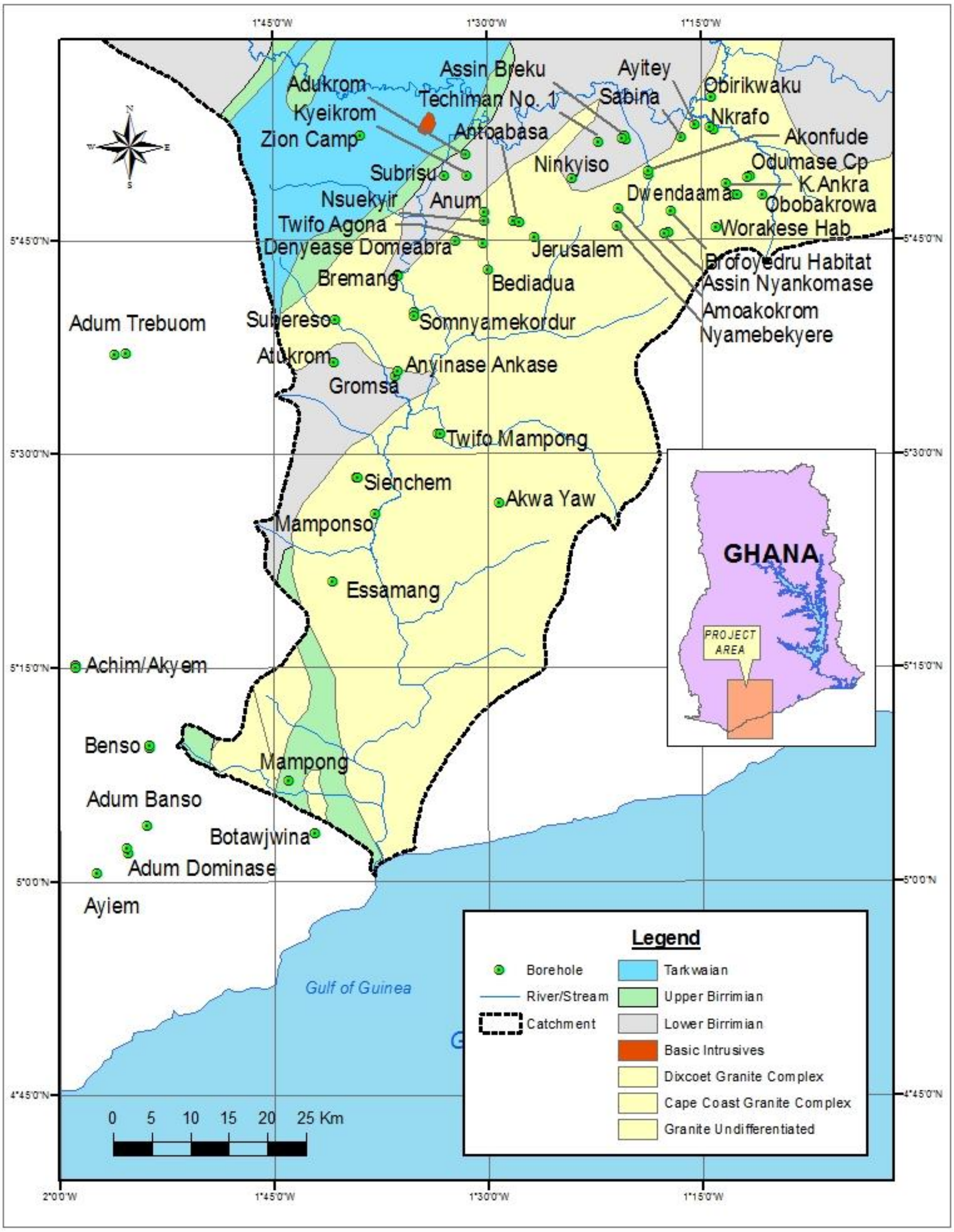

Fig1: Map Showing Sampling Communities (Ghana map Insert) within the different Geological Settings.

3.1.2 Climate

The climate is sub-equatorial wet, with two rainy seasons (May-July and September-November). The mean annual rainfall is relatively high, about 1,500mm but is also very variable, ranging between 1300 mm and 1900 mm. The basin is warm and moist throughout most of the year. Relative humidity is between 70%-80% throughout the year. In the drier seasons, temperatures are around 26ºC in August and 30ºC in March (WRC, 2012).

3.1.3 Vegetation

The Pra Basin lies entirely within the Forest Ecological Zone in Ghana. "Dickson and Benneh (1980) specifically associated the basin with the moist semi-deciduous forest which yields valuable timber species". Due to the expansion of the cocoa industry the original forest has changed to a secondary forest consisting of climbers, shrubs and soft woody plants. Many trees in the upper and middle layers exhibit deciduous characteristics. The vegetation generally thins out towards the coast (GWSC, 1989).

3.1.4 Topography and Drainage

The topography of the basin is generally undulating. The highest elevations occurring in the north, range between 458-610 metres above mean sea level and reduces to the lowland areas near the coast to15-30 metres. The Pra River and its tributaries constitute a major source of water supply to communities within the basin. It is made up of four major tributaries namely the Ofin, Oda, Anum and Birim. The Birim takes its sources in the Atewa Atwiredi range near Kibi whilst all the others take their source from the Mampong-Effiduasi area. These tributaries merge into the lower Pra which then flows into the Gulf of Guinea through its estuary at Shama (GWSC, 1989).

3.1.5 Geology and Soils

The predominant geological formations underlying the topography of the Pra Basin are mainly the Birrimian and Tarkwain both of the pre-cambian origin.

By constitution the Birrimian consists of metamorphosed lava, phyllities, schists and sandstones whilst the Tarkwaian mainly consists of quartzite, phyllites and schists. The soft constituent rocks like shales and phyllites are found in the valley and lower grounds (GWSC,1989).The basin is principally dominated by the forest ochrosol-oxysol intergrade .They also contain more nutrients and are alkaline. They have rather variable drainage properties and therefore require protection against erosion. In the lower Pra nearer the coast, further classification includes the acid gloisol and coastal savannah soil groups (GWSC, 1989).

3.1.6 Economic Activities

The Pra Basin in general has considerable potential for development in agriculture, forestry, tourism, and mining, and provides livelihoods for many through these. Over 63% of the population is engaged in the Agriculture and related sectors of the economy. Both commercial and subsistence agricultural activities are practiced, with cocoa being the main commercial crop (WRC, 2012). In the districts where large scale cocoa farming is practiced within the basin, annual returns in terms of family income are high and the standard of living is appreciable. In the Benso area of the Western region commercial oil palm plantation is prevalent. It was observed that small-scale palm oil industries are situated around Assin North and Benso areas because of large oil palm plantations. Fishing is the main occupation along the coast. Subsistence agriculture is largely practiced with production of food crops such as cassava, plantain, and maize. Of late there has been a surge in small scale mining in the basin with its attendant pollution problem.

3.2 Sample Collection

Samples were collected from 65 boreholes in about 45 communities. The samples were collected two times, January 2012 and April 2012 for the dry season and June and October for the wet season. Samples for nutrient analysis were collected in 1Litre sterile plastic bottles, whilst that for heavy metals were collected in 300 ml plastic containers and acidified with concentrated Nitric Acid (HNO_3) to lower the pH to 2. Some amount of water was pumped out of the boreholes before each sample was taken. These bottles were previously soaked in 5% HNO_3 over-night and thoroughly washed with distilled water. Temperature, pH, and conductivity were measured in the field using Hach Sens ion 156 meter. The samples were transported to the laboratory at a temperature of about 4 ºC in an ice chest for analysis.

3.3 Laboratory Analysis

3.3.1 Determination of Total Metals

3.3.1.1 Sample Preparation and Analysis.

An aliquot of 100 ml of water sample for metal determination is transferred into 125 ml conical flask. 5 ml of concentrated HNO_3 was added and evaporated on a hot plate to the lowest volume before precipitation occurs. Digestion is completed by the appearance of a light-coloured clear solution. The solution was then filtered through 0.45 µm filter paper and transferred into a 100 ml volumetric flask, cooled and top to the mark for analysis. A blank was also prepared through the same procedure (APHA, 1998).

The concentration of Cu, Fe, Mn, Cd, Zn, Pb were determined using Agilent 240FS Atomic Absorption Spectrometer by direct aspiration of the water samples into an air acetylene flame, and Al into nitrous oxide acetylene flame. Se and As were determined using a hydride generant attached to the Atomic Absorption Spectrometer. Hg was determined using AAS- cold Vapour.

3.3.1.2 Determination of Phosphate

Phosphate was determined by Stannous Chloride method using T60 UV spectrometer at a wavelength of 690nm.

Standard phosphate solutions of known concentrations ranging from 0.1 mg/l to 1.0 mg/l were prepared from a high grade anhydrous KH_2PO_4 for use as a calibration curve. For each portion of 50 ml sample, 2 mls of already prepared molybdate reagent and 0.25 mls stannous chloride reagent were added. The same treatment was done to the calibration standards including a blank. The spectrometer was zeroed with the blank and read within 12 minutes at wavelength of 690 nm.The absorbance of the molybdenum blue at this wavelength is proportional to the concentration of the phosphate in the sample (APHA, 1998).

3.3.1.3 Determination of Sulphate

Sulphate was determined by turbidimetric method at a wavelength of 420nm usingT60 UV spectrometer. Standard sulphate solutions of known concentrations (5, 10, 20,40 mg/l) were prepared from a high grade (Analar) anhydrous Na_2SO_4 and read at 420 nm on the spectrometer for a calibration curve. 5 mls of already prepared conditioning reagent was added to 100 mls of sample and mixed by stirring. A few crystals of barium chloride were added whilst still stirring and timed for 60 sec. They were measured on the spectrometer and their concentrations obtained by the help of the calibration curve (APHA, 1998).

3.3.1.4 Determination of Nitrate

Nitrate was determined by hydrazine reduction method. Standard nitrate solutions of known concentrations (0.2, 0.4 0.6, 0.8, 1.0 mg/l) were prepared from a high grade (Analar) KNO_3 and read on the UV spectrometer for calibration curve.10ml each of the sample were pipetted into a test tube and 1.0 ml of 0.3 M NaOH was added, mixed gently after which 1.0 ml reducing mixture was added. They were heated a 60 °C for 10min. In a water bath, cooled to room temperature after which 1.0 ml colour developing reagent was added. The samples with the reagents were mixed thoroughly and read at an absorbance of 520 nm.

3.4 Quality Control

The accuracy of the analysis was ensured by the use of Standard Reference material (NIVA 1042L) provided by the Norwegian Institute of Water Resources alongside the samples. For Hg, As and Se, internal control standard were prepared from high purity commercially prepared reagents. Glass wares used in analysis were thoroughly clean by soaking them overnight in 5% HNO_3 and well rinsed in distilled water before use. Readings were repeated after every ten samples to ensure reproducibility (Table 4).

3.5 Statistical Analysis

An SPSS statistical package was employed for data analysis. Specifically, Mann-Whitney test was used to determine whether significant differences exist between seasonal data. In addition the heavy metal values were correlated with depth of the boreholes

CHAPTER FOUR

4.0 RESULTS

4.1 Physical parameters.

4.1.1 pH, Temperature, and Conductivity

The mean values of the physical parameters of the water samples for each community are presented in Table1 and illustrated graphically in figures 2 and 3.

Table1: Results of physical parameters of water samples.

		pH		Temp °C		EC µS/cm	
Community	**Sample ID**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	BH1	4.90±0.01	6.45±0.21	26.9±0.07	28.2	270±0.5	180±3.0
Ayitey	BH2	5.30	5.94±0.04	27.6±0.02	31.8±0.06	200±2.0	180
Nkrafo*	BH3	5.55±0.02	6.60±0.1	26.7±0.05	28.9±0.05	270±5.2	205±2.0
Obirikwaku	BH5	6.20	6.05±0.1	25.7±0.05	29.5	260±1.3	210
Odumasi	BH6	5.80±0.01	5.56	26.2±0.04	27.5±0.02	150±2.4	110±3.1
OdumasiCamp	BH7	6.20±0.02	5.67±0.2	26.9	27.7	300±4.0	200
Obobakokrowa	BH8	6.90±0.05	5.24±0.06	25.6±0.03	28.7	290±3.4	210±2.4
Dwedaama*	BH9	5.85±0.2	5.82±0.3	26.2±0.01	28.9±0.03	165±1.2	125±2.6
Worakase Habitat	BH11	5.80±0.04	4.73	26.5±0.1	25.7	80	80±1.0
Brofoyedru Habitat	BH12	5.2±0.03	4.47±0.05	28.2	25.6±0.1	120±1.4	100±2.0
AssinNyankumase*	BH13	7.36±0.06	4.89±0.03	28.6±0.1	27.9±0.2	240±3.0	203±3.4
Akonfudi*	BH16	6.40±0.1	5.11±0.03	29.2±0.05	27.0±0.3	395±4.5	295±3.1
AssinBreku*	BH18	6.0±0.1	6.41±0.04	30.5±0.1	27.2±0.1	310±3.5	323±6.0
Techiman No 1	BH21	6.10	5.12	29.1	26.9±0.04	60	60±1.5
Kwame Ankra	BH22	6.51	5.35±0.02	28.0	26.2	143±0.6	110±1.0
Ninkyiso	BH23	5.83±0.05	4.92±0.03	28.2±0.04	26.9	210±4.5	170±3.5
Amoakokrom	BH24	5.80	4.96±0.03	28.8±0.2	27.3±0.05	320±1.0	240±2.2
Nyamebekyere	BH25	5.60	5.63±0.07	27.2±0.1	26.8±0.02	170±5.0	130±3.2
Jerusalem	BH26	6.12±0.3	5.03	30.4±0.06	26.6±0.05	80±3.0	70
Antoabasa*	BH27	5.9±0.1	5.21±0.04	30.2±0.03	27.9±0.04	195±5.5	155±2.2
Bedidua	BH29	6.5±0.05	5.15	28.8	28.3±0.05	220±2.8	170±3.4
Anum	BH30	6.0±0.02	_	28.3±0.04	_	270±2.1	_
Kyeikrom	BH31	5.6±0.1	5.70	31.6±0.05	31.0±0.04	150±3.2	120±1.3
Adukrom	BH32	5.91±0.02	_	27.1±0.05	_	140±0.5	_
Subrisu	BH33	6.00	_	27.0±0.04	_	240±2.0	_
Nsukyir	BH34	5.92	5.40	26.5±0.03	27.3±0.03	170±3.5	170±2.5
DenyeaseDomeabra	BH35	5.61±0.1	5.98±0.060	28.0	27.1±0.04	220±5.0	160±3.0
TwifoMampong*	BH36	6.20	5.07±0.1	28.6	29.4±0.07	710±3.0	405±2.5
Akwa Yaw	BH38	6.60±0.21	_	29.3±0.04	_	130	_

Bremang*	BH39	6.15±0.3	6.12±0.1	29.8±0.01	31.3±0.01	275±0.7	230
TwifoAgona	BH41	5.90±0.04	4.96±0.02	28.8±0.02	29.3±0.01	190	140±4.2
Somnyamekordru*	BH42	5.80±0.05	6.10±0.03	26.8±0.03	28.3±0.05	765±0.5	270±5.6
AtuKrom	BH44	5.60	4.95±0.06	29.5±0.02	28.1	350±7.1	240±6.1
Subresu	BH45	6.10±0.03	5.29±0.02	28.1	28.4±0.03	190±5.5	200
Gromsa	BH46	6.90	4.40±0.04	28.9±0.02	27.1±0.05	190±3.5	150±3.0
AnyinaseAnkase	BH47	6.40±0.07	4.66±0.03	28.5±0.03	26.3	100	90±2.1
Semchem	BH49	6.10±0.05	4.56±0.04	27.2	27.6	400±7.0	300±7.3
Mampong	BH50	5.30±0.02	5.02±0.01	26.4±0.02	27.6±0.02	110±3.5	100±2.2
Essamang	BH51	5.80±0.01	5.60	26.7±0.02	27.6	60±2.0	50
Achim/Akyem*	BH52	6.49±0.02	5.70±0.01	26.8±0.04	26.7±0.03	415±8.8	411±5.6
Ayiem	BH55	5.73±0.03	5.90	28.5±0.01	28.5±0.05	140±2.3	137±2.1
Botawjwina*	BH56	6.55±0.01	6.42±0.03	28.9±0.02	28.8±0.02	769±7.9	756±8.0
Benso*	BH58	5.63±0.02	5.76±0.02	28.1±0.03	27.6±0.02	365±5.8	359±5.7
AdumBanso	BH61	5.64±0.02	5.80	26.5	27.8±0.03	411±3.9	402
AdumDominase*	BH62	5.70±0.01	5.72±.03	28.5±0.02	28±0.04	219±2.6	215±2.1
AdumTrebuom*	BH64	6.25±.03	6.30±0.01	27.7±0.03	26.7±0.01	265±3.2	258±2.3
Min Value		**4.90**	**4.40**	**25.6**	**25.6**	**60**	**50**
Max Value		**7.36**	**6.60**	**31.6**	**31.8**	**769**	**756**

*Borehole averages for communities.

The mean pH for the dry season (January and April,2012) range between 4.9 and 7.9 with the minimum recorded at Sabina and the maximum recorded at Assin Nyankumasi both in the Assin North district of the central Region. The wet season(June and October,2012) recorded values between 4.24 and 6.87 with the minimum being recorded at Twifo Mampong and the maximum at Nkrafo in the Assin south and Assin North of the Central region respectively (Appendix 1A).

The mean temperature for the dry season ranges from a minimum of 25.5 °C to a maximum of 31.6 °C.

The wet season temperature ranged from 25.6 °C to a maximum of 31.8 °C

Electrical Conductivity for the dry season ranges between 60 µs/cm at Essamang and Techiman Number 1 to 1140 µs/cm at Twifo Manpong. The wet season recorded values between 50 µs/cm at Essamang to 906 µs/cm at Botawjwina (Appendix I A).

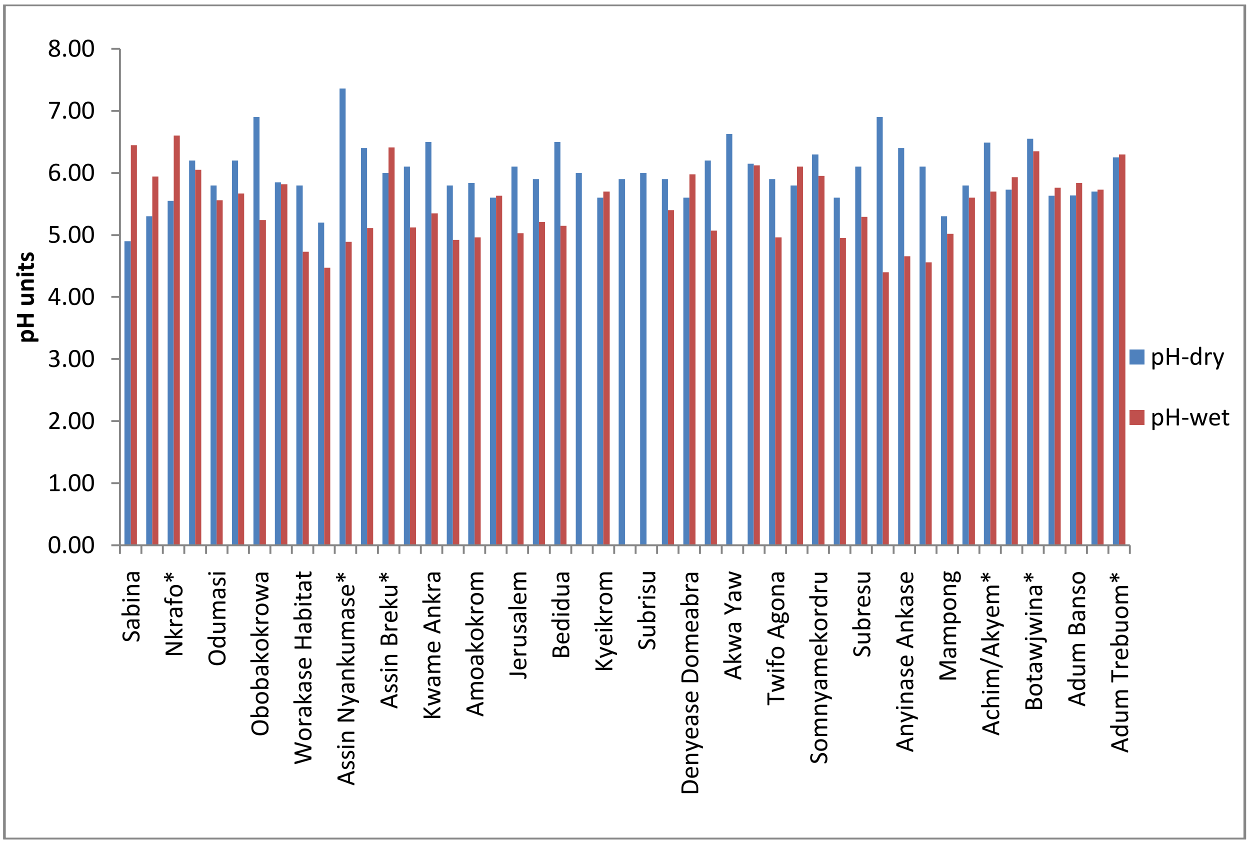

Fig 2: Comparison pH values of water for dry and wet seasons.

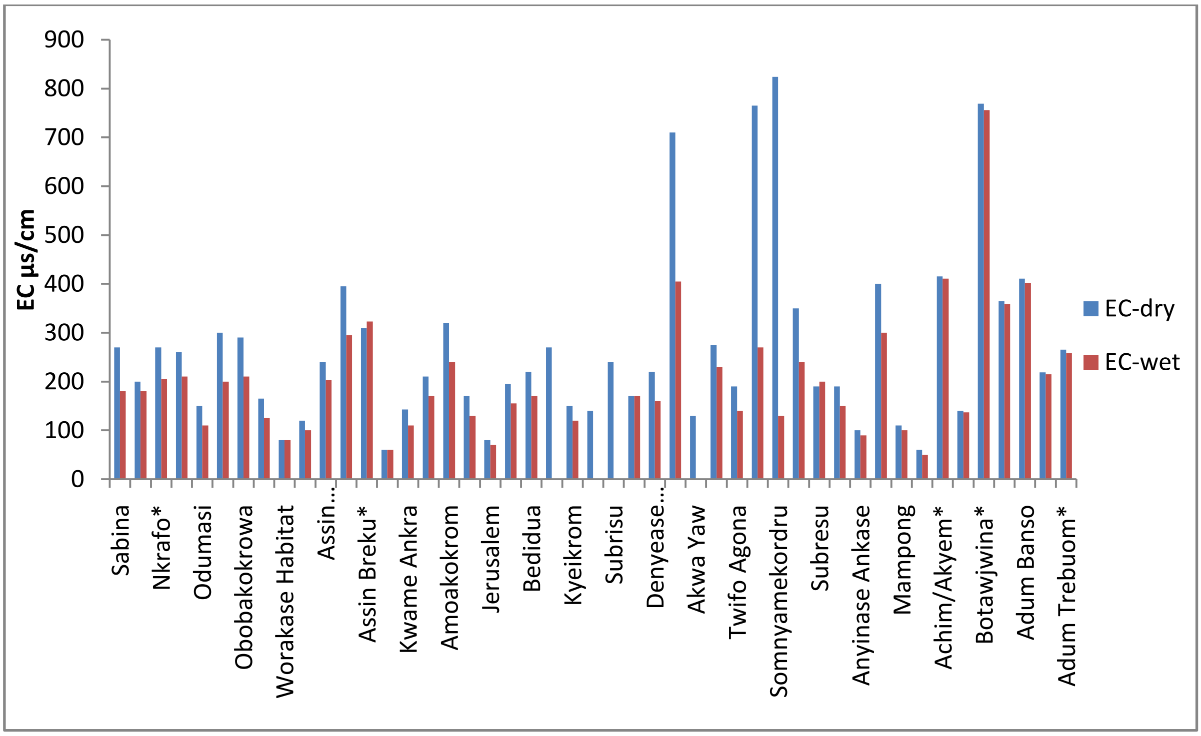

Fig3: Comparison of EC values of water for dry and wet seasons

4.2. Metal Results

The mean values of heavy metals of the water samples are presented in Tables 2A and 2B below.

Table 2A: Metal values of water for dry and wet seasons

	Cu µg/l		Mn µg/l		Zn µg/l		Cd µg/L		Pb µg/l	
Communities	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	53.0±7.1	5±1.7	92±8.3	182±7	2.5	13±1.8	1.0	6.0	62±4.5	55±4.2
Ayitey	5.0±0.4	5±1.1	8±2.2	43±3.4	2.5	7±0.7	1.0	1.0	59±6.7	59±2.8
Nkrafo*	12.5±2.1	5±0.6	20±0.6	40.5±2.3	2.5	2.5	1.0	1.0	38±4.7	44±13
Obirikwaku	20.0±5.7	51±0.6	58±0.7	116±7.2	2.5	68±0.9	1.0	1.0	26±3.5	34±15
Odumasi	5.0±0.2	5±0.5	35±3.3	164±0.9	7±0.8	73±3.4	1.0	1.0	49±0.7	51±9.7
OdumasiCamp	5.0±0.1	5±0.6	50±2.1	322±12	2.5	246±9.1	1.0	1.0	55	2.5
Obobakokrowa	18±4.1	74±9.4	400±21	165±6	2.5	162±7.6	1.0	1.0	59±7.8	55±15
Dwedaama*	59±8.3	105±11	36±0.8	244±7.6	6.25±1.1	53.5±7.2	1.0	1.0	38.5±2.9	2.5
Worakase Habitat	5±0.3	18±0.6	43±0.3	8±0.5	2.5	5	1.0	1.0	40±6.3	2.5
Brofoyedru Habitat	5±0.9	57±3.5	41±3.4	9±0.4	2.5	11±2.1	1.0	5.0±0.2	36±3.3	55
AssinNyankumase*	5±0.8	41±5.4	50.8±4.0	61±2.2	2.5	30	1.0	5.6±	6.33±0.7	9.7±0.3
Akonfudi*	42±7	48±4.1	200±13	209±3.1	34.2±3.2	47.5±3.0	1.0	7.5±0.3	10.3±0.5	17.3±6.5
AssinBreku*	5±1.3	50±5.3	47.5±0.8	53.6±4.5	2.5	10.6±1.2	1.0	5±0.1	37±0.8	14
Techiman No 1	5±1.6	166±4.1	2.5±0.1	9±0.1	43±0.8	191±7.3	1.0	7±0.3	5	10±0.8
Kwame Ankra	5±1.3	31±3.2	2.5	31±1.6	5	192.2	1.0	6±0.2	10±3.1	56±10
Ninkyiso	5	5±1.0	9±0.3	17±0.4	2.5	19±1.9	1.0	4±0.1	2.5	26±9.8
Amoakokrom	5±0.6	60±3.5	87±4.3	11±0.2	2.5	264±11	1.0	12±0.3	2.5	2.5
Nyamebekyere	5±0.7	17±6.3	2.5	49±0.8	2.5	27±1.9	1.0	9±0.3	2.5	23
Jerusalem	5±0.1	119±7.7	2.5	31	98±6.3	183±3.6	3.0±0.1	6±0.1	2.5	11±5.6
Antoabasa*	5±2.0	5±1.1	62±6	43±0.9	2.5	18.5±1.9	1.0	13.5±2.6	2.5	9.25±1.7
Bedidua	5±0.4	21±3.3	27±1.7	45	2.5	28±3.1	1.0	11	2.5	2.5
Anum	5±0.5	_	57±2.8	_	2.5	_	1.0	_	2.5	_
Kyeikrom	5±0.1	5	2.5	2.5	2.5	2.5	1.0	1	2.5	29
Adukrom	5	_	2.5	_	2.5	_	1.0	_	2.5	_
Subrisu	5	_	6	_	2.5	_	1.0	_	8.0±1.7	_
Nsukyir	5±0.3	16±1.3	8±0.9	43±4.1	2.5	27±2.1	1.0	2	2.5	2.5
DenyeaseDomeabra	5±0.3	5	_	126±7.1	_	14±2.5	1.0	9±0.8	2.5	42±0.8
TwifoMampong*	20.0±7	5±0.2	57±2.9	52	16	37±5.2	1.0	10±1.4	2.5	2.5
Akwa Yaw	5	_	21±0.7	0	2.5	_	1.0	_	2.5	0
Bremang*	5±2.0	32.5±3	50±2.4	1034±6.2	2.5	24±2.4	1.0	2	2.5	36±6.6
TwifoAgona	5±1.2	5	37±0.9	71±2.3	2.5	24±6.0	1.0	2	2.5	2.5
Somnyamekordru*	5±1.4	23±2.9	81±1.1	132±3.8	2.5	19±3.3	1.5	6±0.6	5	75±12
AtuKrom	5±1.1	27±0.5	261±3.4	202±2.0	41±3.6	82±6.7	1.0	1	2.5	50±5.6
Subresu	5±1.3	5	103±4.1	839±13	2.5	96±4.0	1.0	1	2.5	5
Gromsa	5±0.9	78±6.3	14±1.3	169±5.3	2.5	34±2.6	1.0	1	2.5	30±3.3
AnyinaseAnkase	5	15±3.2	2.5	41±2.3	2.5	62	1.0	1	24±4.6	5
Semchem*	22±4.4	26.5±4	434±11	569±11	2.5	62.5±13	1.0	2±0.1	23.5±2.4	22±6.1
Mampong	5±0.6	28±5.1	15±3.1	133±4.5	2.5	5	1.0	2	2.5	112±0.8
Essamang	5±0.1	10±3.4	44±2.1	23±3.8	2.5	2.5	1.0	1	31±6.4	2.5
Achim/Akyem*	23±3.2	12±4.1	20±0.1	675±12	20.5±2.2	44±3.5	1.6±0.1	1	11.6±3.3	8.33±4.9

Ayiem	5	15±5.2	553±3.0	234±3.7	21±1.9	228±0.4	1.0	1	8±0.6	2.5
Botawjwina*	24±0.5	59±2.3	136±7	252±3.6	35±5.2	154±7.6	1.5	1	13±0.8	2.5
Benso*	19±3.6	28±0.7	337±14	271±3.4	30.3±3.6	48.2±0.8	1.0	1	13.3±3.7	12.8±1.9
AdumBanso	5	5	330±5.5	199±2.9	16±0.3	29±2.8	1.0	1	15±2.3	2.5
AdumDominase*	23.5±6.4	13.5±3	258±3.0	155±6.8	18±0.5	19.5±3.7	1.0	1	9.75±4.2	2.5
AdumTrebuom*	46±3.8	31±2.7	67±1.0	41±3.7	9.5±0.2	19±4.2	1.0	1	2.5	5.25
Min Value	**5**	**5**	**5**	**5**	**5**	**5**	**1**	**1**	**2.5**	**2.5**
Max Value	**59**	**116**	**553**	**1034**	**98**	**264**	**3**	**16**	**62**	**112**
W.H.O. Guideline	**2000**		**500**		**3000**		**3.00**		**10**	

Table 2B: Metal values of water for dry and wet seasons

	Fe µg/l		Al µg/l		As ug/l		Hg ug/l		Se ug/l	
Community	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	526±13	58±20	26±2.3	5.0	0.03±0.01	5.1±0.2	5.45±0.1	0.63±0.1	10.3	0.005
Ayitey	160±6.7	102	5.0	5.0	0.03	1.29±0.1	5.91±0.1	0.23±0.1	5.4±0.1	0.005
Nkrafo*	325±13	182±14	159±0.9	5.0	0.005	2.02±0.1	12.8±1.1	1.31±0.2	0.005	0.005
Obirikwaku	465±9.5	130±0.8	61±3.5	5.0	0.005	4.11±0.3	7.3±1.0	0.005	0.005	0.005
Odumasi	714±12.8	372±23	55	5.0	0.005	0.06	4.27±0.5	0.005	0.005	0.005
OdumasiCamp	492±10.2	38	237±8.7	5.0	0.005	0.005	4.12±0.3	0.005	0.005	0.005
Obobakokrowa	_	49	5.0	50	0.005	0.005	2.72±0.2	0.005	0.005	0.005
Dwedaama*	62.5±0.8	726±16	7.5±1.4	131	0.005	0.31±0.1	1.25	0.005	0.005	0.005
Worakase Habitat	44±0.9	5	132±6.7	63	0.005	0.005	1.11±0.1	0.005	0.005	1.2±0.2
Brofoyedru Habitat	42±1.4	5	5.0	13	0.02±0.001	0.005	1.36±0.1	15±2.3	0.005	0.005
Assin Nyankumase*	99±3.6	39±6.1	9.6±0.1	330	0.03±	0.005	5.73±0.2	3.94±0.2	0.005	0.005
Akonfudi*	64±0.2	47±0.6	5.0	127	0.05±0.004	0.005	4.41±0.1	0.005	0.005	0.005
AssinBreku*	815±13.6	164±0.7	66	23.6	0.05	0.005	1.48±0.1	3.49±0.3	0.33±0.1	0.005
Techiman No 1	47±0.4	28	195±4.3	134	0.17±0.003	0.005	2.00	0.005	0.35	0.005
Kwame Ankra	106±0.7	19±0.4	5.0	96	0.04	0.005	0.68	0.005	1.41±	0.005
Ninkyiso	409±4.6	15	727±12	497	0.005	0.71±0.1	3.81±0.1	0.005	0.005	0.005
Amoakokrom	1211.3±	28	118±3.5	99	0.13	0.26±0.1	3.69±0.3	0.33±0.1	0.2±	7.2±1.3
Nyamebekyere	1081.7±	40±3.4	296±1.8	129	0.005	0.89±0.1	4.02	0.97±0.2	0.2±	0.005
Jerusalem	5.0	35	182±2.3	25	0.13±0.01	_	1.84±0.1	2.07±0.4	0.35±	6.7±1.3
Antoabasa*	327±2.5	28±1.2	177±7.8	139	0.21±0.01	0.22	4.8	2.0	0.005	3.5±0.2
Bedidua	38	41±2.1	5.0	91	0.05	0.22	6.04±0.4	0.005	0.005	6.7±0.2
Anum	368±7.8	_	162±8.9	_	0.15±0.02	_	0.59±0.1	_	1.16±	_
Kyeikrom	45±1.5	5.0	399±7.1	5.0	0.04	0.005	1.06±0.1	0.005	0.005	0.005
Adukrom	101±3.7	_	157±3.4	0	0.1±0.005	_	2.44±0.2	_	0.005	_
Subrisu	101±2.5	_	5.0	0	0.05	_	2.28±0.2	_	0.005	_
Nsukyir	924±9.7	192±12	5.0	57	0.005	2.4±0.1	3.93±0.2	0.005	0.005	7.2±0.1
Denyease Domeabra	5.0	125±7.2	_	197	0.05	0.45±0.03	1.94±0.1	0.005	0.005	0.005
Twifo Manpong*	129±0.6	26±0.8	611±12	54	0.22±0.1	0.13±0.04	7.03±0.1	0.005	0.005	3.5±0.1
Akwa Yaw	78±3.1	_	17±0.8	_	0.06	_	5.72±0.1	_	0.005	_
Bremang*	347±2.6	2195±36	196±3.0	12	0.5	0.85±0.1	5.18±0.1	3.87±0.2	0.005	0.75
TwifoAgona	220±4.5	135±8.3	5.0	5.0	0.18±0.01	0.87±0.1	4.11±0.2	1.95±0.2	0.005	0.005
Son-nyamekordru*	295±3.8	411±3.2	182±2.6	929	0.24±0.02	0.45	1.66±0.1	5.04±1.1	0.005	0.12±0.
AtuKrom	186±11	406±5.6	43±1.4	567	19.1±0.01	0.06	1.53	7.89±1.1	0.005	0.005
Subresu	5.0	334±12	123±2.8	190	3.01±0.1	_	1.54±0.2	1.350.2	0.005	0.92±0.
Gromsa	113±7.6	115±8.5	5.0	127	1.82±0.05	0.06	0.89	16.4±2.4	0.005	2.4±0.1
AnyinaseAnkase	103±7.8	15	5.0	5.0	1.59±0.1	0	5.12±0.3	0.44±0.1	0.005	0.25
Semchem*	106±6.9	40.5±4.1	5.0	108	1.73±0.2	0.12±0.	4.5±0.2	4.19±0.1	0.005	0.117

Mampong	68±6.8	232±7.9	162±8.9	182	2.11±0.1	0.005	0.005	0.005	0.005	0.005
Essamang	170	5.0	176±6.9	10	2.31±0.1	0.005	0.005	3.96±0.3	0.005	3.5±0.2
Achim/Akyem*	31±5.8	82	14±1.4	86	1.67±0.2	1.68±0.2	1.67±0.1	14.4±3.3	0.221±0.1	0.9±0.3
Ayiem	54±4.9	1840±11	5	94	0.005	1.01±0.1	1.54±0.1	_	0.114±0.1	10.6±2
Botawjwina*	24±2.2	414±7.8	32±4.2	34.5	0.02	0.01	1.85±0.1	2.24±0.3	0.026	0.005
Benso*	14±2.8	88±2.6	23±2.1	104	3.37±0.2	4.38±0.5	2.6±0.1	8.11±1.2	0.014	2.5±0.1
AdumBanso	89±6.7	363±2.9	5	197	16±1.2	0.005	2.83±0.1	0.005	0.005	4.2±0.1
AdumDominase*	141±5.8	807±12.4	188±1.4	204	0.02±0.003	0.04	3.31±0.1	2.96±0.6	0.012	9.1±1.8
AdumTrebuom*	18	118±8.9	444±10	114	0.01	0.03	3.51±0.1	0.005	0.076	4.3±1.2
Min Value	**5**	**5**	**5**	**1**	**0.005**	**0.005**	**0.005**	**0**	**0.005**	**0.005**
Max Value	**924**	**2195**	**727**	**929**	**19.1**	**5.1**	**12.78**	**16.4**	**10.3**	**10.6**
W.H.O Guideline	**300**		**20**		**10**		**2**		**10**	

* Borehole average for a community.

The mean metal concentrations of the communities for the Basin is presented in Table 2A and 2B above, whilst that of the individual boreholes can be located in appendix I C

The mean copper value for the dry season ranged between 5.0 and 83 µg/l with the maximum being recorded at Dwedama in the Assin North District of the Central Region. The wet season recorded values between 5.0 and 191 µg/l with the maximum being recorded by the same borehole (BH10) at Dwedama (Appendix IC).

The mean Manganese value for the dry season ranged between 2.5 and 683 µg/l with the maximum being recorded at Semchem (BH49).The Wet season recorded values between 2.5 and 1544 µg/l with the maximum at Bremang (BH39) in the Agona District of the Central region.

Zinc recorded values between 2.5 and 98 µg/l for the dry season with the maximum at Jerusalem (BH26) in the Assin South District of the Central region. The wet season recorded values between 2.5 and 264 µg/l.

The mean Cadmium value for the dry season ranged between 1.0 and 3.0 µg/l whilst that of the wet season ranged between 1.0 and 16.0 µg/l with the maximum at Antoabasa (BH28).

Lead values ranged between 2.5 and 62 µg/l for the dry season with the wet season recording values between 2.5 and 118µg/l. The maximum values for dry and wet seasons were recorded at Sabina (BH1) and Sumnyamekordru (BH43) respectively.

The mean Iron values for the dry season range between 5.0 and 2130µg/l with the maximum being recorded at AssinBreku (BH18). The wet season recorded values between 5.0 and 2910 µg/l with the maximum recorded at Bremang (BH39).

Aluminium values for the dry season ranged between 5.0 and 727 µg/l with the wet season recording values between 5.0 and 1680 µg/l.

Mean Arsenic values for the dry season range between a detection limit of <0.01 and 19.1 µg/l with the maximum being recorded at Atukrom in the Central region. The wet season recorded values between <0.01 and 7.99 µg/l with the maximum at Benso (BH58).

Mercury for the dry season recorded values between 0.005 and 10.1µg/l with the maximum recorded at Twifo Mampong (BH37). The wet season values ranged between0.005 and 16.4 with the maximum being recorded at Gromsa (BH46).

The mean dry season selenium range between 0.005 and 10.3 µg/l and that of the wet season ranged between 0.005 and 10.6 µg/l with the maximum at Ayiem (BH55) in the Western Region.

Figures 4 to 11are graphical representations of seasonal variations of metal concentrations.

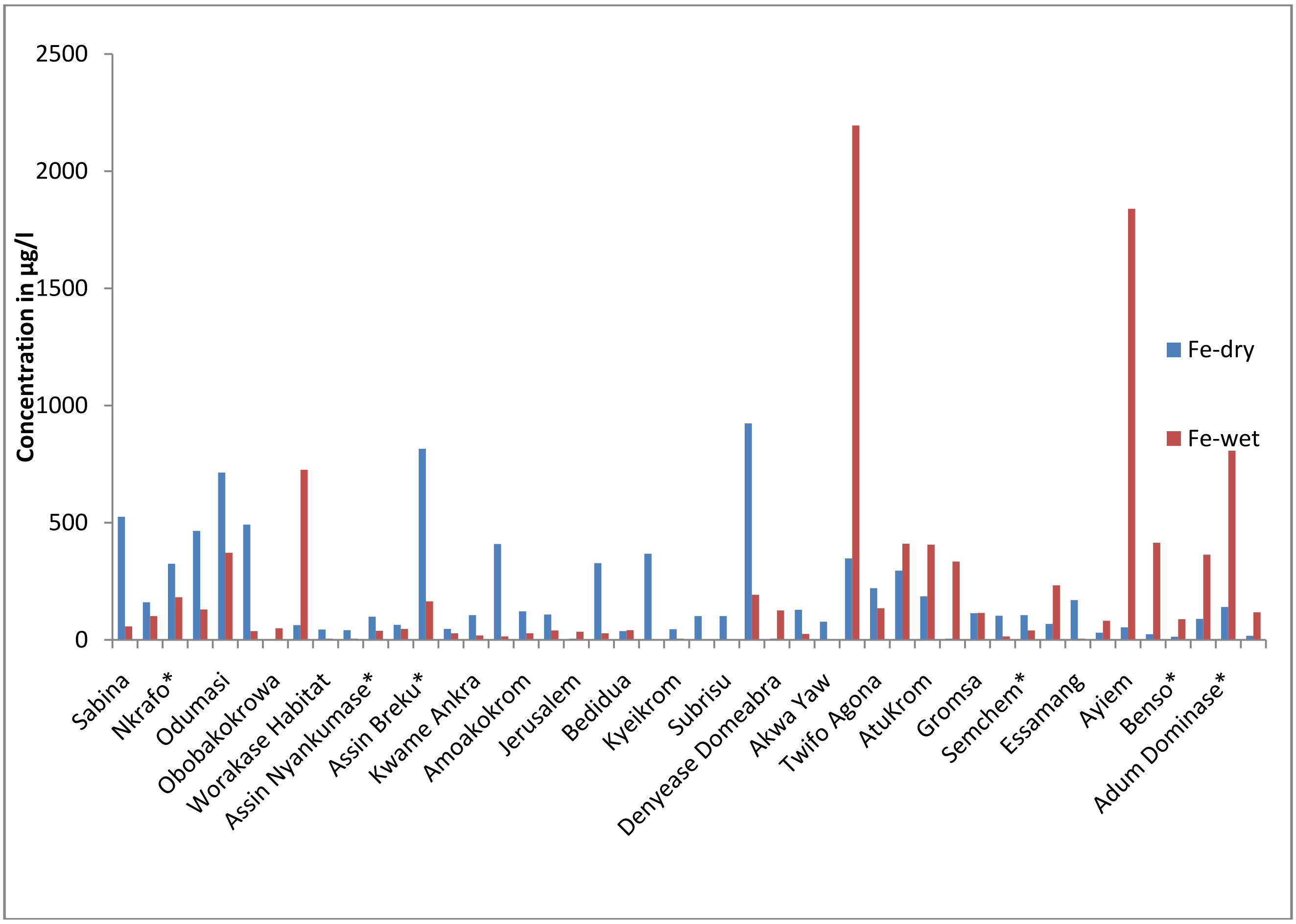

Fig 4: Comparison of Fe values of water for dry and wet seasons.

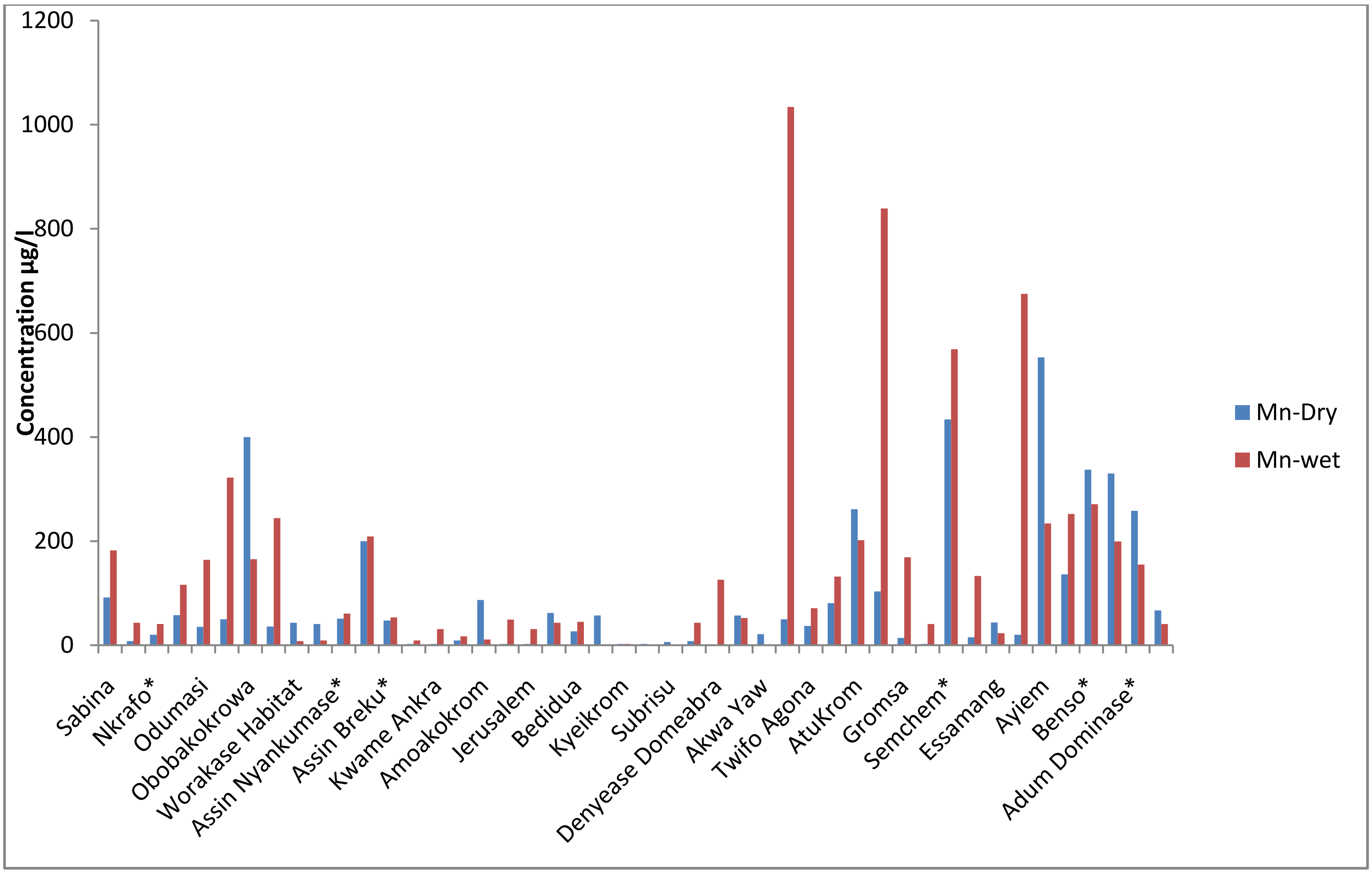

Fig 5: Comparison of Mn values of water for dry and wet seasons.

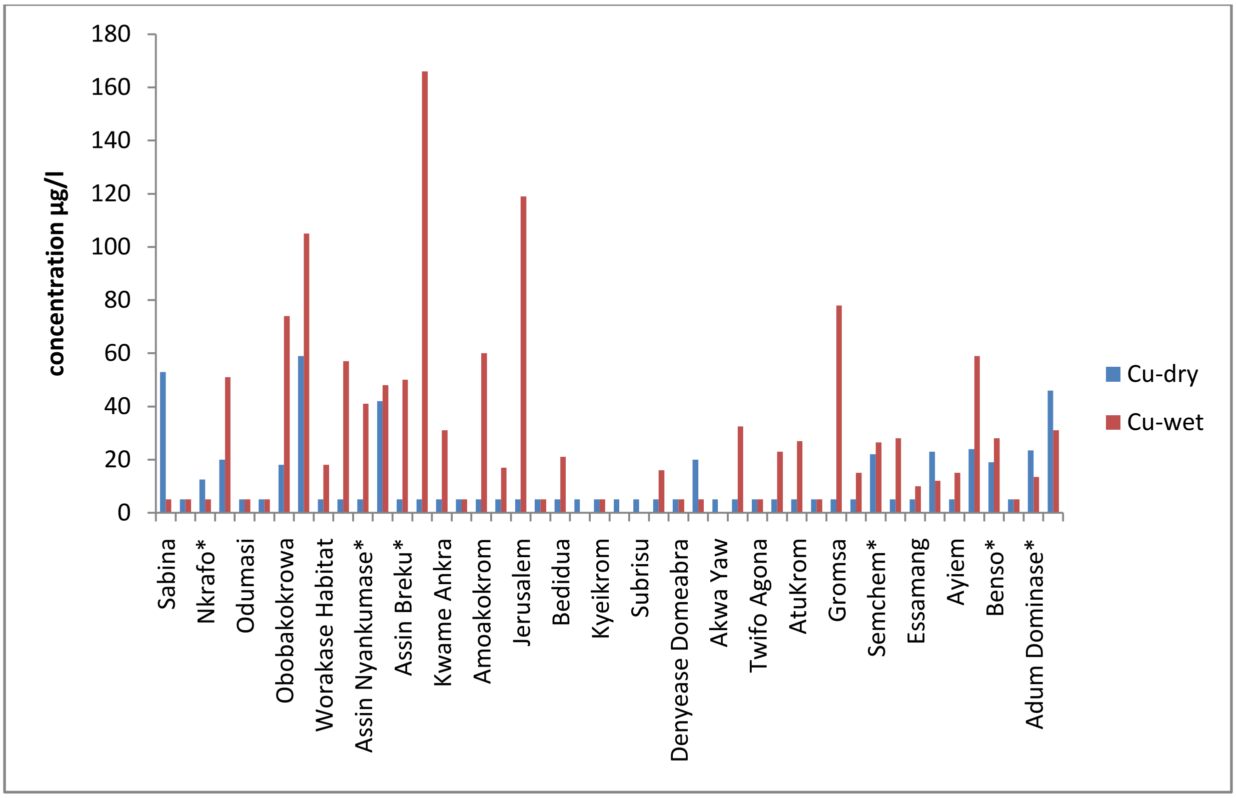

Fig 6: Comparison of Cu values of water for dry and wet seasons.

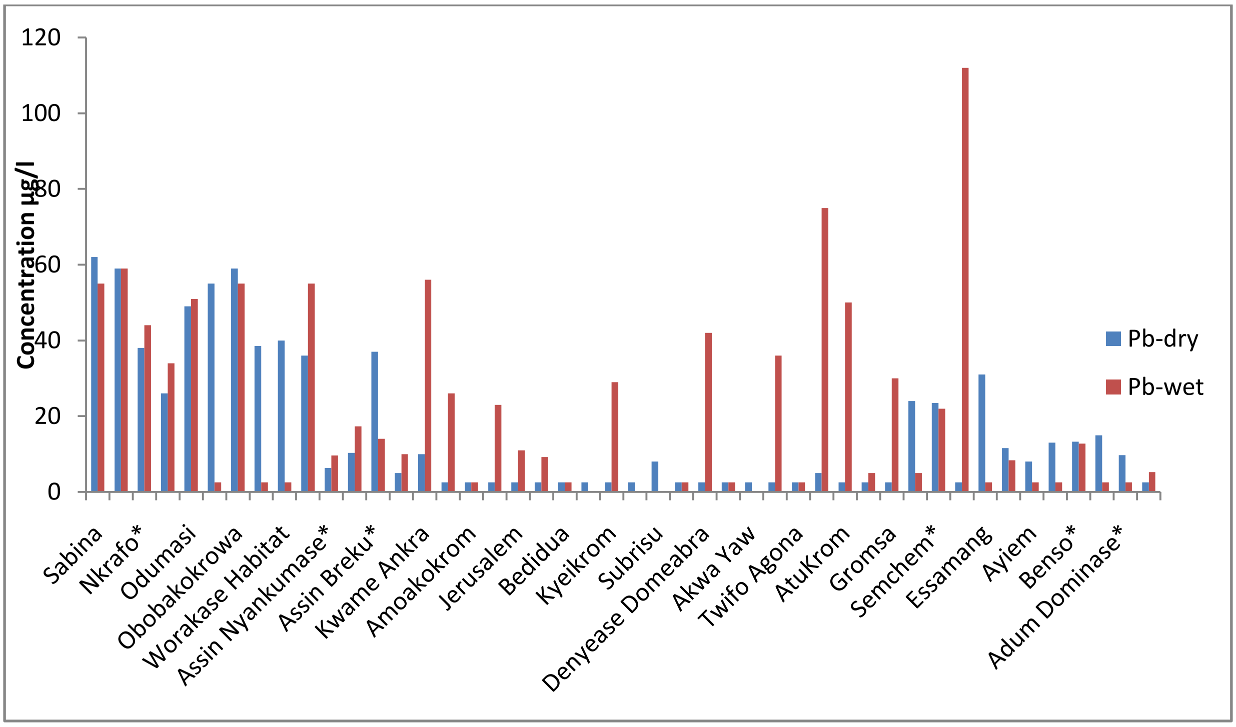

Fig 7: Comparison of Pb values of water for dry and wet Seasons.

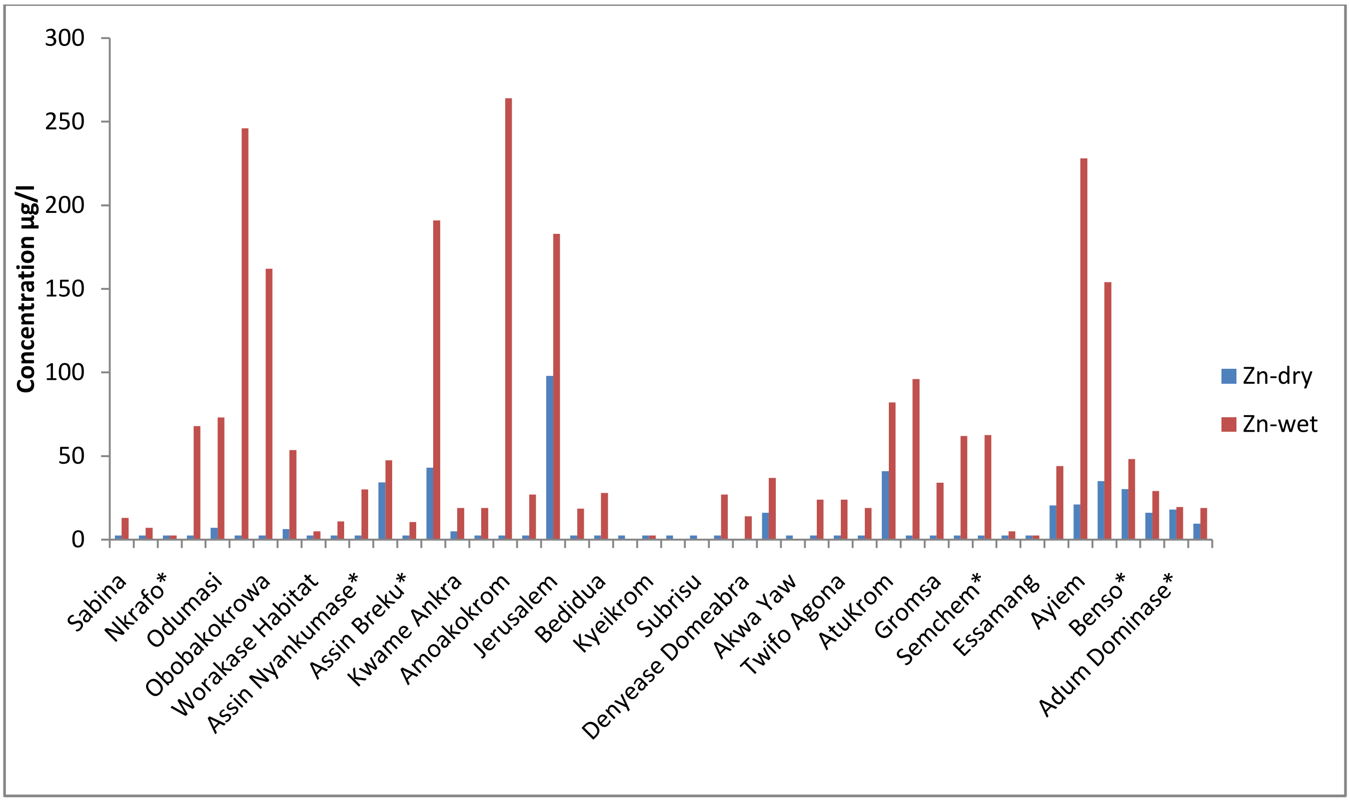

Fig 8: Comparison of Zn values of water for dry and wet seasons.

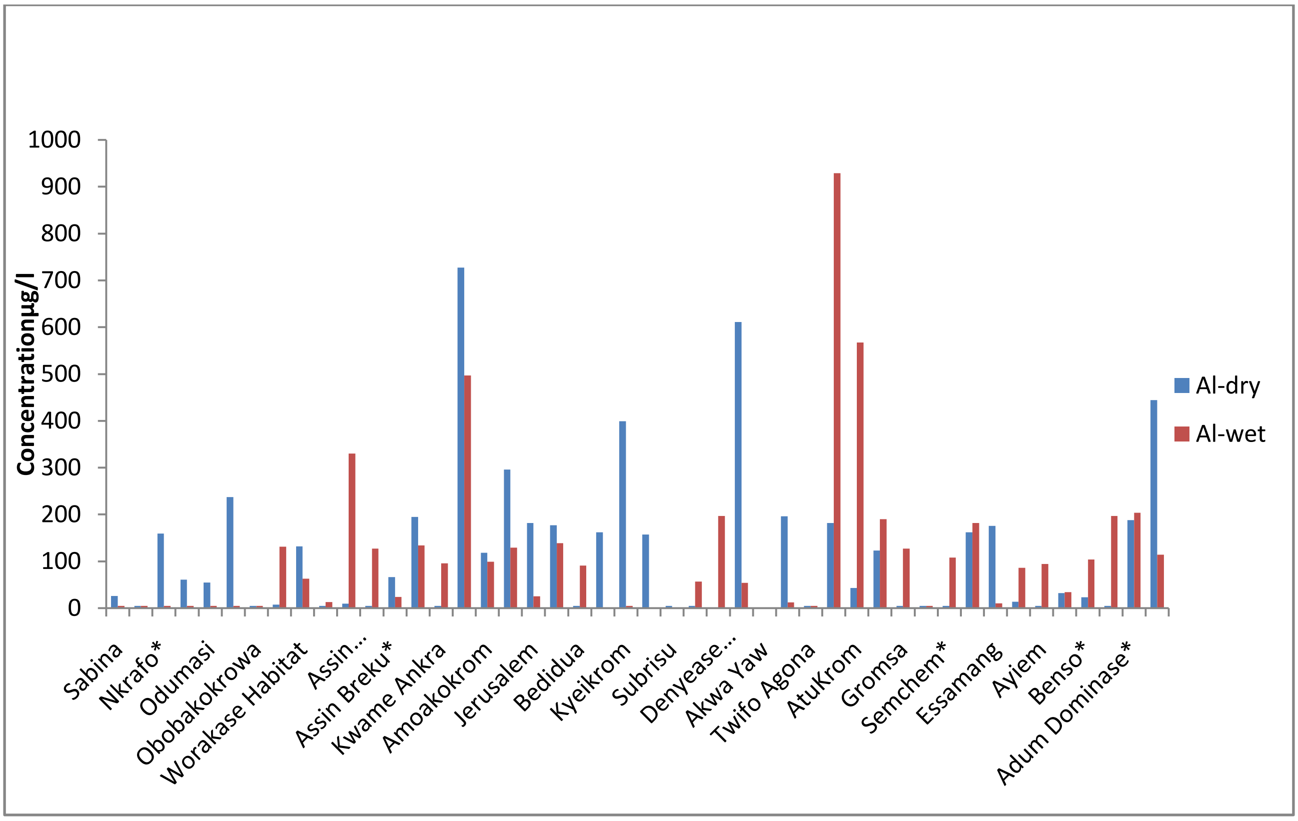

Fig 9: Comparison of Al values of Water for dry and wet seasons.

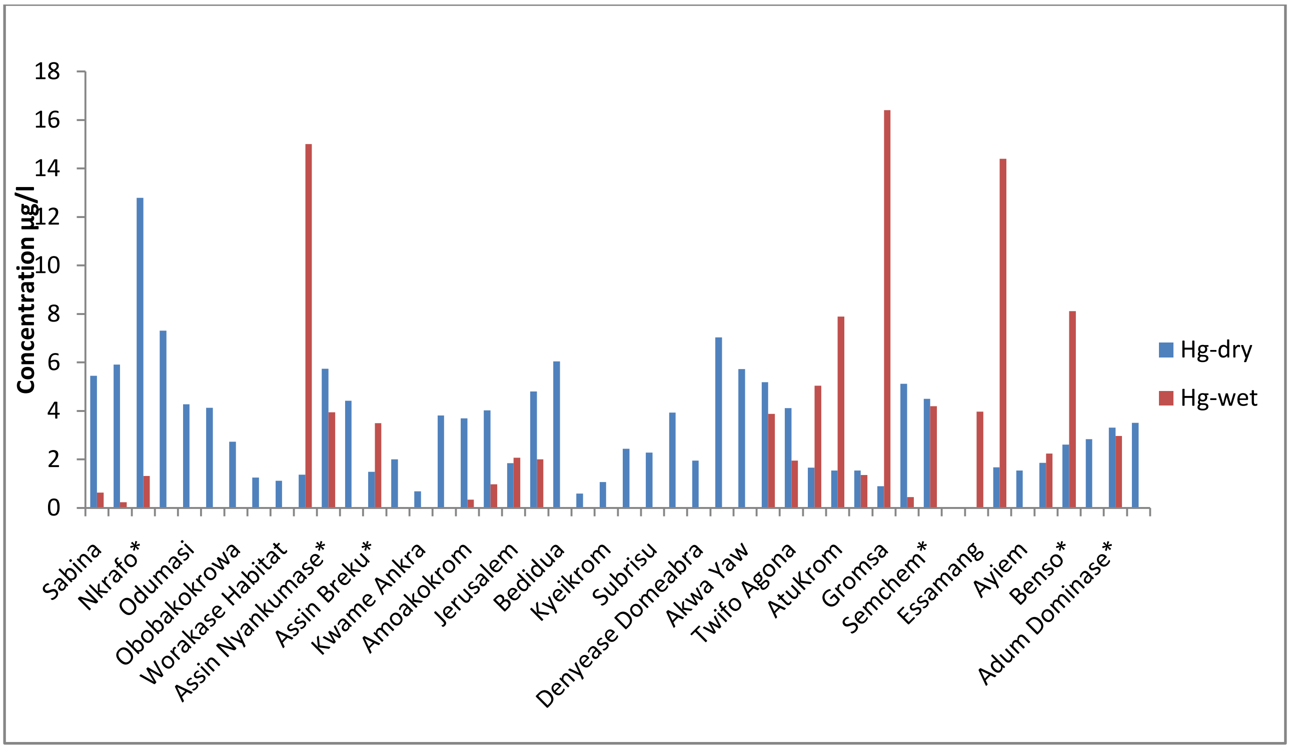

Fig10: comparison of Hg values of water for dry and wet seasons.

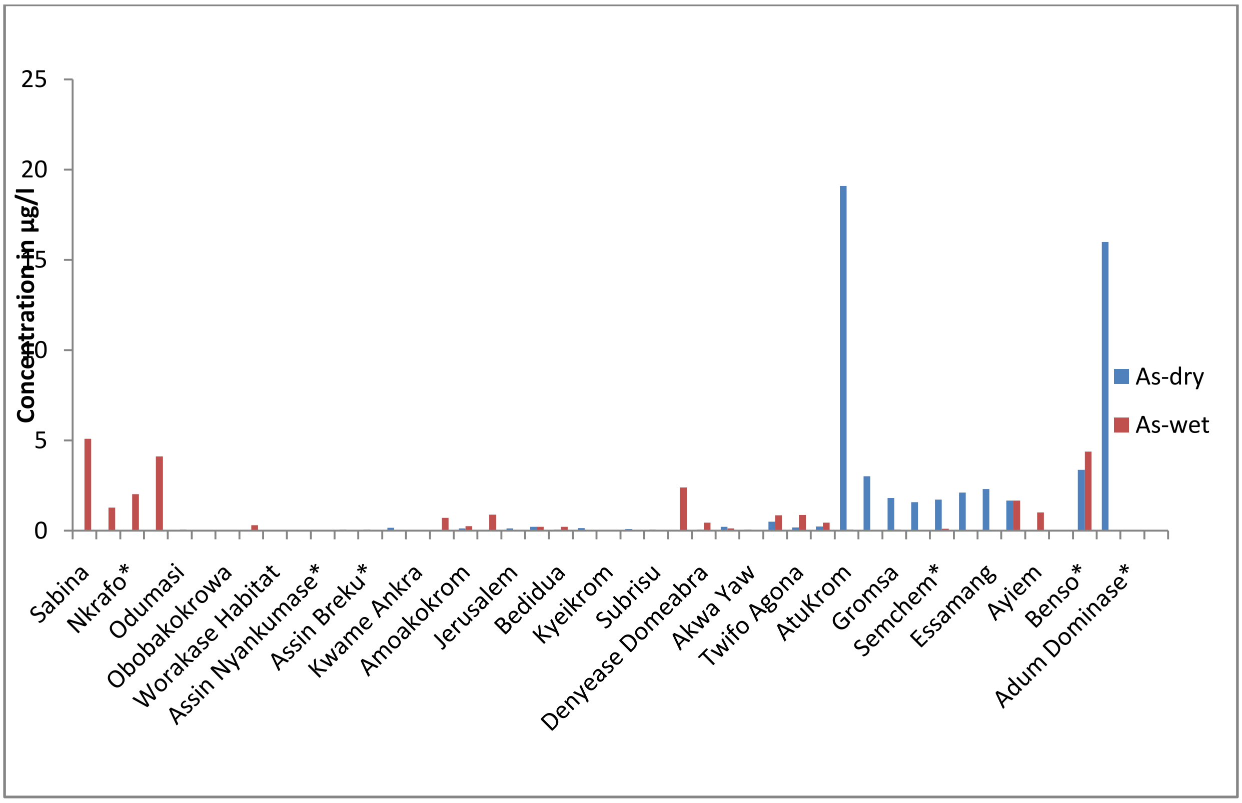

Fig 11: Comparison of As values of water for dry and wet seasons.

4.3 Nutrient Results

Table 3: Seasonal average community nutrient concentrations in the basin.

		P04-P mg/l		S04^{2-} mg/l		N03-N mg/l	
Sample Source	**SamID**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	BH1	0.200	0.368	18.8	19.1	0.392	0.111
Ayitey	BH2	0.180	0.373	8.9	9.2	0.335	0.408
Nkrafo*	BH3	0.045	0.375	7.8	21.4	1.08	0.169
Obirikwaku	BH5	0.180	0.416	18.4	18.5	0.435	0.178
Odumasi	BH6	0.320	0.290	11.8	12.1	2.78	1.37
OdumasiCamp	BH7	0.410	0.303	6.2	30.9	0.666	0.353
Obobakokrowa	BH8	0.160	0.221	43.7	6.5	0.481	0.482
Dwedaama*	BH9	0.410	0.275	24.5	24.7	0.362	0.206
Worakase Habitat	BH11	0.540	0.293	7.4	7.3	2.03	1.55
Brofoyedru Habitat	BH12	0.570	0.501	17.9	17.6	0.759	0.05
AssinNyankumase*	BH13	0.385	0.375	30.8	31.3	2.94	0.937
Akonfudi*	BH16	0.105	0.253	14.7	27.2	0.583	0.366
AssinBreku*	BH18	0.333	0.291	17.6	18.3	0.643	0.208
Techiman No 1	BH21	0.400	0.278	31.7	12.8	0.188	0.451
Kwame Ankra	BH22	0.260	0.429	35.0	9.36	0.372	0.295
Ninkyiso	BH23	0.250	0.308	14.0	12.4	0.755	0.295
Amoakokrom	BH24	1.200	0.334	24.1	23.9	0.622	0.251
Nyamebekyere	BH25	1.900	0.010	7.4	3.6	0.732	0.462
Jerusalem	BH26	3.080	0.380	31.8	7.5	0.918	0.758
Antoabasa*	BH27	0.380	0.569	20.1	29.1	0.592	0.275
Bedidua	BH29	0.480	0.458	10.3	18.1	0.469	0.114
Anum	BH30	0.340	_	16.7	_	0.198	
Kyeikrom	BH31	0.340	0.300	3.6	5.2	0.37	0.43
Adukrom	BH32	0.340	_	22.2	_	0.717	_
Subrisu	BH33	0.140	_	24.2	_	0.28	0.114
Nsukyir	BH34	0.670	0.733	22.2	22.0	0.499	0.205
DenyeaseDomeabra	BH35	0.740	0.789	9.9	15.5	0.328	0.123
TwifoMampong*	BH36	0.614	0.726	18.7	77.9	0.515	0.207
Akwa Yaw	BH38	0.161	_	10.4	_	0.961	
Bremang*	BH39	0.270	0.523	13.1	60.4	0.375	0.111
TwifoAgona	BH41	1.990	0.175	7.5	22.4	0.205	0.091
Somnyamekordru*	BH42	0.614	0.502	12	12.1	0.306	0.378
AtuKrom	BH44	0.429	0.156	58.7	58.2	0.255	0.163
Subresu	BH45	0.156	0.115	62.1	61.9	0.294	0.071
Gromsa	BH46	0.271	0.509	75.7	23.6	0.346	0.23
AnyinaseAnkase	BH47	0.268	0.488	9.1	9.7	0.387	0.141
Semchem*	BH48	0.400	0.498	61.5	54.4	0.326	0.269

Mampong	BH50	0.502	0.707	1.6	32.7	0.718	0.451
Essamang	BH51	0.210	0.121	32.2	14.4	2.24	0.038
Achim/Akyem*	BH52	0.34	0.33	29.8	27.3	0.85	0.83
Ayiem	BH55	0.82	0.75	76.3	77.1	0.59	0.62
Botawjwina*	BH56	0.31	0.30	79.3	74.3	1.13	0.41
Benso*	BH58	0.48	0.39	53.4	54.7	0.28	1.56
AdumBanso	BH61	0.34	0.33	52.4	50.4	0.34	0.44
AdumDominase*	BH62	0.42	0.40	17.9	17.8	0.68	0.68
AdumTrebuom*	BH64	0.47	0.49	23.2	21.3	0.44	0.43

Table 4: Results of NIVA 1042L Reference Material.

Parameter	Observed Value	Expected Value
Al mg/l	0.979±0.04	1.00
As, µg/l	21.1±0.01	20.0
Cd, mg/l	0.123±0.02	0.12
Cu, mg/l	1.14±0.06	1.20
Fe, mg/l	0.332±0.01	0.336
Hg, µg/l	11.6±0.2	10.0
Mn, mg/l	0.191±0.07	0.192
Pb, mg/l	0.495±0.08	0.485
Se, µg/l	9.67±0.3	10
Zn, mg/l	0.095	0.096

The mean dry season value for Phosphate range between 0.03 mg/l to 3.08 mg/l with the maximum at Jerusalem. The wet season recorded values between 0.01 and 0.938 mg/l with the maximum at Bremang.

Sulphate recorded values between 1.60 mg/l and 96.2 mg/l for the dry season and between 3.60mg/l and 79.1mg/l for the wet season.

Mean dry season values for Nitrate ranged between 0.15 mg/l to 5.01mg/l with the maximum recorded at Assin Nyankumasi (BH15). Wet season values ranged between 0.011 to 2.61mg/l (see Appendix IB).

.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Physical Parameters

5.1.1 pH of the Water Samples.

pH is considered as an important ecological factor and provides information on many geochemical equilibrium. The pH of groundwater will vary depending on the composition of the rocks and sediments that surround the travel pathway of the recharge water infiltrating to the groundwater. Groundwater chemistry will also vary depending on how long the existing groundwater is in contact with a particular rock. The pH values measured in the study area are generally low. More than 95% of pH values in the dry season were either acidic or slightly acidic. All values in the wet season were below a pH of 7. Only about 16 % of pH values in the dry season were within the 2004 W.H.O values of 6.5-8.5 for drinking water. The wet season recorded only about 8 % of its values within the W.H.O. guideline value. Kortatsi (2006) reported values between 3.7 and 6.9 in the Ankobra Basin, whilst a mean of 5.71 was reported by Asante et al (2007) in the Takwa township area. The general acidity of the water samples might be due to drainage of metal-rich rocks in the soil and mine drainage (Essumang *et al*., 2011).The results are also consistent with findings by (Ahialey et al, 2010) who reported that mining activities in the Pra Basin "generate acid mine drainage (low pH)." Small scale gold mining operations may expose mineralized rocks to rain water and produce acidic water which can infiltrate into the soil. Mine drainage can therefore introduce acidic water into groundwater supplies (Kuma, 2004). The capacity of leaching toxic metals into groundwater is enhanced by increasing acidity, making it potentially harmful for human consumption. Oxidation of soil organic matter generated in the soil zone could also contribute to the low pH

(Hounslow, 1995; Langmuir, 1997). Water that percolates through soil in poorly buffered areas, usually those with hard igneous rocks, tends to be dominated by dissolved organic acids and can produce low pH values in watercourses (UNEP GEM, 2006; Smedly et al, 1995).This could be the major reason why majority of the boreholes have low pH values given that mining activities do not cover the entire basin.

5.1.2 Temperature

Temperatures ranged between 25.6-31.6 °C and 25.6 -31.8 °C for dry season and wet season, respectively. Approximately 23 % and 15 % respectively of the dry and wet season values were above the W.H.O guideline of 22 to 29 °C. Water temperature could be affected by the weather, storm water and groundwater influx (Fritz, 2001).

5.1.3 Electrical conductivity

Electrical conductivity (EC) gives a measure of the ability of water to conduct an electric current; the greater the content of ions in the water, the more current the water can carry (Dharmappa *et al*., 2000). Approximately 30 % and 25 % values recorded for the dry and wet season respectively were above the W.H.O recommended value of 300 µS/cm for drinking water. High electrical conductivity of the water could be directly attributed to the concentration of dissolved salts or minerals in the water (Dharmappa *et al*., 2000). Groundwater is susceptible to high mineral salt concentration which comes from the dissolution of minerals in the soil as a result of mining activities which disturb mineralized rocks and could release absorbed ions into the water to increase the ionic content, and subsequently the conductivity of the water (Prowse, 1987; Ntengwe, 2006). Generally, wet season values were lower than that of the dry season, which might be as a result of dilution of the wet season values by infiltrating rainwater.

5.2 Metal Parameters

Table 5 below show mechanism by which metals are removed from water by soil as it filters down into the water table.

Table 5: Metal removal mechanism of soil.

Element	Principal Removal Mechanism
Arsenic	Strong associations with clay fractions of soil
Cadmium	Ion exchange, sorption, and precipitation
Copper	Surface sorption, surface complex ion formation, ion exchange, and chelation
Iron	Surface sorption and surface complex ion
Lead	Surface sorption, ion exchange, chelation, and precipitation
Manganese	Surface sorption, surface complex ion formation, ion exchange, and chelation, precipitation
Mercury	Volatilization, sorption, and chemical and microbial degradation
Selenium	Ferric-oxide selenite complexation
Zinc	Surface sorption, surface complex ion formation, lattice penetration, ion exchange, chelation, and precipitation

Source: modified from Crites (1985).

The impact of runoff from mining activities, including leakages from tailing dams on groundwater quality are controlled by pollutant abundance in storm water and pollutant mobility in the vadose zone (Pitt et al.,1999). Several studies have shown that most of the heavy metals are removed, degraded or accumulated with little downward movement in the vadose zone (Hathhorn and Yonge, 1995; Ku and Simmons, 1986; Nightingale, 1987; Legret et al., 1999; Dierkes and Geiger, 1999; Mikkelsen et al., 1997). Crites (1985) suggested five metal removal processes by soil. These are (1) soil surface association, (2) precipitation, (3) occlusion with other precipitates, (4) solid-state diffusion into soil minerals and (5) biological system or residue incorporation. These processes could effectively remove much of the metals and thus protect the underlying groundwater from contamination.

5.2.1 Copper

Most of the samples in the dry season recorded values below detection limit with a few points showing significant values and registering a maximum of 83 µg/l at Dweedama (BH10). The wet season recorded a maximum value of 191 µg/l at the same sampling point (Appendix IC). Generally, Copper is not a threat to groundwater pollution in the study area, since all the samples recorded values below the WHO permissible limit of 2000 µg/l. Values of between 0.04 and 267µg/l was recorded by Kortatsi (2006) in the Densu Basin. Wet season values at certain points show higher values comparatively to dry season values. Generally, it is expected that wet season values should be lower than that of dry season because of dilution by infiltrating rainwater. This is explained by (Leung and Jiao, 2005 and Kortatsi, 2006) that Copper contribution may be due to anthropogenic sources. Comparison of dry and wet seasons, show statistical significant difference ($p<0.05$), Appendix II, suggesting anthropogenic activity. According to (NJDEP, 2012) bulletin, a decrease in concentration during a drought period likely represents the dropping of the water table below a “smear zone” of residual contamination as well as seasonal recharge area variations. The W.H.O recommended limit is 2000µg/l.

5.2.2 Cadmium

The dry season recorded values below detection limit for all the samples except for Jerusalem and Achim (Table 2). Approximately 35 % of wet season values were above the W.H.O recommended value of 3.0 µg/l with elevated values of 12 µg/l and 16 µg/l at Amoakokrom and Antoabasa respectively. Higher wet season may suggest anthropogenic influence (Kortatsi, 2006). Two boreholes, BH27 and BH28 all at Antoabasa recorded 11 and 16µg/l respectively. (Ahialey et al, 2010) reported values between 5 and 13 µg/l in the Basin. As already explained, more heavy metals could be leached out in wet season due to the generally higher water table during the season. In addition, more chemicals may be washed out directly from the vadose zone [2] by infiltrated rainwater during the wet season (Leung and Jiao, 2005).

Cadmium is toxic to man. Cadmium accumulates primarily in the kidneys and has a long biological half-life in humans of 10–35 years. There is some evidence that cadmium may be carcinogenic to experimental animals and it has been implicated in human prostrate carcinoma (W.H.O, 2004;UNEP-GEMS, 2000).There were significant differences between the dry and wet season values ($p<0.05$) indicating possible anthropogenic influence in the boreholes (Appendix II).

[2] Vadose Zone-the region between a water table and the surface of the earth.

5.2.3 Iron

Iron (Fe) occurs naturally from rocks and is found in many surface and groundwater sources at levels ranging 0.3 to 50 mg/L (WHO, 2004). Approximately 15 % and 18 % of dry and wet season values respectively were above W.H.O recommended limit of 300 µg/l. Iron exists in the water as soluble ferrous ion (Fe^{2+}). When exposed to air, the ferrous ion (Fe^{2+}) is oxidised to the ferric state (Fe^{3+}) that is insoluble and precipitates as ferric hydroxide (Appelo and Postma, 1999).

This normally causes brown colouration of the water and stains sinks and laundered textiles. The W.H.O in 1993 limit its concentration in potable water to 300 µg/l because of the aesthetic effect it produces (Kortatsi, 2004). However, an upper limit of 1000 µg/l should suffice for most purposes (WHO, 1993).The highest concentration was recorded in the wet season at Bremang (2910µg/l), a typical mining community where mining activity is vigorously being undertaken along the banks of River Abakrampa. (Ahialey et al, 2010) reported values between 160 and 780µg/l for the Basin compared to this work, 5 – 2910 µg/l. However, no significant difference was observed between the dry and wet seasons ($p>0.05$). Iron, generally does not look problematic in the Basin.

5.2.4 Manganese

Manganese generally dissolves under mildly reducing conditions to produce the mobile divalent manganous ion (Mn^{2+}). When exposed to air, the manganous ion is oxidised to the hydrated oxides that form black colouration and can stain plumbing fixtures and laundered textiles (Hem, 1992; Hounslow, 1995). Approximately 5 % and 11 % of the dry and wet season values respectively were above the W.H.O recommended value of 500 µg/l. Elevated values for the dry season were recorded at Senchiem, Ayim, Benso all in the Western region with values of 683,553 and 540µg/l respectively. Wet season elevations occurred in Bremang (BH39 andBH40), Subresu, Semchem (BH49), Achim (BH52, BH53, BH54) with values of 1544, 523, 839, 983,670, 649, 707 respectively (Appendix IC). Generally, wet season values were higher than dry season values signifying probable anthropogenic contribution. As already explained, more heavy and trace metals are leached out during the wet season as a result of the generally high water table during the season (Leung and Jiao, 2005). It is worth to note that Ayim, Benso ,Achim and Bremang are communities involved in small scale mining activities. However, some heavy metals could be derived naturally. For example, Edmund and Smedley (2000) suggested that Mn could be released by incongruent or disproportionate reactions from silicate or oxide minerals and emerge as potential residence-time indicators.

5.2.5 Lead

High lead concentration in drinking water may result in metabolic poisoning that manifests in symptoms such as tiredness, lassitude, slight abdominal discomfort, irritation, anaemia and, in the case of children, behavioural changes (WHO, 1980). Lead could be found naturally in galena (lead sulphide, PbS), anglesite (lead sulphate, PbSO4), minim (a form of lead oxide with formula Pb3O4), cerussite (lead carbonate, PbCO3) and other minerals. Galena may be the most important natural source.

Generally, the wet season recorded values relatively higher than the dry season values (Fig7). The mean values were 15.8 and 20.1 µg/l for the dry and wet seasons respectively. Approximately 43 % and 41 % of the dry and wet season values were above the W.H.O (1993) recommended value of 10 µg/l. The relatively high concentrated waters were observed in boreholes in the areas underlain by Lower Birimian and Cape Coast granite (Fig1).The high values calls for concern. Although wet season values show relative higher elevation than dry season values, the difference is not statistically significant ($p>0.05$). Therefore, the probable contribution of lead to the aquifers could be of natural geochemical processes.

5.2.6 Aluminium

Approximately 17 % and 11 % of dry and wet seasons respectively recorded values above the W.H.O recommended limit of 200 µg/l. The lower Pra Basin contains potassium feldspars ($KAlSi_3O_8$), albitic feldspars ($NaAlSi_3O_8$) and plagioclase ($CaAl_2Si_2O_8$) (Ahialey et al, 2010). Relatively high values recorded could be as a result of the dissolution of these salts. Generally, Al^{3+} appears to have only little deleterious effect on humans. Nonetheless, its toxicity has been associated with central nervous system disorders including Alzheimer's disease and dialysis dementia (Moskowitz *et al.,* 1986). The incidence of discolouration it produces in drinking water and its distribution systems is the greatest problem associated with the metal. The various concentrations do not show any seasonal dependence. There is also no significant difference between the dry and the wet seasons ($p>0.05$).

5.2.7 Arsenic

Arsenic concentration in the Basin is generally low with dry season elevations at Atukrom and Adu Banso. The wet season had no value above W.H.O recommended limit of 10 µg/l (Table 2). This low levels suggests that arsenic presently poses only limited potential physiological problem to the use of groundwater for drinking purposes. The very low concentration of Arsenic in the Basin suggests the probable effectiveness of the principal removable mechanism (Table 4). Arsenic is a known carcinogen (an agent producing and exciting cancer) and a toxin (Smedley *et al.,* 1995). Long term, low level exposure is said to cause skin cancer through the drinking of contaminated water (W.H.O, 1993), and there is suggestive evidence of increasing risk of bladder, kidney, liver and lung tumours as well (Kortatsi, 2004). There was no significant difference between the dry and the wet season ($p>0.05$).

5.2.8 Mercury

The toxicity of mercury depends on its chemical form. The form of mercury associated with rocks, and with mining and smelting, thus, likely to be associated with groundwater in the Pra basin is inorganic mercury. Gold processing using mercury is by a process known generally as mercury amalgamation, which is widely used by Artisanal miners in the Pra basin. It is reported that both short and long term oral exposure can lead to kidney damage and eventually to kidney failure. It can also cause nausea, vomiting, pain, ulceration and diarrhoea (WHO, 1980). Approximately, 88 % and 42 % of the dry and wet season values respectively were above the W.H.O limit of 1.0µg/l. Dry season values range between 0.005 and 10.1 µg/l at Twifo Mampong (BH37) with the wet season recording values between 0.005 and 16.4µg/l, with the maximum at Gromsa (BH47), a non mining community. However, the wet season values suggest less pollution with respect to the dry season. Pra basin is not known to have mercury in its geological formation. Hence, it is possible mercury contamination is from anthropogenic source via *galamsey* activity. It was also observed during sampling that a number of the boreholes with foot pumps were faulty and lack the pressure required to draw the water out of the aquifers. Hence, the inhabitants devised a means of drawing water by introducing any type of water through the neck of the pumps to generate the necessary pressure. This could be a source of pollution of the boreholes. The relative lower percentage pollution in the wet season might be as a result of rainfall infiltration and percolation resulting in dilution of the aquifers. Studies by Oduro et al, 2012 on surface water including river Pra shows mercury levels between 27.59 µg/l to 48.40µg/l. This high values as a result of the indiscriminate use of mercury may be reasons for finding mercury in the basin. Once the polluted rivers, streams and run-offs find their way into the hydrologic path way, the Hg travellel along the path way far from the source of pollution. There was significant difference between the dry and wet season values ($p<0.05$).

5.2.9 Selenium

Selenium is present in the Earth's crust, often in association with sulphur-containing minerals. Selenium is an essential trace element, and foodstuffs such as cereals, meat and fish are the principal source of selenium in the general population. Levels in drinking-water vary greatly in different geographical areas but are usually much less than 0.01 mg/litre (WHO, 2004).

Almost all the boreholes in both dry and wet season recorded values below the W.H.O guideline value of 10 µg/l with majority of them also below detection. Se is used in the production of photocells, semiconductor, stainless steel and glass. However, none of the above industrial activities exists in the basin.

5.2.10 Zinc

Zn occurs as a natural mineral in many drinking waters. It is an essential dietary nutrient found in virtually all food and potable water in the form of salts or organic complexes (W.H.O, 2004). However, excess zinc can give aesthetic effect on the quality of the water. The W.H.O recommended limit for the metal is 3000 µg/l. Zinc concentration in the basin range between 2.5 -264 µg/l. Zinc concentration does not pose any quality problem for groundwater usage in the basin.

5.3 Nutrient Parameters

5.3.1 Nitrate

The use of pesticides, herbicides, fertilizers, and other materials to increase agricultural yields has some negative effects on groundwater quality. Nitrate from its fertilizer, one of the most widely used agricultural fertilizers, is harmful in drinking waters even in relatively small quantities. Nitrate is very soluble and although some may be used by plants, much of the dissolved nitrate escapes unused into deeper parts of the soil and into groundwater. Nitrate is toxic to humans even in amounts as small as 10 to 15 ppm (Egboka et al, 1989). None of the boreholes recorded values above the W.H.O value of 10 mg/l. However, the highest value of 5.01 mg/l in the dry season was recorded at Assin Nyankumasi. This particular borehole is sited very close to a public latrine, which might have contributed to its relatively high nitrate value. The highest wet season value was recorded at Benso (BH58), where there are commercial oil palm plantations and therefore might have benefited from fertilizer usage.

There is a significant difference between the dry and wet season values ($p<0.05$).

5.3.2 Phosphate

Phosphorus is a nutrient required by all organisms for the basic processes of life. Weathering of certain minerals particularly apatite, provides a natural source of dissolved phosphorous in groundwater (Hitchon et al, 1999). Phosphorus in natural waters is usually found in the form of phosphates ($PO4^{3-}$) (UNEP GEM, 2006).Phosphates are used extensively in the treatment of boiler waters. Orthophosphates applied to agricultural or residential cultivated land as fertilizers are carried into surface waters with storm runoff (APHA,1998).This eventually ends up in groundwater. The W.H.O has not given any guideline value for phosphate, but the U.S EPA recommended a safe value of 2.5 mg/l. Only one borehole (BH26) in the dry season recorded value above the U.S EPA recommended value of 2.5 mg/l. There is a significant difference between dry and wet season values ($p<0.05$) (Appendix II).

5.3.3 Sulphate

Sulphate is an abundant ion in the earth's crust and high concentrations may be present in winter due to leaching of gypsum, sodium sulphate, and some shales (UNEP-GEM, 2006). As a result of oxidation of pyrites and gypsum mine drainage may contain high concentrations of sulphate, leading to groundwater contamination. Sulphate values ranged between 1.6 to 96.2 mg/l in the basin, all below the W.H.O permissible limit of 250mg/l. There is no significant difference between dry and wet season values ($p>0.05$) signifying levels of sulphate in the aquifers are possibly from natural geochemical and hydrological sources.

5.3.4 Statistical Analysis

Correlation analysis using SPSS show little convincing established relationship between heavy metal pollutants and borehole depths. For example, the correlation quoefficient, r, of dry season Hg values against corresponding borehole depth was ($r=0.04$) with ($p<0.05$). Wet season Hg recorded $r=-0.15$, showing a very weak negative correlation. Pb, $r=-0.08$ and -0.36 for dry and wet seasons respectively, Fe, $r=-0.08$ and -0.15 for dry and wet seasons respectively. Borehole depths of the study area ranged between 30 to 96 metres (Appendix IV). Though, no correlation was established between pollutants and depth within this range, Essien and Bassey (2012) showed that at depth of about 100 metres, average compatibility to water quality standards was 86.5 % whilst a depth of 45.45 showed compatibility of 62.6 % to the same standards. Clearly, boreholes within the study area are below the 100m depth. Boreholes below 40m are considered shallow aquifers. Essien and Bassey (2012) concluded that “heavy metals and possible pollutants of groundwater decrease as the depth increases. (i.e.) surface pollutants found it difficult to percolate very deep down into the groundwater aquifer as the depth increases beyond certain threshold value”. The high suspected anthropogenic pollution in the Basin could be as a result of relatively shallow aquifers.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

1. Approximately 84 % and 92 % of dry and wet season pH values respectively, recorded values out of the W.H.O recommended values. The recorded values also show general acidity of boreholes in the study area. More than 95 % of pH values in the dry season were either acidic or slightly acidic. All values in the wet season were below a pH of 7. The general acidity of the water samples might be due to drainage of metal-rich rocks in the soil and mine drainage.
2. Generally, dry season EC values were higher than that of wet season values. The lower values for the wet season can be attributed to dilution by rising water table from rainfall infiltration.
3. Nutrients (Sulphates, Nitrate and Phosphate) values are within the recommended guideline values and therefore do not pose any physiological or aesthetic problem for groundwater use for drinking and other domestic purposes. Despite the usage of phosphate fertilizers for agriculture purposes, it is certain its impact on groundwater has been minimal.
4. Levels of Cadmium, Manganese, Lead and mercury show values above the W.H.O guideline values at certain boreholes as well as strong evidence of contribution by anthropogenic sources. The presence of these metals could be due to the exposure of mineralised rocks to air and acidic water through mining activity. Over 40 % of boreholes had lead above the W.H.O

recommended value of 10 μg/l. This calls for a critical attention. Mercury pollution of the basin is clearly as a result of the indiscriminate prospecting and mining of gold using the amalgamation method. The presence of Mercury in groundwater far away from the mining points calls for concern. Approximately 15 % of boreholes recorded values above W.H.O guideline value for Fe and Al, ostensibly posing potential significant aesthetic difficulty to groundwater quality.

5. There is possibility of Acid Rock Drainage (ARD) occurring in areas where high Fe, Mn/$S0_4^{2-}$, and low pH are recorded. Areas with high Fe, but low Mn and $S0_4^{2-}$ may also indicate ARD since $S0_4^{2-}$ can easily be transformed by redox reactions and precipitate as sulphides.
6. It can be generally concluded that small scale mining operations negatively impact on groundwater quality in the study area. Results from the study do not explicitly show the use of fertilizers for agricultural purposes have any effect on groundwater quality.

6.2 Recommendation

The following recommendations are made based on the outcome of this study:

1. Government should temporarily suspend Small scale mining of gold and take steps to streamline the industry before issuing out licences for prospective miners.
2. The operations of small- scale miners be legalised so that they would be easily monitored. Only licensed miners should be allowed to prospect and

mine for gold if the sustainability of our environment is to be maintained and the pollution of water bodies are to be avoided.

3. There should be effective collaboration between policy makers and regulatory bodies to ensure proper planning and monitoring of activities of the small scale mining industry.
4. The government should strengthen the national regulatory structures and institutions by way of funding to be able to educate and also enforce laws that govern the activities of small scale miners to prevent the destruction and pollution of the environment.
5. Small-scale miners can be assisted in the area of technology in refining gold. Once they are encouraged to form groups, they can be helped with the use of cyanide in refining gold with proper precautions.
6. Further studies are needed to look into the general quality of ground water in the Lower Pra Basin.

REFERENCES

Acid precipitation and health – part 1. Water Quality Bulletin.

Ackah, M., Agyemang, O., Anim A.K,.(2011). Assessment of groundwater quality for drinking and irrigation: the case study of Teiman-Oyarifa Community, Ga East Municipality, Ghana. Proceedings of the International Academy of Ecology and Environmental Sciences, 1(3-4): 186-194.

Acquah, P. C. for UNCTAD. (1995) Natural Resources Management and Sustainable Development the case of the Gold Sector in Ghana.

Adadey, E., (1997). *The role of the mining industry in the economy of Ghana*. In: Proceedings of the National Symposium on the Mining Industry and the Environment. University of Science and Technology/International Development Research Centre Environmental Research Group, Accra, Ghana, pp. 10-17.

Ahialey, E.K., Serfo-Armah, F.,and Kortatsi, B.K,. (2010). Hydrochemical Analysis of Groundwater in the Lower Pra Basin of Ghana. J. Water Resource and Protection, 2010, 2, 864-871.

Akabzaa, T. and Dramani, A. (2001). Impact of mining sector in Ghana: A study of the Tarkwa Mining Region. Report to SAPRI.pp 4-7.

Amankwah, R.K. and Anim-Sackey, C. (2003). Some developments in the small scale mining of precious minerals. Ghana Mining Journal 7, 38–45.

Amegbey, N.A., and Eshun, P.A. (2003). Mercury use and occupational exposure in the Ghanaian small-scale gold mining industry. Ghana Mining Journal 7, 54–60.

Amonoo-Neizer, E.H., and Amekor, E.M.K., (1993). Determination of total arsenic in environmental samples from Kumasi and Obuasi, Ghana. Environ. Health Perspect. 101, 44–49.

Ampofo, J. A. (1997). A survey of microbial pollution of rural domestic water supply in Ghana. *International Journal of Environmental Health Research, 7*, 121-130.

Aninn, T.E., (1990). *Gold in Ghana: Selwyn* Publishers Ltd London, U.K

Ansa-Asare, O. D., and Asante, K. A. (2000). The water Quality of Birim River in South - East Ghana. *West African Journal of Applied Ecology, 1*, 23-33

APHA (1998) "Standard Method for the Examination of Water and Wastewater," 20th Edition, American Public Health Association, Washington D.C., 1998

Appelo C. A. J. and **Postma D. (1999**).Chemical analysis of groundwater. In *Geochemistry, groundwater and Pollution.* AA Balkema/Rotterdam./Brookfield.

Appiah, H. (1998). Organization of small-scale mining activities in Ghana. Journal of the South African Institute of Mining and Metallurgy 98 (7), 307–310.

Aryee, B. N. (2001). Ghana's mining sector: its contribution to the national economy. *Resources Policy, 27*, 61–75

Aryee, B. N., Ntibery, B. K., and Atorkui, E. (2002). Trends In the Small Scale Mining of Minerals in Ghana: a perspetive on its environmental impact. Journal of Cleaner Production 11 (2003) 131-140.

Asante, K.A., Agusa, T., Subramanian, A., Ansa-Asare, O.D., Biney, C.A., Tanabe, S. (2007). Contamination status of arsenic and other trace elements in drinking water and residents from Tarkwa, a historic mining township in Ghana. Chemosphere 66 (2007) 1513–1522.

Ashton, P.J., Love, D., Mahachi, H. and Dirks, P.H.G.M. (2001). An Overview of the Impact of Mining and Mineral Processing Operations on Water Resources and Water Quality in the Zambezi, Limpopo and Olifants Catchments in Southern Africa. CSIR-Environmentek, Pretoria, South Africa and Geology Department, University of Zimbabwe, Harare, Zimbabwe. Report No. ENV-P-C 2001-04.

Baird, C. (1995). Environmental Chemistry W.H. Freeman and Company, New York Press pp.301-302.

Beijer, K. and **Jernelov, A**. **(1979).** Methylation of Hg in Aquatic Environments. In *The biogeochemistry of mercury in the environment.* Elsevier/ North-Holland Biomedical Press, Netherlands

Besseah, B.A(2011) Effects of Small Scale Mining on Water Resources: A Case Study of Bogoso/Prestea Area. Msc. thesis, Department of Theoretical and Applied Biology, Kwame Nkrumah University of Science and Technology, 2011.

Boening D. W. (2000). Ecological effects, transport, and fate of mercury: A general review. *Chemosphere*. **40**: 1335–1351.

Cifuentes, E., and Rodriguez, S. (2005). Urban sprawl water insecurity and enteric diseases in children from Mexico City. Eco Health, (2005), Pp.70–75.

Coakley, G.J (1999). *The minerals Industry of Ghana*. In the U.S. Geological Survey Minerals Year Book. Area report International, 1007 Africa and Middle East, Vol. III.

Crispin, G. (2003). Environmental management in small scale mining in PNG. Journal of Cleaner Production, 11, 175-183.

Crites, R.W., (1985). Micro pollutant removal in rapid infiltration. In: Takashi, A. (Ed.), Artificial Recharge of Groundwater. Butterworth Publishers, Boston, pp. 579–608.

Cunningham, W.P., Cunningham, M.A. and Saigo, B. (2005). Environmental Science: A global Concern. 8th edition.McGraw-hill, Boston

Daily Graphic (June 29, 2010). A report by Asare-Boadu, Kwame and Kyei-Gyau, Roberts on trapped Small scale gold miners. NO.18264.Pp 1 and 3.

Daily Guide on Ghanaweb, 20th August 2012 16:48 GMT

Dharmappa, H.B., Wingroove, K., Sivakuma, M. and Singh, R. (2000).Wastewater and Stromwater minimization in a cool mine. Journal of Cleaner Production 8, 23-34.

Dickson K. B. and Benneh G. (1980). *A New Geography of Ghana*. Longman, London

Dierkes, C., and Geiger, W.F., (1999). Pollution retention capabilities of roadside soils. Water Sci. Technol. 39 (2), 201–208.

Donkor, A.K, Nartey,V.K.,Bonzongo, J.L., and Adotey, D.K.(2006) Artisanal Mining of Gold with Mercury in Ghana. West African Journal of applied Ecology, Vol 9

Dumett, R.E., (1998). *El Dorado in West Africa*: The Gold Mining Frontier, African Labour and Colonial Capitalism in the Gold-coast. Ohio University Press, Athens, OH.

Edmunds, W.M., Smedley, P.L.(2000). Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. Appl. Geochem. 15, 737–752

Egboka,B.C.,Nwankwor,G.I., Orajaka, I.P and Ejiofor, A.O (1989). Principles and Problems of Environmental Pollution of Groundwater Resources with Case Examples from Developing Countries. Environmental Health Perspectives Vol. 83, pp. 39-68.

Essien, E and Bassey, D,.(2012). Spatial Variation Of Borehole Water Quality With Depth In Uyo Municipality, Nigeria. International Journal of Environmental Science, Management and Engineering Research Vol. 1 (1), pp. 1-9

Essumang, D. K., Senu, J., Fianko, J. R., Nyarko, B. K., Adokoh, C. K and Boamponsem, L. (2011). Groundwater Quality Assessment: A physicochemical properties of drinking water in a rural setting of developing countries. Canadian Journal on Scientific and Industrial Research Vol. 2, No. 4.

Fritz, C. (2001). Watershed Information Network: A Watershed Report and Suggested Framework for Integrating Water Quality Monitoring Efforts, July, 2001.

Ghana Water and Sewerage Corporation Report , May 1989.

Ghana Statistical Service,(2002). *Population and Housing Census for 2000; Summary Report of Final Results.* Accra: Ghana Statistical Service.

Ghana Statistical Service,(2012). *Populaton and Housing cencus for 2010*; Summary Report of Final Results. Accra : Ghana Stistical Service.

Government of Ghana. *Small-Scale Gold Mining Law 1989*, PNDC Law 218, 1989

Hathhorn, W.E and Yonge, D.R., (1995). The Assessment of Groundwater Pollution Potential Resulting from Stormwater Infiltration BMP's. Final Technical Report, Research Project T9902, Task 3, Washington State Transportation Center

Hem J. D. (1992). Study and interpretation of the chemical characteristics of natural water. *U.S. Geological Survey Water Supply Paper* 2254

Hilson, G. (2001). 'A Contextual Review of the Ghanaian Small-scale Mining Industry‘, Mining, Minerals and Sustainable Development, no. 76: 2-30

Hounslow, A. W. (1995). Water Quality Data Analysis and Interpretation. Lewis Publishers, Boca Raton, New York.

Hitchon, B., Perkins, H.E and Gunter,W.D., (1999). Introduction to Ground Water Geochemistry. Geoscience Publishing Ltd., Sherwood Park, Alberta, Canada. 310 pp

ILO, (1999).Social and labour issues in small scale mines. Report for the Tripartite Meeting on Social and Labour Issues in Small-scale Mines, Geneva, 17–22 May 1999. International Labour Office.

IDRC(1999). Cut and Run**:** *Illegal Logging and Timber Trade in the Tropics.* International Development Research Centre 1999. (http://www.idrc.ca/en/ev-9319-201-1-DO_TOPIC.html.

Karikari, A. Y., Bernasko, J. K., and Bosque-Hamilton, E. K. (2007). An Assessment of Water Quality of Angaw River in Southeastern Ghana. *West African Journal of Applied Ecology, 11* (1), 1-11.

Kesse, G.O. (1985). Mineral and Rock Resources of Ghana. Balkema, Holland

Kortatsi, B.K. (2004). 'Hydrochemistry of groundwater in the mining area of Tarkwa-Prestea, Ghana', PhD thesis, University of Ghana, Legon-Accra, Ghana

Kortatsi, B.K. (2006). Concentration of Trace Metals in Boreholes in the Ankobra Basin, Ghana. West African Journal of Applied Ecology Vol. 10, pp 73-87

Ku, H.F.H., and Simmons, D.L., (1986). Effects of Urban Stormwater Runoff on Groundwater Beneath Recharge Basins on LongIsland, New York. US Geological Survey Water Resources Investigations Report 85-4088. Prepared in cooperation withLong Island Regional Planning Board, Syosset, New Your.USGS, Denver, CO.

Kuma, J.S. (2004). 'Is groundwater in the Tarkwa gold mining district of Ghana potable? ' Environmental Geology, vol. 45, pp. 391-398.

Lacerda, L. D. (1997). Global mercury emissions from gold and silver mining. Water, Air, Soil Poll. 97: 209–221.

Langmuir, D. (1997). Aqueous Environmental Geochemistry. Prentice Hall Upper Saddle River, New Jersey 07458.

Legret, M., Nicollet, M., Miloda, P., Colandini, V., Raimbault, G.(1999). Simulation of heavy metal pollution from stormwater infiltration through a porous pavement with reservoir structure. Water Sci. Technol. 39 (2), 119–125.

Leung, C.M., and Jiao, J.J., (2005). Heavy metal and trace element distributions in groundwater in natural slopes and highly urbanized spaces in Mid-Levels area, Hong Kong. Water Research. 40 (2006) 753 – 767

Lodenius L. and **Malm O.** (1998). Mercury in the Amazon, *Rev. Environ Contam. Toxicol.* **152**: 25–52.

Lombe, W. C. (2003). Small scale mining and the environment: Bloom beyond the doom and gloom, J. Cleaner Prod. 11: 95–96

McClure, R. and Schneider, A. (2001). The Seattle Post Intelligencer: More than a century of mining has left the West deeply scarred.

Meech J. A., Veiga M. M and **Troman. D**. **(1995).** Reactivity of mercury from gold mining activities in darkwater ecosystems. *Ambio.* **27**(2): 92–98

Metals. Technical Report Series, No. 647. Vienna, Austria

Mikkelsen, P.S., Hafliger, M., Ochs, M., Jacobsen, P., Tjell, J.C.,Boller, M. (1997). Pollution of soil and groundwater from infiltration of highly contaminated stormwater: a case study. Water Sci. Technol. 36 (8–9), 325–330.

Ministry of Water Resources, Works and Housing (2007). National Water Policy, Accra, Ghana.

Moskowitz P. D., Coveney E. A., Hamilton L. D., Kaplan E. and **Medeiros W. H. (1986**).*Identifying human population at risk from acid deposition mobilised materials in drinking water supplies: A preliminary pilot study.* Pollut 12: 167-172.

Nightingale, H.I. (1987). Water quality beneath urban runoff water management basins. Water Resour. Bull. 23 (2), 197–205.

NJDEP (2012). Technical Guidance: Site Remediation Program -Monitored Natural Attenuation. New Jersey Department of Environmental Protection, ver 1.0.

Ntengwe, F. W. (2006). Pollutant loads and water quality in streams of heavily populated and industrialized towns. Physics and Chemistry of the Earth, 31: 832–839.

Ntibrey, B.K. (2001) Small scale mining of precious minerals in Ghana— a strategy to improve environmental performance. M.Sc. thesis, School of Mines, Institute of Mining and Mineral Engineering, Kwame Nkrumah University of Science and Technology, 2001

Obuasi and Bolgatanga Areas, Ghana. *Report Prepared for ODA under the ODA/BGS Technology Development*

Oduro, W.O., Bayitse, R., Carboo, D., Kortatsi, B., Hodgson, I. (2012). Assessment of Dissolved Mercury in Surface Water along the Lower Basin of River Pra in Ghana. International Journal of applied Science and Technology. Vol 2 No.1 228-235.

Olajire, A.A. and Imeokparia, F.E. (2001) Water Quality Assessment of the Osum River, Studies on Inorganic Nutrients, Environmental Monitoring and Assessment 69, 17-28.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M.., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., and Trustrum, N.A. (2005). —Fine-grained sediment in river systems: environmental significance and management issues.|| River Research and Applications 21:693-717.

Pfeiffer W. C. and **Larceda L. D.** (1988). Mercury input into the Amazon Region, Brazil. *Environ Technol. Lett.* **9**: 325–330.

Pitt, R., Clark, S., Field, R., (1999). Groundwater contamination potential from stromwater infiltration practices. Urban Water 1, 217–236.

Project Underground (2000): Gold Mining in Ghana Destroys Livelihoods, Health and the Environment, Drill bits & Tailings, 22 Dec., Vol.5, No. 19 http:// www.moles.org/ProjectUnderground/drillbits/5_19/4.html

Prowse, C.W. (1987).The Impact of Urbanization on Major ion Flux through Catchments: A Case Study in Southern England. Water, Air and Soil Pollution. 32: 277-290.

Prüss-Üstün, A., Bos, R., Gore, F., & Bartram, J. (2008).*Safer Water, Better Health: costs, benefits and sustainability of interventions to protect and promote health.* Geneva: World Health Organization

RRG. (2008) "Acid Mine Drainage and Effects on Fish Health and Ecology: A Review". Reclamation Research Group Publication, Bozeman, MT

Rozkowski, A. and Rozkowski, J. (1994).Impact of mine waters on river water quality in the upper Silesian Coal Basin. Fifth International Mine Congress, Nottingham 18-23 September, Pp.811-821

Schäfer, A., Rossiter, H. M., Owusu, P. A., & Awuah, E. M. (2010). Chemical drinking water quality in Ghana: Water costs and scope for advanced treatment. *Science of the Total Environment, 408*, 2378–2386.

Shoko, D.S.M. and Love, D. (2005).Gold panning legislation in Zimbabwe – what potentials for sustainable management of river resources. In*:* Mathew, K. and Nhapi, I. (Eds.) Water and Wastewater Management for Development Countries. IWA Water and Environmental Management Series, IWA Publishing, London, pp499-512.

Skousen, J., Politan, K., Hilton, T., and Meek, A. (1990). Acid mine drainage treatment systems: chemicals and costs. Green Lands, 20(4): 31-37.

Smedley, P.L., (1996). Arsenic in rural groundwater in Ghana. J. Afr. Earth Sci. 22, 459–470.

Smedley P. L., Ednunds W. M., West J. M., Gardner S. J. and **Pelig-BA K. B.** (1995). Vulnerability of Shallow Groundwater Quality due to Natural Geochemical Environment. Health problems related to Groundwater in the Obuasi and Bolgatanga Areas, Ghana. *Report Prepared for ODA under the ODA/BGS Technology Development and Research Programme, Project 92/5.*

Telmer, K.H. and M.M., Veiga. (2008). World emissions of mercury from artisanal and small scale gold mining. In: Mercury Fate and Transport in the Global Atmosphere: Measurements, Models and Policy Implications. Interim Report of the UNEP Global Mercury Partnership, Mercury Transport and Fate Research Partnership Area. July 14. http://www.cs.iia.cnr.it/UNEP-MFTP/index.htm.

Ullrich S. M., Tanton T. W. and **Abdrashitova S. A.** (2001). Mercury in the aquatic environment: A review of factors affecting methylation. *Crit. Rev. Environ. Sci. Technol*. **31** (3): 241–293

UNESCO. (2010). *The Millennium Development Goals and Water* . Retrieved December 12, 2010, from World Water assessment programmme: http://www.unesco.org/water/wwap/facts_figures/mdgs.shtml.

United Nations Environment Programme (UNEP), (2000). Global Environment Monitoring System/Water Programme.

United Nations Environment Programme (UNEP), (2006). Global Environment Monitoring System/Water Programme

UN-Water/Africa.(2006).*African Water Development Report.* Addis Ababa: UNECA.

Water Resources Commission (WRC), (2008). Ghana's Water Resources. http://www.wrcgh.org/ghanaswaterresources.html

Water Resources Commission (WRC),(2012). Pra River Basin-Integrated Water Resources Management Plan, June 2012.

Weatherhead, E. K., & Howden, N. J. (2009). The relationship between land use and surface water resources in the UK. *Land Use Policy, 26S*, S243-S250.

World Health Organisation (WHO) (1980).*Recommended health-based limits in occupational exposure to trace elements.*

World Health Organisation *(WHO) (1993). Guidelines for drinking water quality. Revision of the 1984 guidelines.Final task group meeting. Geneva 21–25 September 1992.*

World Health Organisation(WHO) (2004). Guidelines for Drinking-water Quality. Vol. 1 : 3rd ed, Geneva.

Appendix I

Appendix I.A: Physical values for individual Boreholes.

		pH		Temp °C		EC µS/cm	
Sample Source	**Sample ID**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	BH1	4.90	6.45	26.9	28.2	270	180
Ayitey	BH2	5.30	5.94	27.6	31.8	200	180
Nkrafo	BH3	5.22	6.87	27.1	30.1	360	260
Nkrafo	BH4	5.0	6.33	26.3	27.6	180	150
Obirikwaku	BH5	6.2	6.05	25.7	29.5	260	210
Odumasi	BH6	5.8	5.56	26.2	27.5	150	110
OdumasiCamp	BH7	6.2	5.67	26.9	27.7	300	200
Obobakokrowa	BH8	6.9	5.24	25.6	28.7	290	210
Dwedaama	BH9	6.4	6.26	25.7	27.3	240	180
Dwedaama	BH10	5.3	5.37	26.7	26.3	90	70
Worakase Habitat	BH11	5.8	4.73	26.5	25.7	80	80
Brofoyedru Habitat	BH12	5.2	4.47	28.2	25.6	120	100
AssinNyankumase	BH13	6.9	4.90	29.2	27.6	470	70
AssinNyankumase	BH14	7.3	5.09	28.5	28.5	180	380
AssinNyankumase	BH15	7.9	4.69	28.1	27.8	70	160
Akonfudi	BH16	6.5	5.07	29.3	26.8	290	230
Akunfudi	BH17	6.3	5.14	29.1	27.2	500	360
AssinBreku(SDA)	BH18	6.0	6.41	30.5	26.4	140	260
AssinBreku(Gyidi)	BH19	6.3	5.53	28.7	27.3	290	230
AssinBreku	BH20	5.7	5.70	28.3	28	500	480
Techiman No 1	BH21	6.1	5.12	29.1	26.9	60	60
Kwame Ankra	BH22	6.5	5.35	28.0	26.2	143	110
Ninkyiso	BH23	5.8	4.92	28.2	26.9	210	170
Amoakokrom	BH24	5.8	4.96	28.8	27.3	320	240
Nyamebekyere	BH25	5.6	5.63	27.2	26.8	170	130
Jerusalem	BH26	6.1	5.03	30.4	26.6	80	70
Antoabasa	BH27	5.9	5.34	30.2	28.3	170	140
Antoabasa	BH28	5.9	5.08	29.2	27.6	220	170
Bedidua	BH29	6.5	5.15	28.8	28.3	220	170
Anum	BH30	6.0	_	28.3	_	270	_
Kyeikrom	BH31	5.6	5.70	31.6	31	150	120
Adukrom	BH32	5.9	_	27.1	_	140	_
Subrisu	BH33	6.0	_	27.0	_	240	_
Nsukyir	BH34	5.9	5.40	26.5	27.3	170	170
DenyeaseDomeabra	BH35	5.6	5.98	28.0	27.1	220	160
TwifoMampong	BH36	6.0	4.24	28.6	29.6	279	220
TwifoMampong	BH37	6.4	5.90	30.7	29.1	1140	590

Akwa Yaw	BH38	6.6	_	29.3	_	130	_
Bremang	BH39	6.3	6.18	29.8	31.2	310	260
Bremang	BH40	6.0	6.06	29.2	31.4	240	200
TwifoAgona	BH41	5.9	4.96	28.8	29.3	190	140
Somnyamekordru	BH42	5.3	6.24	26.8	28.1	710	410
Somnyamekordru	BH43	6.3	5.95	27.4	28.4	824	130
AtuKrom	BH44	5.6	4.95	29.5	28.1	350	240
Subresu	BH45	6.1	5.29	28.1	28.4	190	200
Gromsa	BH46	6.9	4.40	28.9	27.1	190	150
AnyinaseAnkase	BH47	6.4	4.66	28.5	26.3	100	90
Semchem	BH48	6.6	4.88	29.9	29.6	560	200
Semchem	BH49	6.1	4.56	27.2	27.6	400	300
Mampong	BH50	5.3	5.02	26.4	27.6	110	100
Essamang	BH51	5.8	5.6	26.7	27.6	60	50
Achim/Akyem	BH52	6.5	6.5	26.8	26.4	423	417
Achim/Akyem	BH53	6.7	6.5	27.2	26.6	371	368
Achim/Akyem	BH54	6.3	6.1	26.1	27.2	453	449
Ayiem	BH55	5.7	5.9	28.5	28.5	140	137
Botawjwina	BH56	6.7	6.5	29.2	28.8	615	605
Botawjwina	BH57	6.4	6.2	28.7	28.8	923	906
Benso	BH58	5.6	6.3	27.8	27.5	156	521
Benso	BH59	5.2	5.4	27.3	28.1	412	153
Benso	BH60	6.1	5.6	29.2	27.4	527	403
AdumBanso	BH61	5.6	5.8	26.5	27.8	411	402
AdumDominase	BH62	5.5	5.7	28.2	28.2	343	339
AdumDominase	BH63	5.9	5.7	28.7	27.8	93.4	90.9
AdumTrebuom	BH64	6.1	6.0	27.1	26.6	196	188
AdumTrebuom	BH65	6.4	6.6	28.3	26.9	333	327
Min Value		**4.9**	**4.24**	**25.6**	**25.6**	**60**	**50**
Max Value		**7.9**	**6.87**	**31.6**	**31.8**	**1140**	**906**

Appendix IB :Nutrient Values for Individual Boreholes

		P04-P mg/l		SO_4^{2-} mg/l		N03-N mg/l	
Sample Source	**SamID**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	BH1	0.200	0.368	18.8	19.1	0.392	0.111
Ayitey	BH2	0.180	0.373	8.9	9.2	0.335	0.408
Nkrafo	BH3	0.060	0.278	4.7	31.3	0.192	0.011
Nkrafo	BH4	0.030	0.473	10.9	11.4	1.96	0.327
Obirikwaku	BH5	0.180	0.416	18.4	18.5	0.435	0.178
Odumasi	BH6	0.320	0.290	11.8	12.1	2.78	1.37
OdumasiCamp	BH7	0.410	0.303	6.2	30.9	0.666	0.353
Obobakokrowa	BH8	0.160	0.221	43.7	6.5	0.481	0.482
Dwedaama	BH9	0.560	0.234	35.0	35.0	0.243	0.071
Dwedaama	BH10	0.250	0.316	14.0	14.4	0.482	0.34
Worakase Habitat	BH11	0.540	0.293	7.4	7.3	2.03	1.55
Brofoyedru Habitat	BH12	0.570	0.501	17.9	17.6	0.759	0.05
AssinNyankumase	BH13	0.160	0.496	55.6	56.9	3.22	0.073
AssinNyankumase	BH14	0.351	0.288	18.1	18.9	0.582	1.29
AssinNyankumase	BH15	0.643	0.342	18.7	18.1	5.01	1.45
Akonfudi	BH16	0.030	0.208	10.9	28.7	0.301	0.341
Akunfudi	BH17	0.180	0.298	18.4	25.6	0.677	0.391
AssinBreku(SDA)	BH18	0.410	0.257	4	43.2	0.753	0.053
AssinBreku(Gyidi)	BH19	0.210	0.373	43.7	6.14	0.986	0.518
AssinBreku	BH20	0.380	0.345	6	5.69	0.272	0.053
Techiman No 1	BH21	0.400	0.278	31.7	12.8	0.188	0.451
Kwame Ankra	BH22	0.260	0.429	35.0	9.36	0.372	0.295
Ninkyiso	BH23	0.250	0.308	14.0	12.4	0.755	0.295
Amoakokrom	BH24	1.200	0.334	24.1	23.9	0.622	0.251
Nyamebekyere	BH25	1.900	0.010	7.4	3.6	0.732	0.462
Jerusalem	BH26	3.080	0.380	31.8	7.5	0.918	0.758
Antoabasa	BH27	0.490	0.632	21.9	31.6	0.702	0.197
Antoabasa	BH28	0.270	0.506	18.3	26.6	0.482	0.352
Bedidua	BH29	0.480	0.458	10.3	18.1	0.469	0.114
Anum	BH30	0.340	_	16.7	_	0.198	
Kyeikrom	BH31	0.340	0.300	3.6	5.2	0.37	0.43
Adukrom	BH32	0.340	_	22.2	_	0.717	_
Subrisu	BH33	0.140	_	24.2	_	0.28	0.114
Nsukyir	BH34	0.670	0.733	22.2	22.0	0.499	0.205
DenyeaseDomeabra	BH35	0.740	0.789	9.9	15.5	0.328	0.123
TwifoMampong	BH36	0.669	0.532	23.8	77.9	0.671	0.255
TwifoMampong	BH37	0.558	0.92	13.6	77.8	0.36	0.16
Akwa Yaw	BH38	0.161	_	10.4	_	0.961	-
Bremang	BH39	0.271	0.109	22.6	76.2	0.339	0.079
Bremang	BH40	0.268	0.938	3.6	44.6	0.412	0.142

TwifoAgona	BH41	1.990	0.175	7.5	22.4	0.205	0.091
Somnyamekordru	BH42	0.669	0.866	13.6	13.8	0.242	0.146
Somnyamekordru	BH43	0.558	0.137	10.4	10.4	0.369	0.609
AtuKrom	BH44	0.429	0.156	58.7	58.2	0.255	0.163
Subresu	BH45	0.156	0.115	62.1	61.9	0.294	0.071
Gromsa	BH46	0.271	0.509	75.7	23.6	0.346	0.23
AnyinaseAnkase	BH47	0.268	0.488	9.1	9.7	0.387	0.141
Semchem	BH48	0.362	0.491	91	77.5	0.349	0.388
Semchem	BH49	0.437	0.506	31.9	31.2	0.304	0.151
Mampong	BH50	0.502	0.707	1.6	32.7	0.718	0.451
Essamang	BH51	0.210	0.121	32.2	14.4	2.24	0.038
Achim/Akyem	BH52	0.37	0.34	26.9	23.9	0.33	0.32
Achim/Akyem	BH53	0.33	0.32	27.2	25.2	0.15	0.17
Achim/Akyem	BH54	0.32	0.33	35.4	32.9	2.08	2.01
Ayiem	BH55	0.82	0.75	76.3	77.1	0.59	0.62
Botawjwina	BH56	0.29	0.35	62.4	69.4	0.26	0.32
Botawjwina	BH57	0.33	0.24	96.2	79.1	0.54	0.49
Benso	BH58	0.44	0.42	13.9	78.9	0.28	2.61
Benso	BH59	0.42	0.37	72.3	14.9	2.71	0.50
Benso	BH60	0.57	0.38	73.9	70.3	0.40	_
AdumBanso	BH61	0.34	0.33	52.4	50.4	0.34	0.44
AdumDominase	BH62	0.44	0.40	21.6	21.6	0.63	0.67
AdumDominase	BH63	0.40	0.39	14.2	13.9	0.73	0.69
AdumTrebuom	BH64	0.53	0.58	24.2	22.5	0.51	0.55
AdumTrebuom	BH65	0.41	0.40	22.2	20.2	0.36	0.30
Min		**0.030**	**0.010**	**1.6**	**3.6**	**0.15**	**0.011**
Max		3.080	**0.938**	**96.2**	**79.1**	**5.01**	**2.61**
W.H.O Limit		_		250		10	

Appendix IC: Metal Values for individual boreholes in the Basin.

		Cu µg/l		Mn µg/l		Zn µg/l		Cd µg/L		Pb µg/l		Fe µg/l		Al µg/l		As µg/l		Hg ug/l		Se ug/l	
Sample Source	**SamID**	**Dry**	***Wet***	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Wet**	**Dry**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Sabina	BH1	53	5	92	182	2.5	13	1	6	55	62	526	58.0	26	5	0.03	5.1	5.45	0.63	10.3	0.005
Ayitey	BH2	5	5	8	43	2.5	7	1	1	59	59	160	102	5	5	0.03	1.29	5.91	0.23	5.4	0.005
Nkrafo- A	BH3	5	5	27	58	2.5	2.5	1	1	50	22	576	352	251	5	0.005	2.49	4.51	0.19	0.005	0.005
Nkrafo-B	BH4	20	5	13	23	2.5	2.5	1	1	38	54	75	13	67	5	0.005	1.56	8.27	1.12	0.005	0.005
Obirikwaku	BH5	20	51	58	116	2.5	68	1	1	34	26	465	130	61	5	0.005	4.11	7.3	0.005	0.005	0.005
Odumasi	BH6	5	5	35	164	7	73	1	1	51	49	714	372	55	5	0.005	0.06	4.27	0.005	0.005	0.005
OdumasiCamp	BH7	5	5	50	322	2.5	246	1	1	2.5	55	492	38	237	5	0.005	0.005	4.12	0.005	0.005	0.005
Obobakokrowa	BH8	18	74	400	165	2.5	162	1	1	55	59	0	49	5	5	0.005	0.005	2.72	0.005	0.005	0.005
DwedaamaA	BH9	35	19	0	458	2.5	13	1	1	2.5	38	38	1308	5	35	0.005	0.31	0.96	0.005	0.005	0.005
DwedaamaB	BH10	83	191	36	31	10	94	1	1	2.5	39	87	144	10	228	0.005	0.005	1.54	0.005	0.005	0.005
WorakaseHabitat	BH11	5	18	43	8	2.5	5	1	1	2.5	40	44	5	132	63	0.005	0.005	1.11	0.005	0.005	1.22
BrofoyedruHabitat	BH12	5	57	41	9	2.5	11	1	5	55	36	42	5	5	13	0.02	0.005	1.36	15	0.005	0.005
AssinNyankumase	BH13	5	87	2.5	10	2.5	12	1	5	2.5	2.5	42	24	19	23	0.03	0.005	0.76	1.84	0.005	0.005
AssinNyankumase	BH14	5	31	67	62	2.5	35	1	2	24	14	186	61	5	499	0.01	0.005	8.18	10	0.005	0.005
AssinNyankumase	BH15	5	5	83	111	2.5	42	1	10	2.5	2.5	68	32	5	468	0.02	0.005	8.25	0.005	0.005	0.005
Akonfudi	BH16	5	72	141	162	2.5	33	1	7	32	2.5	40	67	5	79	0.05	0.005	3.69	0.005	0.005	0.005
Akunfudi	BH17	79	24	258	256	66	62	1	8	2.5	18	88	27	5	175	0.04	0.005	5.13	0.005	0.005	0.005
AssinBreku(SDA)	BH18	5	5	44	132	2.5	19	1	8	37	48	2130	483	112	27	0.05	0.005	2.38	10.46	0.005	0.005
AssinBreku(Gyidi)	BH19	5	93	96	24	2.5	5	1	4	2.5	15	249	5	5	39	0.05	0.005	0.53	0.005	0.005	0.005
AssinBreku	BH20	5	5	2.5	5	2.5	8	1	3	2.5	48	68	5	81	5	0.06	0.005	1.55	0.005	0.99	0.005

Techiman No 1	BH21	5	166	2.5	9	43	191	1	7	10	5	47	28	195	134	0.17	0.005	2.00	0.005	0.35	0.005
Kwame Ankra	BH22	5	31	2.5	31	5	19	1	6	56	10	106	19	5	96	0.04	0.005	0.68	0.005	1.41	0.005
Ninkyiso	BH23	5	5	9	17	2.5	19	1	4	26	2.5	409	15	727	497	0.005	0.71	3.81	0.005	0.005	0.005
Amoakokrom	BH24	5	60	87	11	2.5	264	1	12	2.5	2.5	121	28	118	99	0.13	0.26	3.69	0.33	0.2	7.24
Nyamebekyere	BH25	5	17	2.5	49	2.5	27	1	9	23	2.5	108	40	296	129	0.005	0.89	4.02	0.97	0.2	0.005
Jerusalem	BH26	5	119	2.5	31	98	183	3	6	11	2.5	5	35	182	25	0.13	0	1.84	2.07	0.35	6.67
Antoabasa-A	BH27	5	5	53	14	2.5	12	1	11	2.5	2.5	476	21	179	147	0.25	0.06	3.86	3.41	0.005	7.03
Antoabasa-B	BH28	5	5	71	72	2.5	25	1	16	16	2.5	178	35	176	132	0.16	0.39	5.74	0.6	0.005	0.005
Bedidua	BH29	5	21	27	45	2.5	28	1	11	2.5	2.5	38	41	5	91	0.05	0.22	6.04	0.005	0.005	6.71
Anum	BH30	5	5	57	50	2.5	2.5	1	1	2.5	2.5	368	300	162	100	0.15	0.17	0.59	0.53	1.16	0.005
Kyeikrom	BH31	5	5	2.5	2.5	2.5	2.5	1	1	29	2.5	45	5	399	5	0.04	0.005	1.06	0.005	0.005	0.005
Adukrom	BH32	5	0	2.5	0	2.5	0	1	0	0	2.5	101	0	157	0	0.1	0	2.44	0	0.005	0
Subrisu	BH33	5	0	6	0	2.5	0	1	0	0	8	101	0	5	0	0.05	0	2.28	0	0.005	0
Nsukyir	BH34	5	16	8	43	2.5	27	1	2	2.5	2.5	924	192	5	57	0.005	2.4	3.93	0.005	0.005	7.16
DenyeaseDomeabra	BH35	5	5	0	126	0	14	1	9	42	2.5	5	125	0	197	0.05	0.45	1.94	0.005	0.005	0.005
TwifoMampong	BH36	20	5	93	101	2.5	27	1	10	2.5	2.5	178	34	697	44	0.34	0.02	3.95	0.005	0.005	6.93
TwifoMampong	BH37	20	5	21	2.5	30	46	1	11	2.5	2.5	81	18	526	64	0.09	0.25	10.1	0.005	0.005	0.005
Akwa Yaw	BH38	5	0	21	0	2.5	0	1	0	0	2.5	78	0	0.017	0	0.06	0	5.72	0	0.005	0
Bremang	BH39	5	53	53	1544	2.5	32	1	1	30	2.5	181	2910	5	19	0.09	1.15	2.98	2.28	0.005	1.49
Bremang	BH40	5	12	47	523	2.5	16	1	3	43	2.5	514	1480	386	5	0.005	0.54	7.38	5.46	0.005	0.005
TwifoAgona	BH41	5	5	37	71	2.5	24	1	2	2.5	2.5	220	135	5	5	0.18	0.87	4.11	1.95	0.005	0.005
Somnyamekordru	BH42	5	41	89	169	2.5	9	1	6	33	2.5	441	489	359	179	0.05	0.36	3.33	1.04	0.005	0.005
Somnyamekordru	BH43	5	5	73	95	2.5	29	2	5	118	7	150	334	5	1680	0.43	0.54	0.005	10.04	0.005	0.23
AtuKrom	BH44	5	27	261	202	41	82	1	1	50	2.5	186	406	43	567	19.1	0.06	1.53	7.89	0.005	0.005
Subresu	BH45	5	5	103	839	2.5	96	1	1	5	2.5	5	334	123	190	3.01	0	1.54	1.35	0.005	0.92
Gromsa	BH46	5	78	14	169	2.5	34	1	1	30	2.5	113	115	5	127	1.82	0.06	0.89	16.4	0.005	2.35
AnyinaseAnkase	BH47	5	15	2.5	41	2.5	62	1	1	5	24	103	15	5	5	1.59	0	5.12	0.44	0.005	0.25
Semchem	BH48	23	48	185	155	2.5	18	1	1	9	21	108	35	5	31	1.52	0.07	4.5	8.22	0.005	0.005
Semchem	BH49	20	5	683	983	2.5	107	1	4	35	26	105	43	5	185	1.93	0.17	4.67	0.17	0.005	0.23

Mampong	BH50	5	28	15	133	2.5	5	1	2	112	2.5	68	232	162	182	2.11	0.005	0.005	0.005	0.005	0.005
Essamang	BH51	5	10	44	23	2.5	2.5	1	1	2.5	31	170	5	176	10	2.31	0.005	0.005	3.96	0.005	3.5
Achim/Akyem	BH52	5	5	9	670	12	31	1	1	11	12	21	111	5	138	0.005	5.02	1.38	13.7	0.124	0.432
Achim/Akyem	BH53	34	26	8	649	2.5	66	3	1	5	5	5	99	32	59	1	0.02	1.86	16.2	0.493	0.951
Achim/Akyem	BH54	30	5	43	707	47	35	1	1	9	18	67	36	5	60	4.01	0.01	1.78	13.3	0.047	1.18
Ayiem	BH55	5	15	553	234	21	228	1	1	2.5	8	54	1840	5	94	0.005	1.01	1.54	0	0.114	10.6
Botawjwina-A	BH56	25	76	46	5	39	178	2	1	2.5	10	33	547	5	15	0.05	0.01	2.06	1.01	0.048	0.005
Botawjwina-B	BH57	23	43	227	500	31	130	1	1	2.5	16	15	281	59	54	0.005	0.01	1.64	3.48	0.005	0.005
Benso	BH58	5	36	540	51	21	85	1	1	14	8	15	243	5	90	0.01	7.99	2.36	2.81	0.031	3.45
Benso	BH59	47	43	330	481	39	57	1	1	22	18	12	16	5	54	10.1	0.05	2.46	9.76	0.005	1.56
Benso	BH60	5	5	140	281	31	2.5	1	1	2.5	14	15	5	59	170	0.01	5.1	2.97	11.77	0.005	0
AdumBanso	BH61	5	5	330	199	16	29	1	1	2.5	15	89	363	5	197	16	0.005	2.83	0.005	0.005	4.2
AdumDominase	BH62	5	5	250	178	14	8	1	1	2.5	17	265	275	5	5	0.02	0.03	4.07	2.55	0.005	9.92
AdumDominase	BH63	42	22	265	132	22	31	1	1	2.5	2.5	18	1340	372	404	0.02	0.05	2.56	3.36	0.018	8.36
AdumTrebuom	BH64	58	5	45	41	14	27	1	1	2.5	2.5	10	230	444	114	0.01	0.03	3.51	0	0.076	0
AdumTrebuom	BH65	34	26	89	41	5	11	1	1	8	2.5	26	5	5	5	0.01	0.05	2.88	0.005	0.005	8.11
Min Value	**Min**	**10**	**<10**	**<5**	**<5**	**<5**	**<5**	**<2**	**<2**	**<5**	**<5**	**<10**	**<10**	**<10**	**<10**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
Max Value	**Max**	**83**	**191**	**683**	**1544**	**98**	**264**	**3**	**16**	**118**	**62**	**2130**	**2910.0**	**727**	**1680**	**19.1**	**7.99**	**10.1**	**16.4**	**10.3**	**10.6**
W.H.O P. Limit	**WHO**	**2000**		**500**		**3000**		**3.00**		**10**		**300**		**20**		**10**		**1**		**10**	

Appendix II : Statistical summary of the 65 samples analysed.

Parameter	Min.	Max.	Mean	Median	Stdev.	P-Value	W.H.O(2004)
Temp.,°C	25.6	31.8	28	27.9	1.33	_	_
PH, pH units	4.24	7.90	5.80	5.79	0.58	_	6.5-8.0
EC, µs/cm	55	1140	264	214	183	_	_
N03, mg/l	0.08	3.8	0.59	0.39	0.67	0.011	10
S04, mg/l	1.6	96.2	28.5	20.6	22.9	0.443	250
P04, mg/l	0.02	3.1	0.44	0.36	0.34	0.255	_
Al, µg/l	5	1204	117	38	202	0.383	20
As, µg/l	0.005	13.5	0.85	0.04	2.42	0.397	10
Cd, µg/l	1	16	2.3	1	2.07	0.001	3
Cu, µg/l	5	83	21.5	10	31.2	0.017	2000
Fe µg/l	5	2910	218	66	375	0.188	300
Hg µg/l	0.005	13.2	3.1	1.5	3.5	0.001	1
Mn µg/l	2.5	1544	142	58.5	210	0.068	500
Pb µg/l	2.5	118	18	8	21.5	0.835	10
Se µg	0.005	10.6	0.95	0.005	2.12	0.233	10
Zn µg/l	2.5	264	30.4	15	40.5	0.001	500

Appendix III: Reference (NIVA 1042L) material and internal control values

Parameter	Observed Value	Expected Value	Deviation	%Relative Deviation
Al mg/l	0.979	1.00	-0.021	-2.1
As, µg/l	22.1	20.0	2.10	10.5
Cd, mg/l	0.123	0.12	0.003	2.5
Cu, mg/l	1.14	1.20	-0.06	-5
Fe, mg/l	0.332	0.336	-0.004	-1.2
Hg, µg/l	12.1	10.0	2.1	21
Mn, mg/l	0.191	0.192	-0.001	-0.5
Pb, mg/l	0.495	0.485	0.01	2.1
Se, µg/l	9.67	10	-0.33	-3.3
Zn, mg/l	0.095	0.096	-0.001	-1.04

Appendix IV: Borehole Depths and corresponding pump type.

Samp.source	Samp.ID	BH ID	Lat	Long	BH Depth(m)	Pump type
Sabina	BH1	380 BU1	5.86974	-1.27172	45.0	Foot pump
Ayitey	BH2	094 BU3	5.88353	-1.25584	30.0	Foot pump
Nkrafo	BH3	098 BU3	5.87809	-1.23364	57.0	Foot pump
Nkrafo	BH4	096 BU3	5.88087	-1.23862	42.0	Foot pump
Obirikwaku	BH5	099 BU3	5.91571	-1.23661	42.0	Foot pump
Odumase Camp	BH6	405 BU2	5.82454	-1.19147	51.0	Foot pump
Odumase Camp	BH7	407 BU2	5.82181	-1.19419	51.0	Foot pump
Obobakokrowa	BH8	246 J BU1	5.82490	-1.17768	42.0	Foot pump
Dwedaama	BH9	442BU1	5.90170	-1.20496	45.6	Foot pump
Dwedaama	BH10		5.80159	-1.20575		Foot pump
Worakese Habitat	BH11		5.76443	-1.13154	66.0	Foot pump
Brofoyedru Habitat	BH12	101 BU3	5.73346	-1.28457	51.0	Foot pump
AssinNyankomase	BH13	103BU3	5.75724	-1.29063	96.0	Foot pump
AssinNyankomase	BH14	089BU3	5.75719	-1.29084	45.0	Foot pump
AssinNyankomase	BH15	105BU3	5.75897	-1.28652	63.0	Foot pump
Akonfudi	BH16	01WL1	5.82570	-1.30988	48.00	Hand pump
Akonfudi	BH17	071BU3	5.82950	-1.31011	90.0	submersible
AssinBreku (Gyidi)	BH18	102 BU3	5.87059	-1.33603	51.0	Foot pump
AssinBreku (SDA)	BH19	100 BU3	5.86625	-1.34094	30.0	Foot pump
AssinBreku	BH20	072BU3	5.86801	-1.34094	48.0	submersible
Techiman No.1	BH21	396 BU3	5.80432	-1.36792	51.0	Foot pump
Kwame Ankra	BH22	411 BU3	5.81542	-1.38199	39.0	Foot pump
Ninkyiso	BH23		5.82117	-1.39912		Foot pump
Amoakokrom	BH24	337 BU3	5.85972	-1.25611	33.0	Foot pump
Nyamebekyere	BH25	339 BU3	5.80139	-1.72139	51.0	Foot pump
Jerusalem	BH26	0502B1/6/097-01	5.81667	-1.71750		
Antoabasa	BH27		5.77196	-1.46878		Foot pump
Antoabasa	BH28		5.7702	-1.46948	51	Foot pump
Bediedua	BH29		5.77278	-1.49722	60.0	
Anum	BH30	086BU3	5.7825	-1.0222	54.0	Foot pump
Kyiekrom	BH31	090BU3	5.82611	-1.52361	30.0	Foot pump
Adukrom	BH32					
Subrisu	BH33		5.82474	-1.54799		
Nsuekyir	BH34	219 BU1	5.68667	-1.49722	33.0	Foot pump
DenyeaseDomeabra	BH35	092 BU3	5.74806	-1.53806		
TwifoMampong	BH36		5.52016	-1.55449	63.0	Foot pump
TwifoMampong	BH37		5.52359	-1.55681	51.0	submersible
Akwa Yao	BH38					
Breman	BH39	260 BU2	5.70878	-1.60277	36.0	Foot pump
Breman	BH40		5.70720	-1.60261		

TwifoAgona	BH41	263 BU2	5.74595	-1.50398	33.0	Foot pump
Somnyamekordur	BH42	138 BU1	5.66046	-1.58376	45.0	Foot pump
Somnyamekordur	BH43	033BU3	5.66046	-1.58376	30.0	Foot pump
AtuKurom	BH44	026BU3	5.63657	-1.67850	51.0	Foot pump
Subreso	BH45	048D035 BU3	5.65596	-1.67676	69.0	Foot pump
Gromsa	BH46	032 BU3	5.58991	-1.60607	33.0	Foot pump
AnyinaseAnkase	BH47	030 BU3	5.59446	-1.60279	42.0	Foot pump