

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
KUMASI**

COLLEGE OF SCIENCE

**ASSESSMENT OF GROUNDWATER QUALITY IN MINING COMMUNITIES: A
CASE STUDY OF THE TARKWA MINING AREA IN THE WESTERN REGION OF
GHANA**

BY

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DECLARATION

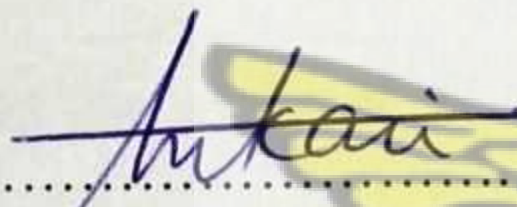
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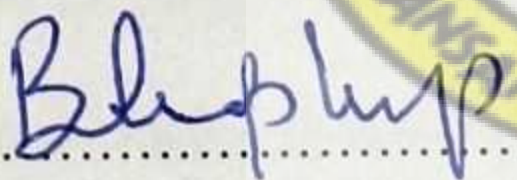
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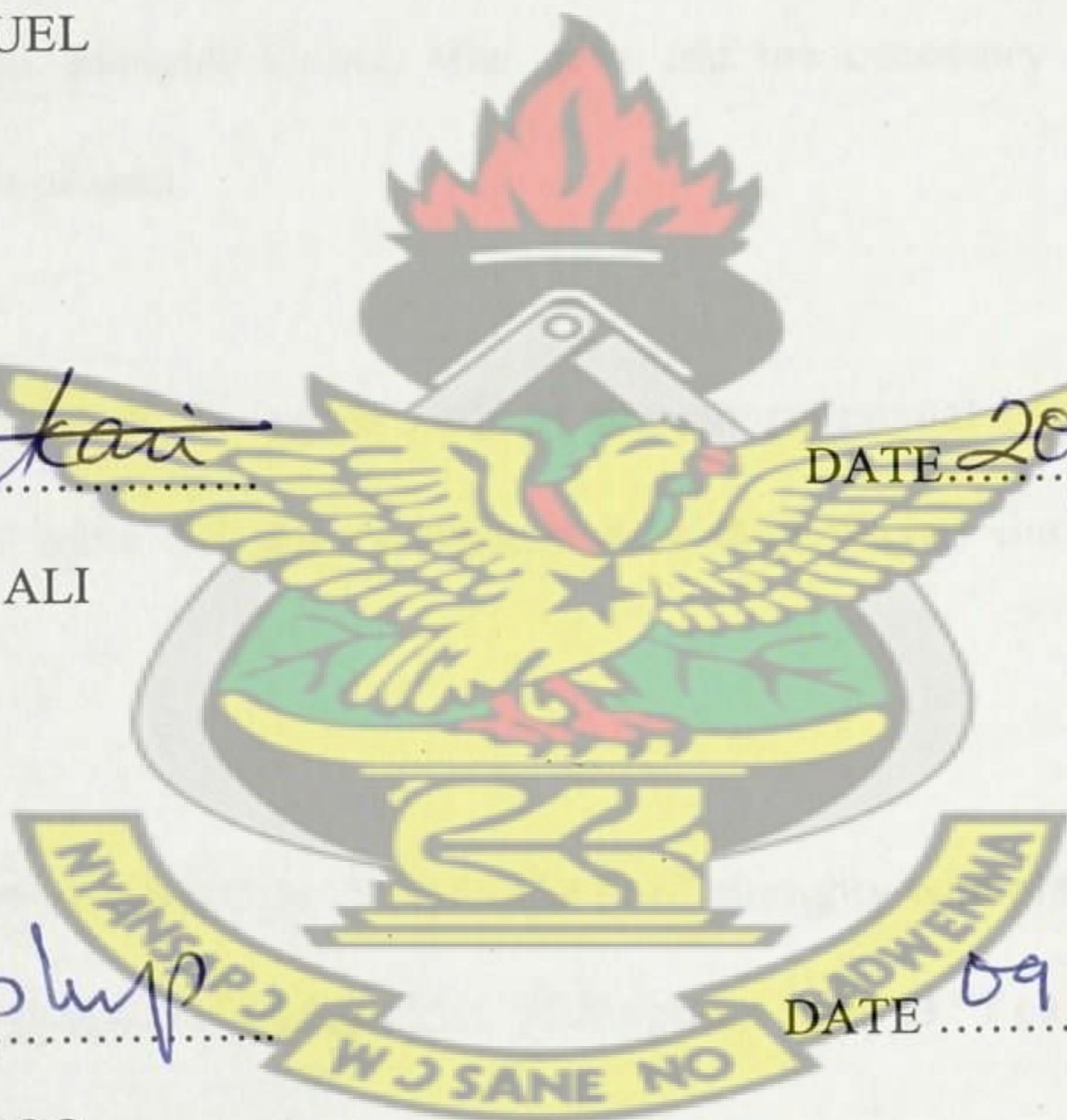
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ABSTRACT

There is the general perception that mining activities have severe adverse effects on the environment, particularly groundwater quality. Based on this, groundwater quality in the Tarkwa area, which has a fair concentration of mining activities, was studied for any correlation with the various mining operations in the area. Groundwater samples from boreholes and hand-dug wells were studied for their quality in terms of the physico-chemical properties, major ions, and selected heavy metals. The concentrations of the parameters were compared with the WHO guidelines for drinking water quality. The results show wide variations in the parameters investigated; the pH ranges from 4.03 - 6.98 and the TDS from 44 – 563, these indicate that the groundwater in the Tarkwa area is mildly acidic but reasonably fresh. Generally, the concentrations of the major ions in the groundwater across the communities were good for drinking water quality. Again, the water types or the hydrological facies were plotted using the Piper diagram software. The concentrations of some of the parameters (Pb, Ni, Cd, Mn and Fe) were problematic; however, those of some heavy metals like (Zn, Cu, As, and Hg) were generally low for what would have been expected of a town with a long history of mining operations.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Groundwater makes up about 20% of the world's fresh water supply, which is about 0.61% of the entire world's water, including oceans and permanent ice (Columbia Water Center, 2009). In rural areas of USA, 96% of domestic water is supplied from groundwater (Todd, 1980), while in Asia groundwater provides about half of the drinking water supply. The percentage is even much higher in Europe about 98% in Denmark and 94% in Portugal (Chapman, 1996). The dominant role of groundwater resources is clear and their use and protection is, therefore, of fundamental importance to human life and economic activity.

In Africa, the crucial role groundwater plays as a decentralized source of drinking water supply for dispersed rural communities and urban areas cannot be overstated. Africa has a large percentage of rural communities, which are dispersed; in Ghana about 70% of the population live in rural areas. A centralized water supply system for such places is not practical and would be too expensive. Groundwater is often available close to where it is required and can be developed cheaply and progressively to meet demand with lower capital investment than many surface water schemes. It is therefore not surprising that most African countries rely extensively on groundwater systems. Groundwater is of particular importance in Africa where several countries rely on a combination of hand-dug wells and public boreholes for their drinking water supply. It is also the main source of irrigation water in rural areas, as well as a vital safety net for dry season food security. In the urban centres, groundwater is an important source of affordable municipal and private freshwater supplies.

However, uncontrolled expansion of housing, together with increasing sewage and effluent leakage, indiscriminate waste disposal, and industrial and commercial activities including mining operations, all lead to the increasing deterioration and subsequent pollution of groundwater quality and to mounting public health problems (Xu and Usher, 2006).

The severity of groundwater pollution is partly dependent on the characteristics of waste or leachate –i.e. its volume, composition, concentration of the various constituents, time rate of release of the contaminants, the size of the area from which the contaminants are derived, and the density of the leachate among others. A range of groundwater pollution problems can be associated with mining activities. Both surface and underground mines usually extend below the water table and often major dewatering facilities are required to allow mining to proceed. The water pumped, either directly from the mine or from specially constructed boreholes, may be highly mineralized and its usual characteristics include low pH (down to pH 3) and high levels of iron, aluminium and sulphate (Chilton *et al.*, 1995). Disposal of this mine drainage effluent to surface water or groundwater can cause serious impacts on water quality for all uses.

The concentration of mining operations in Tarkwa has been a major source of both groundwater and surface water pollution. Large deposits of mine wastes, ore stockpiles and waste rocks are heaped around the plants of the mining concessions (Armah *et al.*, 2010). Weathering of the heaped waste materials results in the release of toxic chemicals into the environment. Harmful metals released from mine tailings include mercury, arsenic, lead and cadmium; these chemicals constitute the major pollutants of groundwater (Akabzaa and Darimani, 2001). Notwithstanding this, information on the impact of mining

operations on groundwater quality, especially the extent and trend is inadequate within the Tarkwa mining area (Kuma and Ewusi, 2009).

Three large scale surface mining operations -Goldfields Ghana Limited, AngloGold Ashanti Iduapriem Mine and Ghana Manganese Company- are located within 7 km radius of Tarkwa. It is therefore important to know the impact of these mining activities on the groundwater quality of the communities within the Tarkwa area whose main source of water is groundwater. The study will also provide a source of information for the mining industries for proactive environmental interventions for the protection of the natural groundwater quality. On the other hand the people living in the mining communities will be informed about the risk of groundwater contamination and/or pollution.

1.2 PROBLEM STATEMENT

Mining operations may cause adverse changes in the environment of surrounding communities. Such changes do not only affect the inhabitants in terms of life-threatening illnesses, but also the destruction of vital natural resources such as groundwater. There is the perception also that groundwater has the capability of naturally purging itself of contaminants, and thus free from posing any eminent health risk, is strong. According to the WHO, about five million people die every year from drinking polluted water (Anon, 2001). There is therefore the need to assess groundwater quality in these mining communities.

One of the major assets of any nation is its water resources, of which groundwater is a major component. It is therefore important to assess and/or monitor the quality and identify the extent of groundwater contamination/pollution resulting from anthropogenic

activities, including mining. The assessment will enable preventive measures to be taken, while the knowledge of extent of pollution will inform on the level of treatment, if any, required to make the water potable.

1.3 OBJECTIVES OF THE STUDY

The main objective of the study was to investigate the level of contamination of groundwater in the mining communities in the Tarkwa area. These were achieved mainly by determining for both shallow and deep wells within the Tarkwa area.

- The concentrations of some heavy metals (e.g. Pb, Mn, Hg, As, Ni, Cu, Zn and Cd) in the groundwater.
- The concentrations of the major ions –i.e. Na^+ , Ca^{2+} , Mg^{2+} , K^+ , HCO_3^- , Cl^- , SO_4^{2-} , NO_3^- .
- And some physico-chemical parameters –e.g. pH, TDS, EC, DO in the groundwater.

1.4 SCOPE OF WORK

The study was limited to the Tarkwa area and the communities where mining activities are prevalent –i.e. New Atuabo (GGL), Tamso (GMC) and Terberebie (AGA, Iduapriem Mine). A general study of the communities was also undertaken, this involves taking the GPS locations, climate (temperature, rainfall and evaporation), soil type (geology) vegetation and land use. The investigation of the water quality parameters were limited to the heavy metals, major ions and physico-chemical parameters listed in Section 1.3.

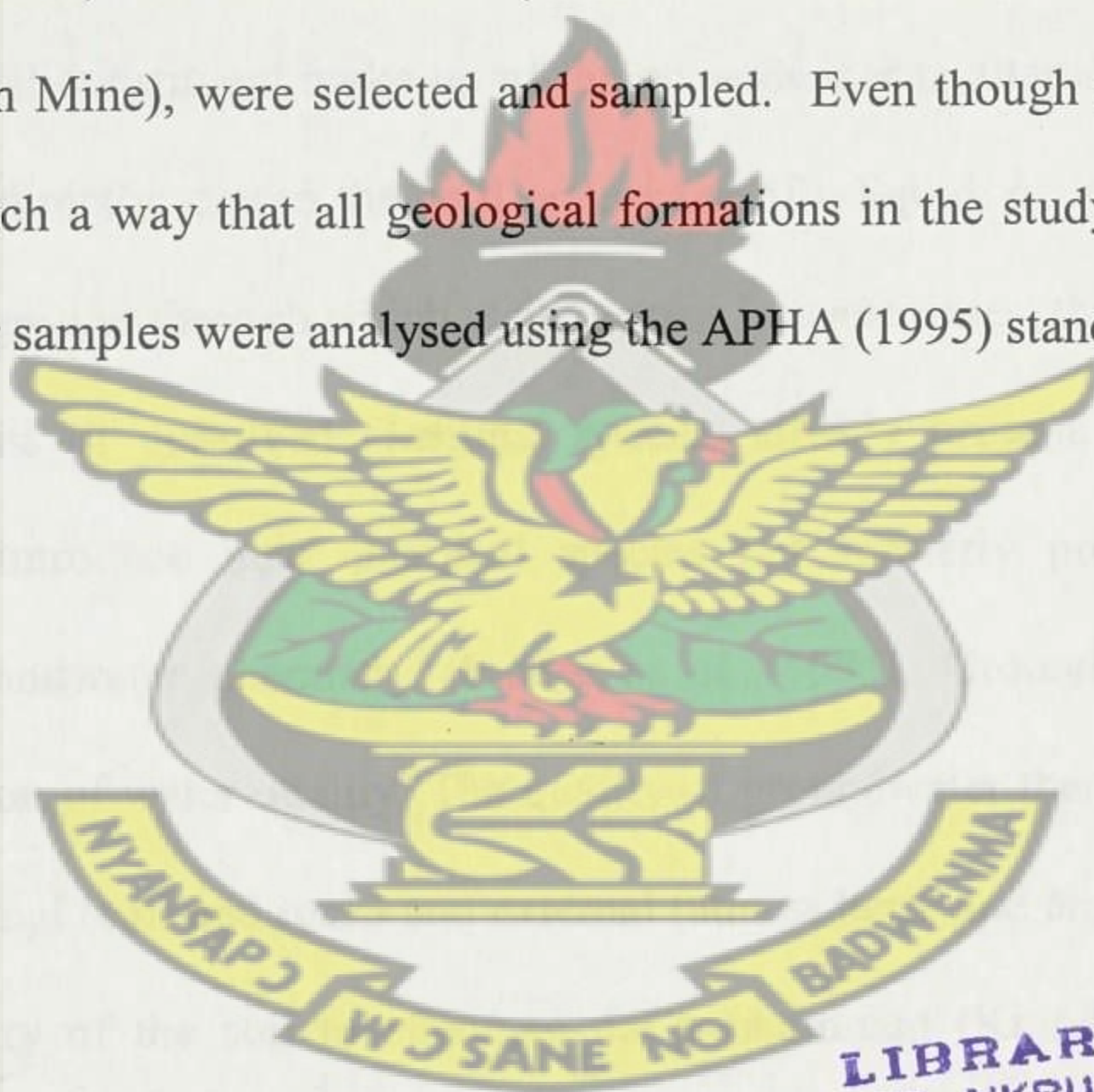
1.5 METHODOLOGY

The investigation involved a desk study and primary and secondary data collection and collation. The study was undertaken in four communities, namely: New Atuabo and

Esamang Kakraba (GGL), Tamso (GMC) and Tebrebie (AGA, Iduapriem Mine), which are typical mining communities. A general study of the communities involved recording their GPS locations, climate (temperature, rainfall and evaporation), soil type (geology), vegetation and landuse. Sources of drinking water supply and the water quality, and sanitation facilities of the communities were also studied.

1.5.1 Sampling and Laboratory Analysis

Five random groundwater point sources from each of the communities -namely (GMC), Tamso, New Atuabo, Essaman Kakraba (Goldfields Ghana Ltd., Tarkwa) and Terberebe (AGA, Iduapriem Mine), were selected and sampled. Even though random, the samples were taken in such a way that all geological formations in the study area were covered. The groundwater samples were analysed using the APHA (1995) standard methods.



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CHAPTER TWO

LITERATURE REVIEW

2.1 OCCURRENCE OF GROUNDWATER CONTAMINATION

The chemical make-up of groundwater is a reflection of where the water has been, and what kind of material it has flowed through or over. As a result, most groundwater contains a wide variety of dissolved inorganic chemicals (Freeze *et al.*, 1985). Indeed the ground, and the water that makes up groundwater, are intimately connected, and as we alter the groundwater or the path that the water takes, the chemical constituent make-up of the water also changes (Focazio *et al.*, 2000). Groundwater contamination therefore occurs when the chemical constituent make-up of the groundwater is altered as a result of man's activities, either directly, due to the spill or leakage of a liquid, or indirectly, through the alteration of the ground through which water passes. In some cases, the alteration may raise the concentrations of dissolved chemical species already present. In other cases, the alteration may introduce new chemical species not formerly present in the natural background groundwater chemistry (Freeze *et al.*, 1985). Groundwater contamination causes degradation of water quality. The quality of groundwater therefore depends on the inputs from internal (soil and rock) and external (atmospheric and anthropogenic) sources, and on the ability of the soil to attenuate the contaminant (Kinniburgh and Edmunds, 1986).

2.1.1 Contaminants Migration in Groundwater

Most groundwater contamination arises from sources (activities) at the earth surface –e.g. spills from mining, and non-point agricultural contaminants are all introduced at or near the surface, and before they enter the groundwater system, there is an initial percolation phase in which the contaminants move downward through the unsaturated soil moisture zone to the water table (USGS, 2008). The unsaturated zone plays a significant role in

determining what percentage of the mass of the contaminants migrates from the ground surface to the underlying groundwater (Freeze *et al.*, 1985). Some contaminants, can initially find their way into the ground in a dry state, (especially the unsaturated zone). But subsequent movement of the constituents requires dissolution in the soil moisture and downward percolation under the influence of infiltration due to precipitation. The rate of migration of contaminants in groundwater is therefore dependants on the type of contaminants, namely soluble contaminants that dissolve in groundwater, insoluble contaminants that are lighter than water and insoluble contaminants that are heavier than water (Freeze *et al.*, 1985). Most inorganic and many organic chemical constituents are soluble. They dissolve in groundwater and form elongated plumes of contamination that arise at a point source and stretch out in the direction of the groundwater flow paths. Those that have solubility greater than 1000mg/l are highly soluble; those that have solubility less than 100mg/l are practically insoluble. For the insoluble contaminants, those with a specific gravity less than 1.0 are "floaters"; those with a specific gravity greater than 1.0 are "sinkers"(Freeze *et al.*, 1985).

2.1.2 Sorption and Precipitation as Factors of Contaminants Migration

The transportation of contaminants, especially metals with groundwater is normally affected by sorption to solid aquifer material (Appelo and Postma, 1999). According to Charest (1998), the most important chemical retention mechanisms are sorption processes and precipitation. These mechanisms and the mobility of metals are affected by a number of different parameters e.g. the oxidation state of the metal ion, pH and Eh, notwithstanding the solubility, transportation and toxicity differ between different metal species (Asklund and Eldvall, 2005).

Sorption can be used as a general term that actually includes several different processes. Adsorption is one of such processes and involves the adherence of a molecule dissolved in

a fluid phase (i.e., a solute in a solvent) to a solid phase (the sorbent), thus removing it from solution (McCarty, 1996). The process occurs due to electrostatic forces present at the surface of mineral grains which form the solid phase of an aquifer (Charest, 1998). There may also be a thermodynamic gradient driving the solute to the sorbent as in the case of hydrophobic solute in water (Charest, 1998). Adsorption is a non-destructive, reversible process. Absorption on the other hand suggests that the chemical (contaminants) is taken up into the solid and exchange involves the replacement of one chemical for another at the solid surface. Absorption occurs when the contaminant finds its way into the lattice of the absorbing mineral (Charest, 1998).

Chemisorption is similar to adsorption in that it involves the adherence of a solute molecule to the surface of a solid phase. The difference is that solute actually forms a chemical bond at the surface of the sorbent. The amount of solute that can be removed from solution is limited due to the specificity of the chemical bonds that form. Only specific chemisorbents will sorb a particular solute. This fact also limits the sorbed layer to a thickness of one molecule. Indeed, the fact that a chemical bond is formed does make chemisorption irreversible and it is therefore effective at immobilizing a contaminant (Charest, 1998).

The precipitation of an inorganic contaminant can reduce its concentration in groundwater and immobilize it. For precipitation to occur the solution has to become oversaturated with respect to the inorganic contaminant to be precipitated (Charest, 1998). A number of factors affect the solubility of inorganics in aquifers. For instance, Ion pairing, the interaction between a cation and anion in solution tends to increase the carrying capacity of the solution for the cation (Charest, 1998). In most aquifer environments, these factors

tend to increase the solubility and make it less likely that an inorganic will be removed from solution by precipitation (Brady *et al.*, 1997). Therefore, although, precipitation is a possible attenuation route, it cannot be considered to be substantial.

2.2 ENVIRONMENTAL GEOCHEMISTRY OF MINE WATER

Groundwater in mining districts is mostly heavily contaminated and acidified as a result of oxidation of pyrite and other sulphide minerals contained in the mine tailings. In most cases, these tailings are characterised with elevated concentrations of heavy metals. Sulphide minerals such as pyrite occur in most sulphide deposits associated with mining waste. The oxidation of these minerals in the presence of oxygen and water produces acid mine water which manifests as AMD (Acid Mine Drainage). The effect of the contaminated water from the mines can persist for more than 10 km beyond the source (Naicker *et al.*, 2003). The release to the environment of such mining water/waste can be profound and sometimes very destructive to the ecosystems. It is worth mentioning that in most cases metals become an environmental and health issue because of anthropogenic activity, of which mining is an integral component, though there are a few examples of local metal pollution through natural weathering (Asklund and Eldvall, 2005).

2.2.1 Reactive Minerals in Mine

Sulphide minerals such as arsenopyrite, bournonite, chalcopyrite, galena, pyrite, sphalerite and tennalite are stable in reducing environments (Zeeli and Hodgson, 2007). Mining exposes these minerals to atmospheric conditions (air and water); an environment in which they are unstable.. They react to form oxidic phases that are in equilibrium in the new environment. In doing so, sulphur is released and reacts with the water to form sulphuric acid. This may lower the pH of mine waters to around two. At pH below five, many toxic metals go into solution in the acid water so the concentration of metals in solution increases (Kortatsi, 2004).

2.2.2 Acid Mine Drainage (AMD)

Acid mine drainage (AMD), also known as acid rock drainage (ARD), refers to the outflow of acidic water from (usually abandoned) metal mines. This phenomenon occurs when groundwater comes into contact with rock rich in sulphide. These sulphide minerals oxidize in the presence of water and oxygen, the by-product being a highly acidic, sulphate-rich drainage (Fripp *et al.*, 2000). Indeed both surface and underground mining can accelerate oxidizing conditions (Fripp *et al.*, 2000), often these mining operations progress below the water table, so water must be constantly pumped out of the mine in order to prevent flooding (Fripp *et al.*, 2000). When a mine is abandoned, the pumping ceases, and water floods the mine. This introduction of water is the initial step in most acid rock drainage situations. On the parts of Asklund and Eldvall (2005), they stated that sulphide minerals can be oxidized through three different processes namely: chemical oxidation with oxygen, chemical oxidation with Fe^{3+} and oxidation catalyzed by micro-organisms. In fact all these reactions accelerate at low pH. In the Tarkwa area however, the problem of AMD should be expected. This is due to the fact that Tarkwa town abound in defunct (closed) underground mine pits which have been illegally taken over by Galamsey operators who on daily basis pump out (though unspecified) but very high quantity of water to land surface. The abandoned underground mine pits are also most likely to serve as an underground point source for groundwater recharge. Unfortunately, water from abandoned underground mine pits are characterised with low pH down to about three. This phenomenon coincides with the findings of Kuma (2004), who found out that, the pH levels of the water including groundwater in the Tarkwa area is consistently low and has high concentrations of sulphate, silica, aluminium, iron, and manganese, and shows little variation during the year. Figure 2.1 shows an abandoned underground mine pit situated in the Tamso area of Tarkwa.



Figure 2.1: Abandoned underground mine pit located in the Tamso area.

2.2.3 Major Inorganic Contaminants Related to Mining

Inorganic contaminants (e.g., metals, metalloids, and ions) enter the hydrologic cycle as a result of mining activities, groundwater pumping, and other industrial activities, all of which are prevalent in the Tarkwa mining area. Inorganic contaminants like: hydrochloric acid, sodium chloride, and sodium carbonate change the acidity, salinity, or alkalinity of water, making it undrinkable or unsuitable for the support of animal and plant life. It could have effects which can result in dire consequences for higher mammals such as humans (Dawson, 2004).

Notwithstanding this, major ions, principally Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , SO_4^{2-} , Si, and minor ions such as fluoride as well as some trace elements are generally essential for human health and metabolism (Safe Drinking Water Comm., 1980). Again, (Freeze and Cherry, 1979) found out that the intake of some major ions such as: sodium, sulphate and chloride by humans of water with concentrations of these ions above the recommended limits are generally not harmful. When Na^+ exceeds the recommended limit of 200 mg/L,

the water tastes salty. Similarly, maximum chloride concentration permissible in drinking water is 250 mg/L primarily because of taste (Kortatsi, 2004).

However, if some of these substances particularly the minor ions and trace elements occur in the water above certain limits, they become hazardous to health or impact sensory effect to the water that makes it objectionable to the consumer (Kortatsi, 2004). In the Tarkwa mining area previous work on water quality issues have been conducted mainly by Kuma and Ewusi (2009), Kortatsi (2004), and Asklund and Eldvall (2005). Some of their findings particularly on physico-chemical parameters are presented below.

2.2.3.1 Sulphate

The presence of sulphate in drinking water results in a noticeable change of taste. The lowest taste threshold concentration for sulphate is approximately 250 mg/l. The physiological effects resulting from the intake of large quantities of sulphate are catharsis, dehydration, and gastrointestinal irritation. Water containing magnesium sulphate at levels above 600 mg/l acts as a purgative in humans. Sulphate may also contribute to the corrosion of distribution systems. Drinking water should not have sulphate levels exceeding 500mg/l (WHO, 1996). Previous studies in the Tarkwa area show maximum levels in groundwater to be 21.0 mg/l and maximum levels in surface water to be 490 mg/l (Kuma, 2004).

2.2.3.2 Nitrate and Nitrite

Nitrate and nitrite are naturally occurring ions that are part of the nitrogen cycle. The nitrate ion (NO_3^-) is the stable form and it can be reduced by microbial action to a nitrite ion (NO_2^-) which is a relatively unstable oxidation state for the ion. It is the nitrite ion that constitutes the toxicity to humans. It is involved in the oxidation of normal haemoglobin to methaemoglobin, which is unable to transport oxygen to the tissues. Health guideline for

nitrate-nitrogen is set to 10 mg/l. This value should not be expressed in terms of nitrate-nitrogen but as nitrate itself which is the chemical entity of health concern, and the guideline value for nitrate alone is therefore 50 mg/l (WHO, 1996). Previous studies show maximum levels in groundwater to be (NO_3^-) 27.0 mg/l (Kortatsi, 2004) and maximum levels in surface water to be (NO_3^-) 60 mg/l (Kuma, 2004).

2.2.3.3 Sodium and Potassium

Sodium and potassium are the most important minerals occurring naturally. The major source of both cations may be weathering of rocks (Singh *et al.*, 1999) besides the sewage and industrial effluents. Sodium and potassium concentrations are also influenced by the cation exchange mechanism. The WHO guideline limit for sodium in drinking water is 200 mg/L. When Na^+ exceeds the recommended limit of 200 mg/L, the water tastes salty. A previous study in the Tarkwa mining area indicates that, the groundwater in the area is excellent with respect sodium (Kortatsi, 2004).

2.2.3.4 Calcium and Magnesium

Total hardness is an important criterion for ascertaining the suitability of water for domestic, drinking and many industrial uses (Karanth, 1994). The hardness of natural waters depends mainly on the presence of dissolved calcium and magnesium salts. Hardness of water for domestic use relates mainly to its reaction with soap. Since soap is precipitated principally by Ca^{2+} and Mg^{2+} , hardness is defined as the sum of the concentrations of these ions expressed as mg/L of CaCO_3 . Water with hardness in the range 0–60 mg/L, 61–120 mg/L, 121–180 mg l-1 and > 180 mg/L are regarded as soft, moderately hard, hard and very hard, respectively (Kortatsi, 2004). Previous studies in the Tarkwa mining area shows that the groundwater varies largely in total hardness from 10 mg/L to 358 mg/L (Kortatsi, 2004).

2.2.3.5 pH

pH is the measure of acidity or alkalinity of water. Acidity increases the capacity of the water to attack geological materials and leach toxic trace metals into the water making it potentially harmful for human consumption strong acidity can therefore render groundwater susceptible to trace metal pollution if these metals are present in the rock matrix through which the water percolates. Additionally, acidity gives sour taste to water. For the reason of taste, the WHO (1993) limits the pH range for water potability to 6.5–8.5. Previous studies show maximum pH range in groundwater to be 5–6.9 (Kortatsi, 2004).

2.2.3.6 Electrical Conductivity (EC)

The importance of Electrical Conductivity (EC) is its measure of salinity which greatly affects the taste and thus has a significant impact on the user acceptance of the water as potable (Pradeep, 1998). Electrical conductivity talks about the conducting capacity of water which in turn is determined by the presence of dissolved ions and solids. Higher the ionizable solids, greater will be the EC. The WHO permissible limit for EC in water is 600 micromh/cm (Jameel and Sirajudeen, 2006). Previous studies in the Tarkwa area shows a range in groundwater to be 37–780 mS/cm (Kortatsi 2004).

2.2.4 Trace and Heavy Metal Contaminants

The assessment of metal contamination is an important aspect of most water quality assessment programmes. The Global Environment Monitoring System (GEMS) programme GEMS/WATER includes ten metals Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Mercury (Hg), Zinc (Zn), Nickel (Ni), Aluminum (Al), Iron (Fe), and Manganese (Mn). Arsenic and Selenium (Se) (which are not strictly metals) are also

included (Chapman, 1996). Some of these metals, such as Mn, Zn and Cu, when present in trace concentrations are important for the physiological functions of living tissue and regulate many biochemical processes. For example inadequate dietary zinc intake can lead to appetite loss; poor growth and development, birth defects, slow wound healing and skin lesion. The same metals, however, discharged into natural waters at increased concentrations in sewage, industrial effluents or from mining operations can have severe toxicological effects on humans and the aquatic ecosystem (Chapman, 1996). Mercury and cadmium are some examples of non-essential metals.

2.2.4.1 Mercury

Mercury is said to pose the most physiological problem associated with groundwater for drinking purposes. Oral ingestion of inorganic mercury is rapidly accumulated in the kidney and it is very irritating to the gastrointestinal tract and can cause nausea, vomiting, pain, ulceration, diarrhoea and kidney damage, including kidney failure. Toxicity to the brain and nervous system has also been reported, following large doses of inorganic mercury taken medicinally (WHO, 1993). Previous studies in the Tarkwa area show maximum levels in groundwater to be 0.037 mg/l (Kortatsi, 2004).

2.2.4.2 Cadmium

Cadmium is chemically similar to zinc and occurs naturally with zinc and lead in sulphide ores. Cadmium concentrations in unpolluted natural waters are usually below 1 µg/l. It generally gets into water by corrosion of galvanized pipes or by improper waste disposal (Florida dept. of environment, 2008). When one is exposed to this chemical for a long time, it can result in kidney damage. Previous studies in the Tarkwa area show maximum levels in groundwater to be 0.003 mg/l (Kortatsi, 2004).

2.2.4.3 Nickel

This inorganic metal generally gets into water from mining and refining operations (Florida Dept. of Env., 2008). The nickel ion content of groundwater may increase as a result of the oxidation of natural nickel containing ferrosulphide deposits (Florida dept. of environment, 2008). Nickel concentrations in drinking water around the world are normally below 20µg/l, (Asklund and Eldvall 2005) although levels up to several hundred micrograms per litre in groundwater and drinking water have been reported. WHO (1993) guideline maximum value set for drinking water for nickel is 0.02mg/l to protect against the risk of these adverse effects, drinking water which meets the WHO guideline is associated with little to none of the risk and should be considered safe with respect to nickel. Previous studies in the Tarkwa mining area show maximum levels in groundwater to be 0.076 mg/l (Kortatsi, 2004).

2.2.4.4 Arsenic

In groundwater, the presence of arsenic is largely the result of minerals dissolving from naturally weathered rocks and soils over time. (Florida Dept. of Environment, 2008). The level of arsenic in natural waters generally varies between 1 and 2 µg/l. Concentrations may however be elevated in areas containing natural sources, values as high as 12 mg/l have been reported (Asklund and Eldvall, 2005) As can be converted into insoluble compounds and can be co-precipitated with the hydroxides of Fe and Mn in an aqueous medium under certain conditions (Smedley and Kinniburgh, 2001). A provisional guideline value of 0.01 mg/l is recommended. The guideline value has been derived on the basis of estimated lifetime cancer risk (WHO, 1996). Previous studies in the Tarkwa area show maximum levels in groundwater to be 0.046 mg/l (Kortatsi, 2004) and maximum levels in surface water to be 0.137 mg/l (Kuma, 2004).

2.2.4.5 Zinc

Zinc occurs as a natural mineral in many drinking waters and is an essential dietary nutrient and a beneficial element in human metabolism. Inadequate dietary zinc intake can lead to appetite loss; poor growth and development, birth defects, slow wound healing and skin lesions (Kortatsi, 2004). Too much zinc intake however (at least 10 times the recommended daily dose) can produce gastrointestinal disturbances such as pain, cramping, nausea and vomiting, diarrhoea and pancreatic toxicity (Kortatsi, 2004). In water, excess zinc also produces aesthetic effect (metallic taste) on the water for which reason the WHO (1993) recommended a limit of 3.0 mg/L for potable water. Previous studies in the Tarkwa area show that zinc concentration does not pose quality problem for groundwater supply and development, only 1% of the boreholes in the area exceeded WHO recommended limit (Kortatsi, 2004).

2.2.4.6 Manganese

Manganese concentrations above 0.1 mg/l impart an undesirable taste to drinking water. Even at about 0.02 mg/l, manganese will form coatings on piping that may later tear off as a black precipitate (Asklund and Eldvall, 2005). When manganese compounds in solution undergo oxidation, manganese is precipitated. Humans can however consume as much as 20 mg/day without any apparent ill effects (Asklund and Eldvall, 2005). Manganese is therefore believed to have a neurotoxic effect; a provisional health-based guideline value of 0.5 mg/l is therefore proposed to protect public health (WHO, 1996). Previous studies in the Tarkwa area show maximum levels in groundwater to be 1.3 mg/l (Kortatsi, 2004) and maximum levels in surface water to be 2.43 mg/l (Kuma, 2004).

2.2.4.7 Lead

Lead is the most common of the heavy elements, accounting for 13 mg/kg of the earth's crust. More than 80% of the daily intake of lead is derived from the ingestion of food, dirt,

and dust (Florida Dept. of environment, 2008). Lead is possible human carcinogen and it is also a cumulative poison so that any increase in the body burden of lead should be avoided. A provisional tolerable daily intake is set to 3.5 μg of lead per kg of body weight for infants lead to a calculated guideline value of 0.01 mg/L in potable water. As infants are considered to be the most sensitive subgroup of the population, this guideline value will also be protective for other age groups (WHO, 1996). Previous studies show maximum levels in groundwater to be 0.026 mg/l (Kortatsi, 2004) and maximum levels in surface water to be <0.05 mg/l (Kuma, 2004).



CHAPTER THREE

MATERIALS AND METHODS

3.1 THE STUDY AREA

The study area is Tarkwa which is the administrative capital of the Tarkwa Nsuaem municipality. Tarkwa has nearly a century of gold mining history and has the largest concentration of mining companies in a single district on the continent of Africa (Akabzaa and Darimani, 2001). Currently, large scale mining companies found in the area include: Goldfields Ghana limited Tarkwa, AngloGold Ashanti Iduapriem Mine and Ghana Manganese Company limited Nsuta. The area lies within the main gold belt of Ghana that stretches from Axim in the southwest, to Konongo in the northeast (Kortatsi, 2004). Figure 3.1 shows the location of Tarkwa.

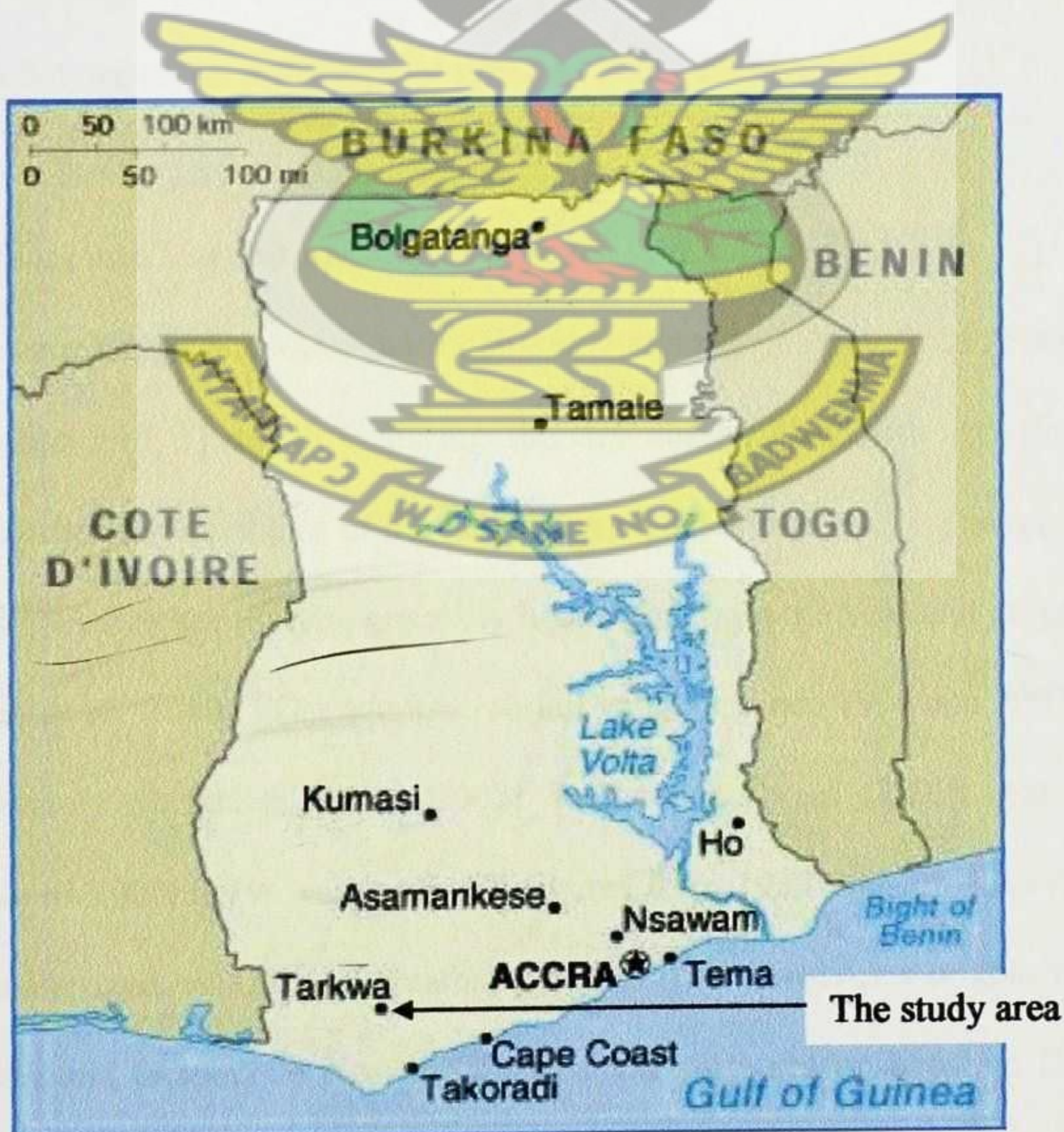


Fig. 3.1 Location of the study area (Source: Anon, 2001)

3.1.1 Geology and Soil

Tarkwa is located on the contact between Tarkwaian rocks due west and older Birimian super-group of Ghana to the east. The Birimian system is divided into upper and lower Birimian series and has a higher content of heavy metals than the Tarkwaian system. For instance Dzigbodi-Adjimah, (1993) found out that: the veins of the Birimian in the Tarkwa area consist of quartz with carbonate minerals, green sericite, carbonaceous partings and metallic sulphides as well as arsenides of Fe, As, Zn, Au, Cu, Sb and Pb. The upper part of the Birimian is made up of volcanic and pyroclastic origin, this part also consist of bedded groups of green lava. The rocks of the Tarkwaian system on the other hand consist of the Kawere group, the banket series, the Tarkwa phyllite and the Huni sandstone (Kuma and Younger 2001). Figure 3.2 shows the geological map of the Tarkwa area. The soils in the Tarkwa area consist mainly of silty-sands with minor patches of laterite mostly on hilly areas which belong to the forest oxysol group of soils (TNMA, 2010).

3.1.2 Climate and Vegetation

The area is very humid and warm with daily temperatures ranging from 28 to 30°C during the wet season and 31 to 33°C during the dry season (Dickson and Benneh, 1980). Sunshine duration for most part of the year averages 7 hours per day. The area experiences high rainfall; relative humidity is generally high throughout the year and ranges from 70 to 90% (Armah *et al.*, 2010). The average rainfall value between 1994 and 2002 is 1576 mm or approximately 62 inches (Obiri, 2007). Kuma and Ewusi (2009) also indicated an annual mean of 1900mm/yr. using rainfall figures from 1939 to 2008. The climate of the area is characterized by seasonal weather patterns. This involves a double wet season in April to June and October to November and a main dry season between December and February (Armah *et al.*, 2010).

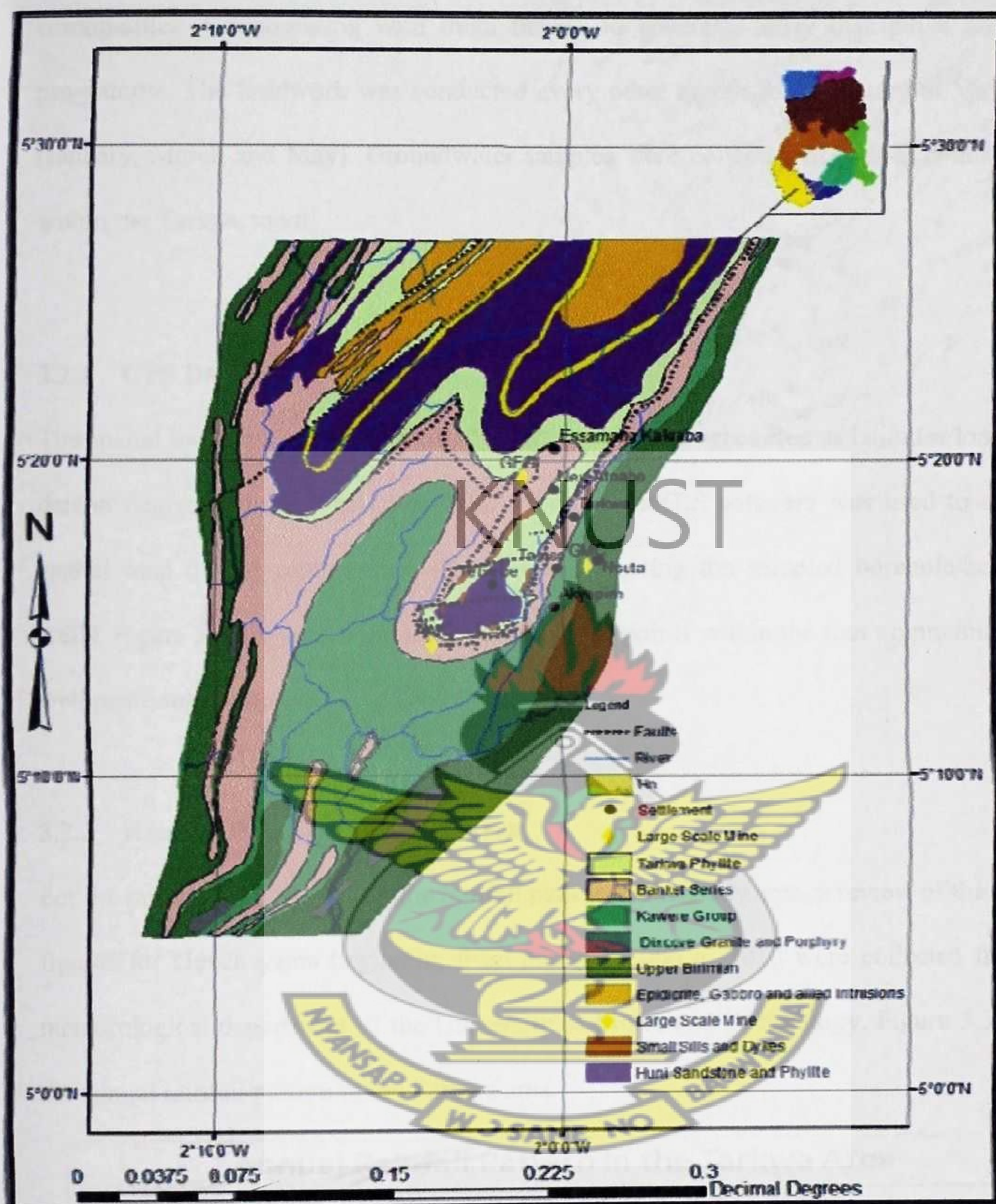


Figure 3.2: Simplified Geological Map of the Tarkwa Area (Modified from Kortatsi, 2004)

3.2 FIELD METHODS

The sampling plan was drawn in July, 2010 in consultation with Water and Sanitation Department of the Tarkwa Nsuaem Municipality and the Environmental Monitoring Department of Goldfields Ghana limited, Tarkwa Mine. These two organizations have statistics on the type, location, number of wells/boreholes within the Tarkwa mining

communities. Collaborating with them helped to ensure a fairly distributed sampling programme. The fieldwork was conducted every other month from January to May 2011 (January, March and May). Groundwater samples were collected from four communities within the Tarkwa town.

3.2.1 GPS Data Collections

The spatial locations of the boreholes/hand dug wells were recorded as latitudes/longitudes data.in degrees, minutes seconds (DMS) format. ArcGIS software was used to create a spatial map of the communities (Study area) showing the sampled borehole/hand dug wells. Figure 3.4 shows the groundwater sampling points within the four communities, the well positions are marked green and black.

3.2.2 Rainfall Data for the Study Area

For the purpose of establishing the rainfall pattern of the study area, a review of the rainfall figures for eleven years beginning from the year 2000 to 2010 were collected from the meteorological department of the University of Mines and Technology. Figure 3.3 shows the annual rainfall pattern in the Tarkwa area.

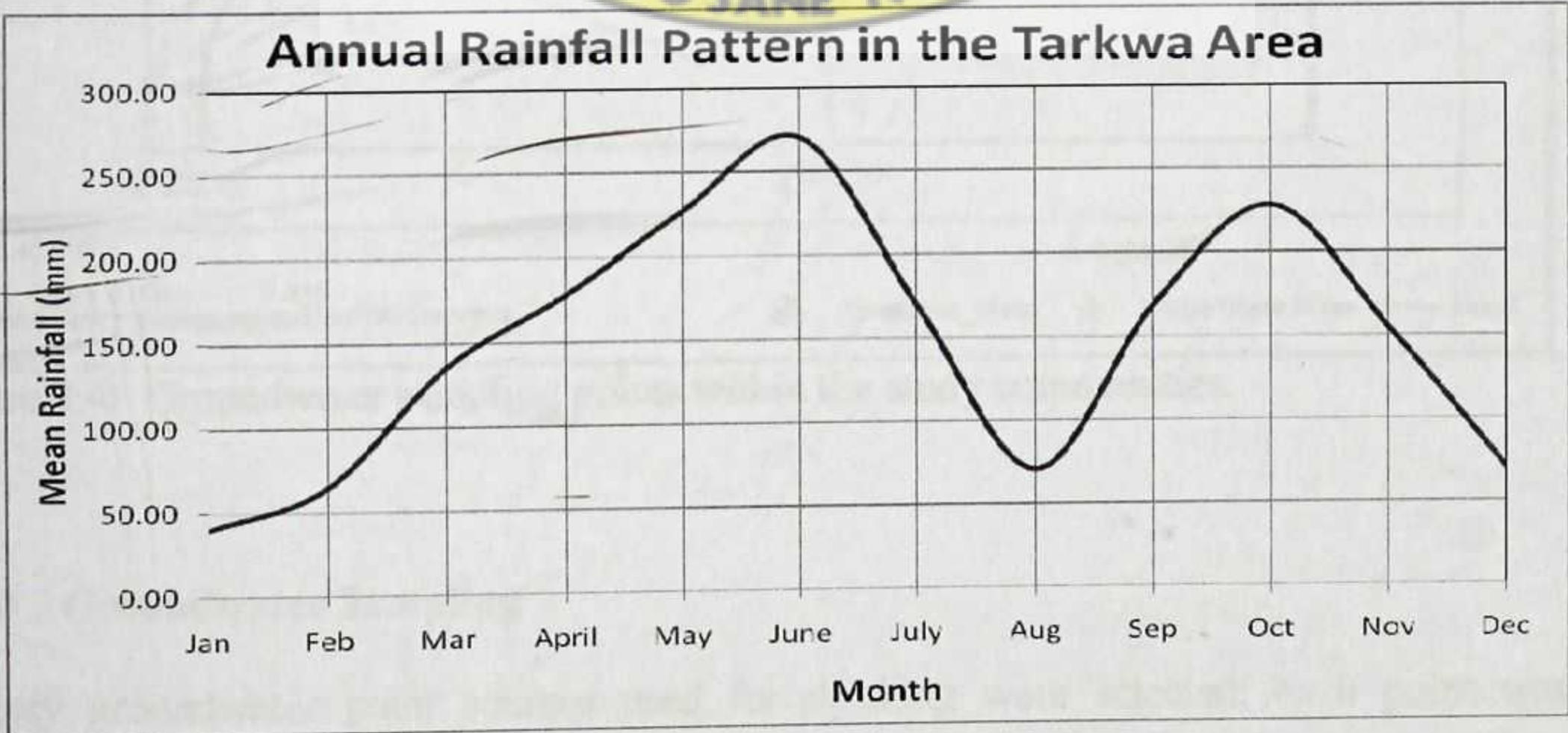


Figure 3.3: Annual Rainfall Pattern in the Tarkwa Area.

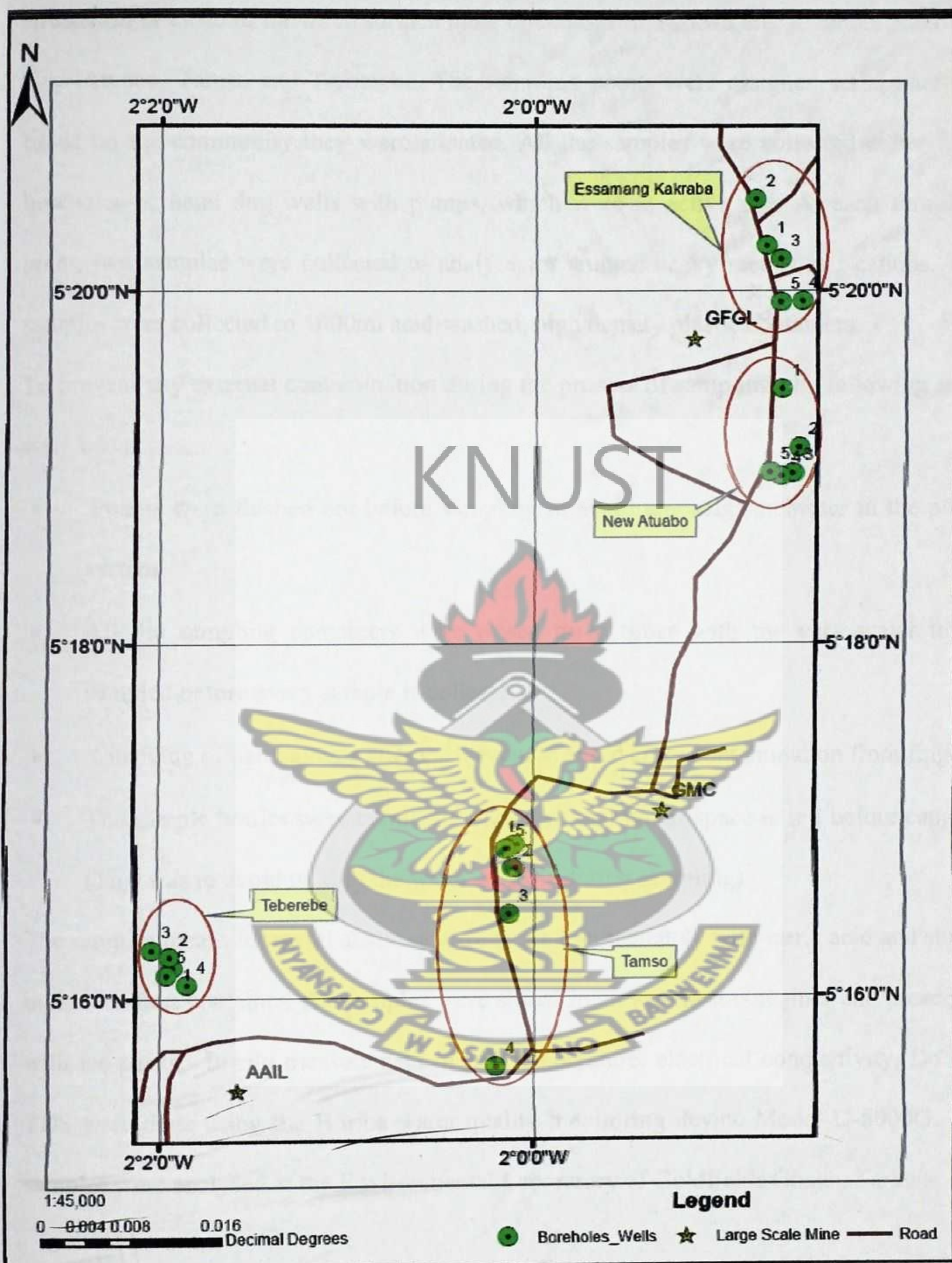


Figure 3.4: Groundwater sampling points within the study communities.

3.2.3 Groundwater Sampling

Twenty groundwater point sources used for drinking were selected; each point was sampled three times (January, March, and May). The selected communities which are

situated in or close to the three surface mine operations in Tarkwa are: Essaman Kakraba, New Atuabo, Tamso and Terberebe. The sampling points were assigned serial numbers based on the community they were situated. All the samples were collected either from boreholes or hand dug wells with pumps, which were in active use. At each sampling point, two samples were collected to analyse for anions, heavy metals and cations. The samples were collected in 1000ml acid-washed, high density plastic containers.

To prevent any external contamination during the process of sampling, the following steps were taken:

- Pumps were flushed out before sampling to avoid any stagnant water in the pump system.
- All the sampling containers were rinsed three times with the very water to be sampled before every sample is collected.
- Changing of hand gloves after each event to avoid cross contamination from fingers
- The sample bottles were completely filled so that no air space is left before capping (This was to avoid mixing the water with air during sampling).

The samples meant for metal analyses were treated immediately with nitric acid and stored in an ice-chest container. All samples were stored in an ice-chest container and preserved with ice packs. In-situ measurement of pH, temperature, electrical conductivity, Do and TDS were done using the Horiba water quality monitoring device Model U-5000G. The samples were analysed at the Environmental Laboratory of Goldfields Ghana, Tarkwa.

3.3 LABORATORY AND ON-SITE ANALYSIS

3.3.1 On-Site Analyses

The on-site analyse was achieved by collecting the samples in a 2000ml container, after which the cell of the Horiba water quality monitoring device is immersed in the water.

Measurements for the parameters were taken (read) on-screen after stable values were achieved from the Horiba device. The device is rinsed with distilled water and cleaned with a tissue paper in readiness for further readings.

3.3.2 Heavy Metals and Cations Analyses

The following metals namely, Nickel (Ni), Iron (Fe), Cadmium (Cd), Lead (Pb), Manganese (Mn), Zinc (Zn), Copper (Cu), Mercury (Hg), Arsenic (As) and the cations, Sodium (Na), Calcium(Ca), Magnesium(Mg) and Potassium(K) were analysed at the Environmental Laboratory of Goldfields Ghana limited Tarkwa mine, by the Atomic Absorption Spectrometer (Varian spectra AAS240). The samples are prepared by collecting 100ml into the sample bottles, after they have thoroughly been rinsed with the very water to be sampled and vacuum filtered through a 0.45 micrometer membrane filter. As part of the quality assurance procedure, a blank prepared from distilled water as well as the standard reference solution for the individual parameters are used to calibrate the instrument after the required lamp has been fixed into the instrument. Again, the standard reference solutions are used as spiked samples.

3.3.3 Analyses of Anions

Three anions Chloride, Sulphate and Nitrate was analysed for their concentrations using the Hach DR 5000 Spectrophotometer instrument. Each sample was prepared with a blank (distilled water), the preparation involves using the sample cells with the sample to be analysed. For each sample two cells were required, -one for the sample and the other for the blank. The cells were filled with 10ml each of the sample and distilled water respectively, samples are dozed with the appropriate reagent. The cells were then swirled to enable thorough mixing of the specimen with the reagent; the cell with the blank is used to calibrate the spectrophotometer.

- Chloride (Cl^-), the reagents used were 1ml of mercuric thiocyanate and 0.5ml of ferric iron solution, which is put in the sample. The mercuric thiocyanate is first put into the sample and swirled after which the ferric iron solution is added. A two minute reaction time is allowed for the specimen before they are placed in the cell holder of the spectrophotometer for reading.
- Sulphate (SO_4^{2-}), the reagent for sulphate is Sulfaver4 powder, one each is poured into the prepared samples. A five minute reaction period is allowed before calibration and reading
- Nitrate (NO_3^-) is determined by colorimetry using nitraVer5 nitrate reagent powder, the reaction is also five minute.b

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3.3.4 Alkalinity and Hardness Analyses

Total alkalinity and hardness were determined by titration using standard methods. The concentrations were then calculated as;

$$\text{Total alkalinity} \left(\frac{\text{mg}}{\text{l}} \right) = \frac{\text{Volume of HCL} \times 1000}{\text{Volume of sample}}$$

Total Hardness is also calculated as;

$$\frac{\text{mL of EDTA used} \times B \times 1000}{\text{Volume of sample}}$$

Where B = mg of CaCO_3 equivalent to 1000 ml of EDTA titrant or by multiplying the end point by 10.

CHAPTER FOUR

RESULTS

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4.1 MEAN MONTHLY RESULTS

The monthly mean results of the water quality analyses for the parameters which showed elevated concentrations across the four communities are presented in Figures 4.1 to 4.9, with their permissible WHO guideline values for drinking water quality.

Table 4.1: Summary result of groundwater chemistry

Parameter	Unit	Min.	Max.	Average*	St. Dev.	WHO GV
pH		4.03	6.98	5.49	0.701844	6.5-8.5
TDS	mg/l	44	563	154.81	124.5117	1000 mg/l
E.C	$\mu\text{S/cm}$	69.4	898*	239.42	122.4373	300 $\mu\text{S/cm}$
Total Hardness		20.33	581.38	87.95	46.50478	
Temperature	$^{\circ}\text{C}$	22.8	28.51	24.63	0.875517	
DO		2.1	5.9	3.61	0.495806	
Calcium	mg/l	1.42	22.17	8.36	4.123728	
Potassium	mg/l	0.20	29.8	3.70	3.263268	
Magnesium	mg/l	0.42	17.17	3.55	2.956615	
Sodium	mg/l	2.50	83.26	20.42	13.63679	200 mg/l
Chloride	mg/l	2.50	193	30.19	23.57648	250 mg/l
Sulphate	mg/l	<1	58	7.1	10.23009	250 mg/l
Nitrate	mg/l	1.3	101.3	27.51	18.59746	50 mg/l
Cadmium	mg/l	<0.001	0.01	0.001	0.001468	0.003mg/g
Nickel	mg/l	0.007	0.04*	0.02	0.006674	0.02 mg/l
Iron	mg/l	0.01	0.77*	0.20	0.128234	0.3 mg/l
Lead	mg/l	0.001	0.104*	0.008	0.012582	0.01 mg/l
Manganese	mg/l	0.01	1.34*	0.31	0.231012	0.4mg/l
Zinc	mg/l	<0.01	0.56	0.05	0.072661	3.0 mg/l
Copper	mg/l	0.01	0.19	0.04	0.029623	1-2 mg/l
Mercury	ug/l	<0.002	<0.002	<0.002		1.0 ug/l
Arsenic (total)	ug/l	<1	1.3	1.3	0.382971	10 ug/l

* Values exceeding WHO guideline values for drinking water are marked

The detailed results including conductivity, temperature, dissolved oxygen, total dissolved solids (TDS) as well as the chemical parameters (heavy metals and major ions) within the study area are presented in Table 4.1.

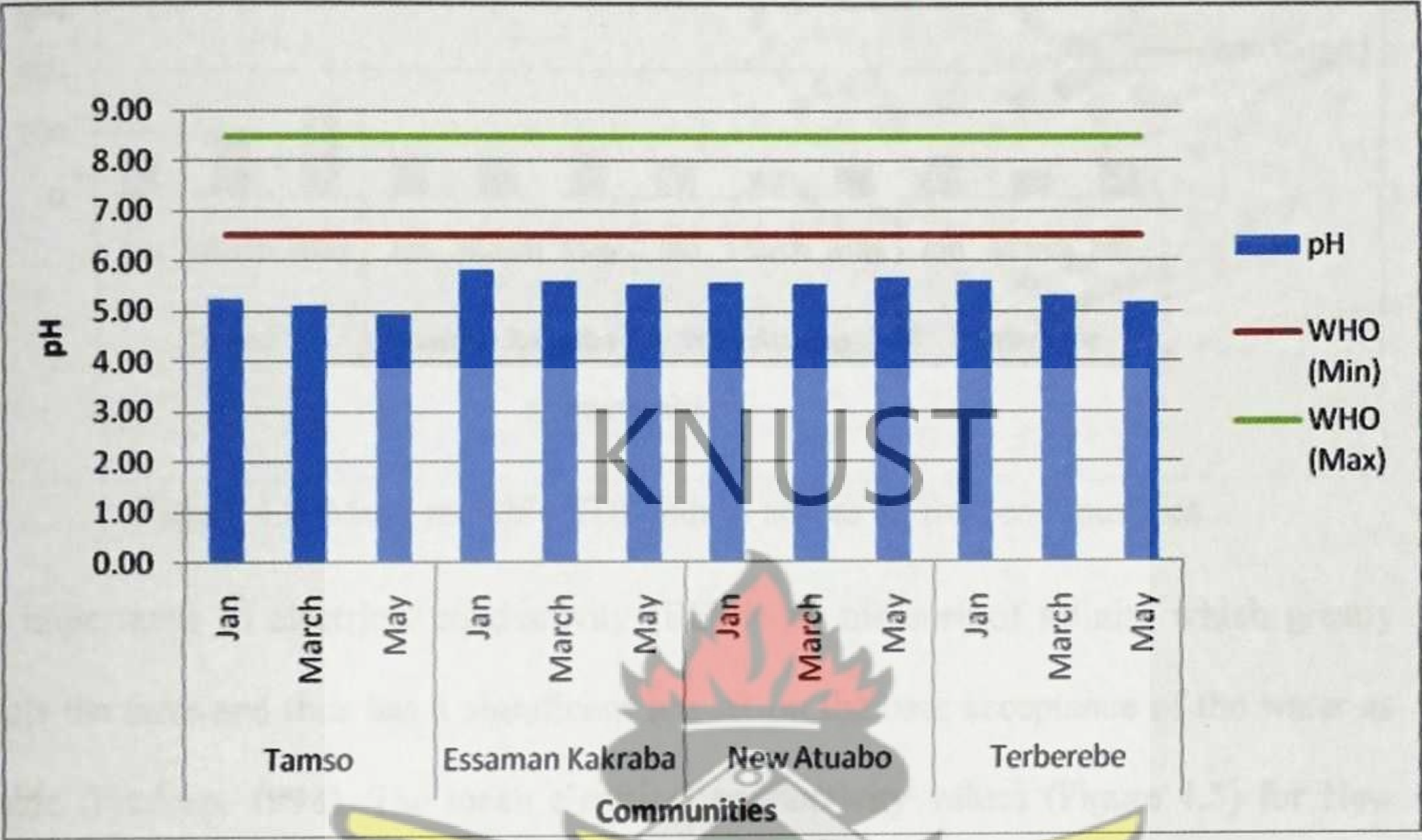


Figure 4.1 Mean monthly pH values across all four communities.

The mean monthly pH values show that the groundwater within the Tarkwa mining communities is generally mildly acidic, since all the four study areas recorded pH values below the WHO guideline value for drinking water. The mean TDS results (Figure 4.2) across all the four communities are excellent since they were consistently low and below 1000 mg/L (WHO, 1993).



Figure 4.2: Mean monthly TDS values across all four communities

The importance of electrical conductivity (EC) is its measure of salinity which greatly affects the taste and thus has a significant impact on the user acceptance of the water as potable (Pradeep, 1998). The mean electrical conductivity values (Figure 4.3) for New Atuabo and Terberebe were low, while Tamso and Essaman Kakraba recorded elevated concentrations during the months of March and May.

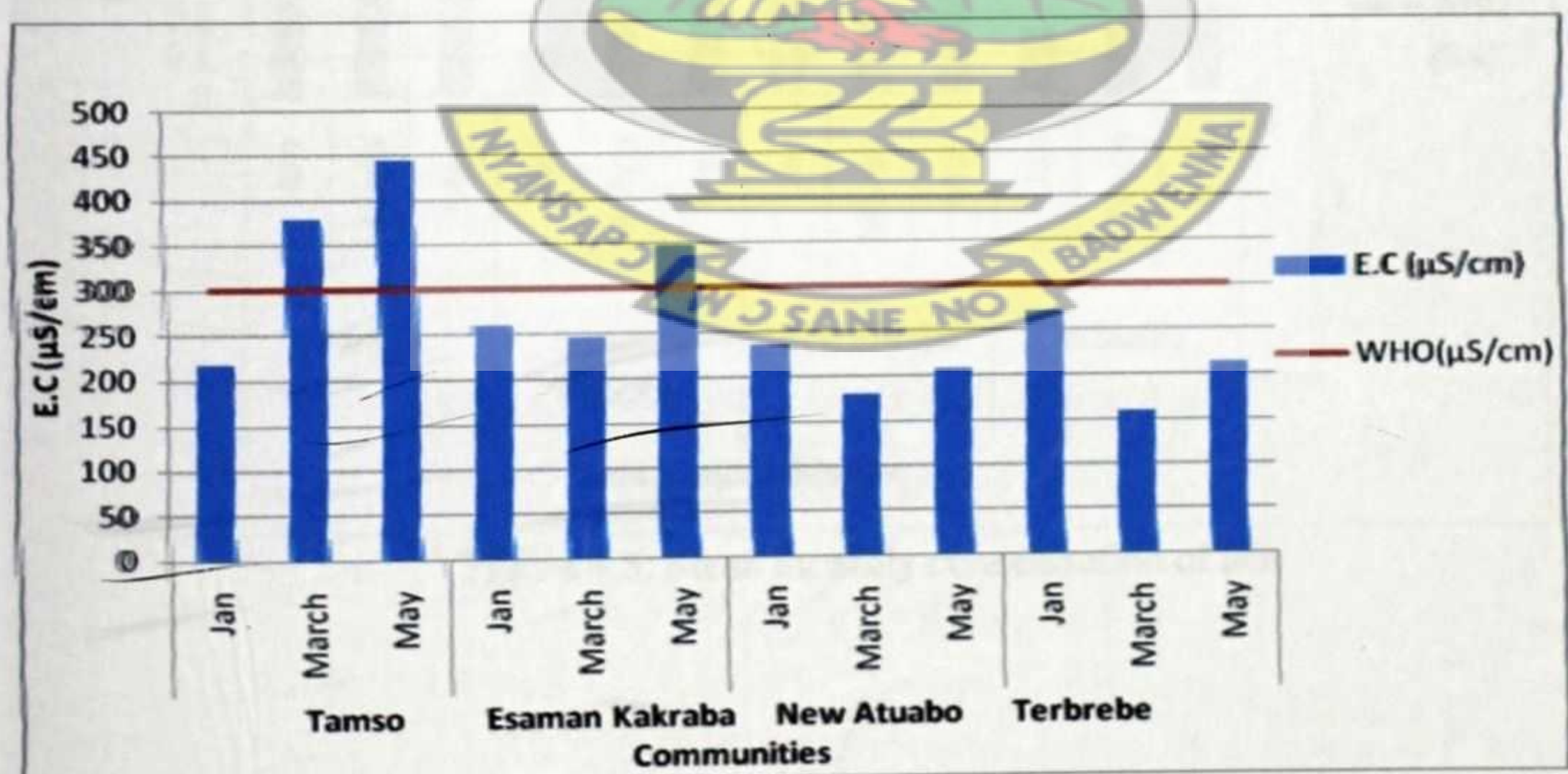


Figure 4.3 Mean monthly Electrical Conductivity (EC) values across all four communities

Figures 4.4 to 4.9 show the heavy metals which recorded elevated concentrations during the monthly readings across all four communities.

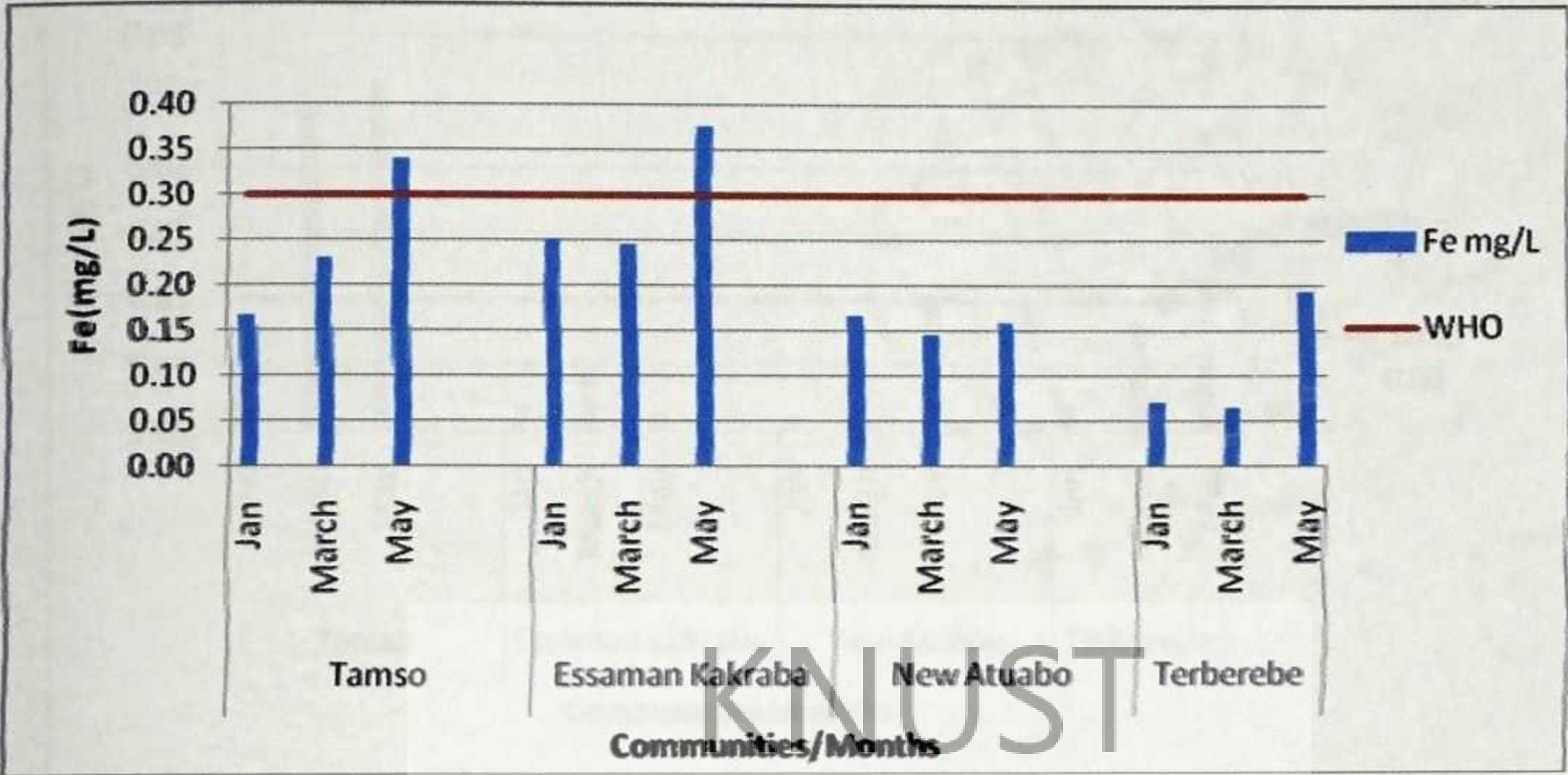


Figure 4.4: Mean monthly concentration of Fe

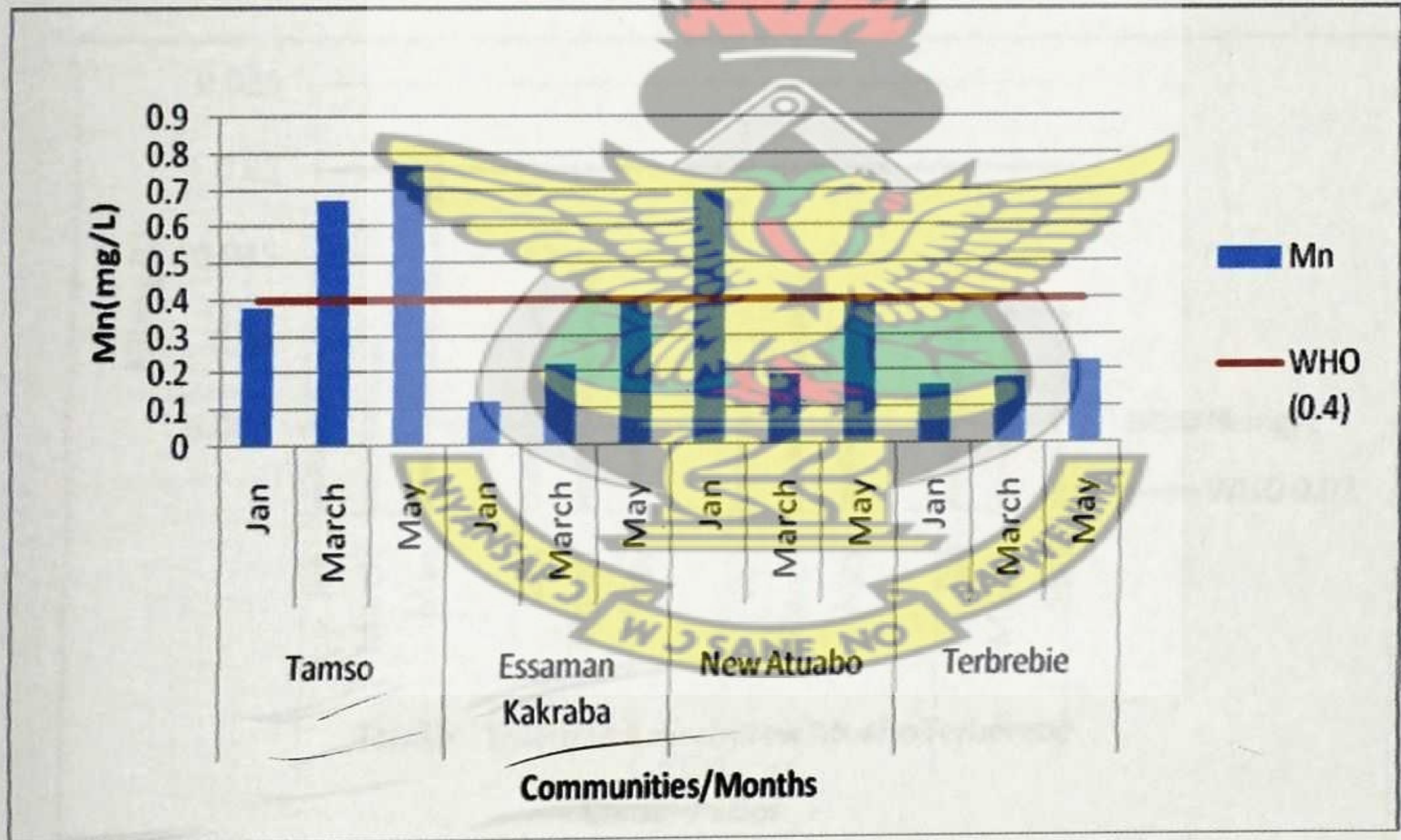


Figure 4.5: Mean monthly concentration of Mn

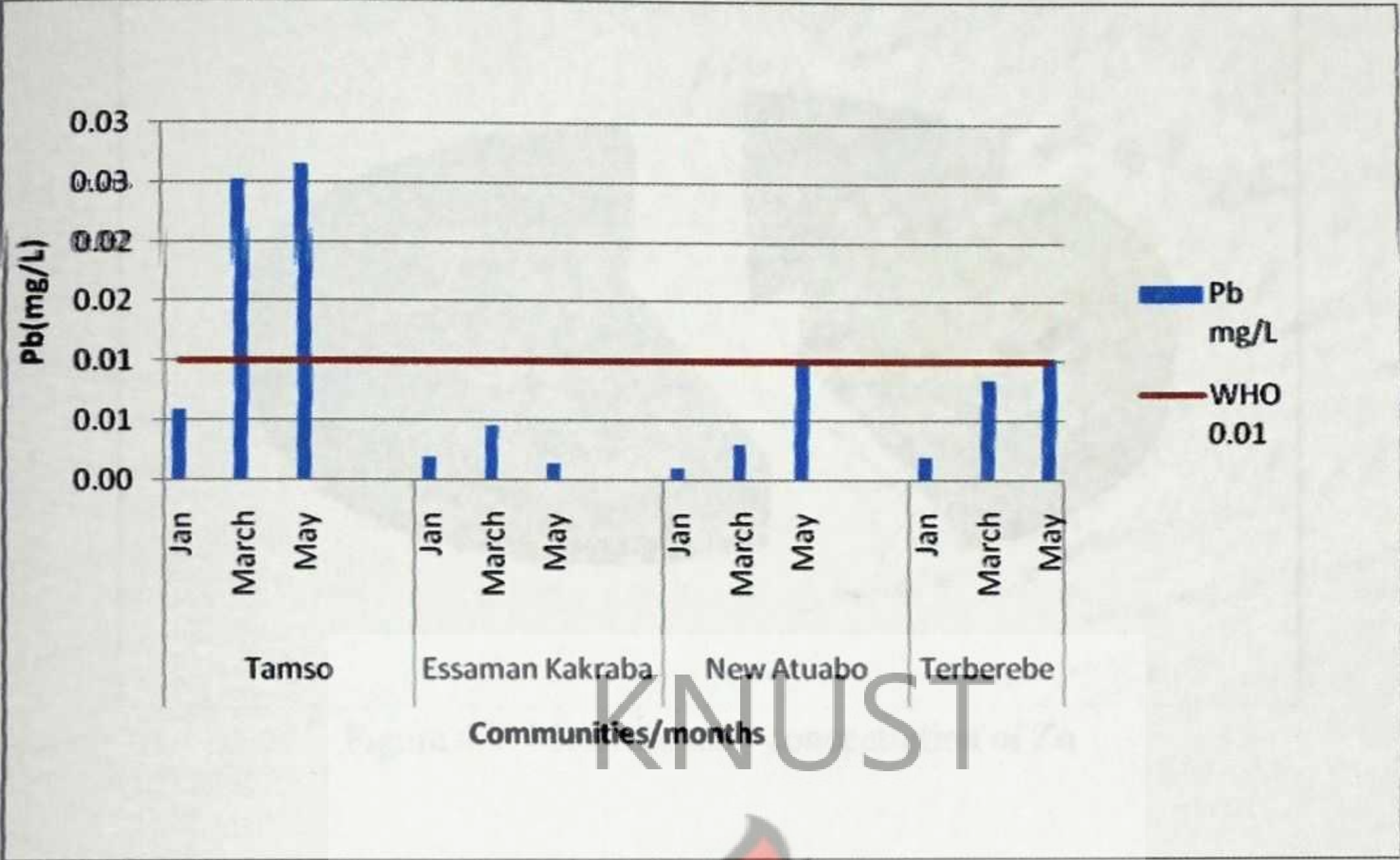


Figure 4.6: Mean monthly concentration of Pb

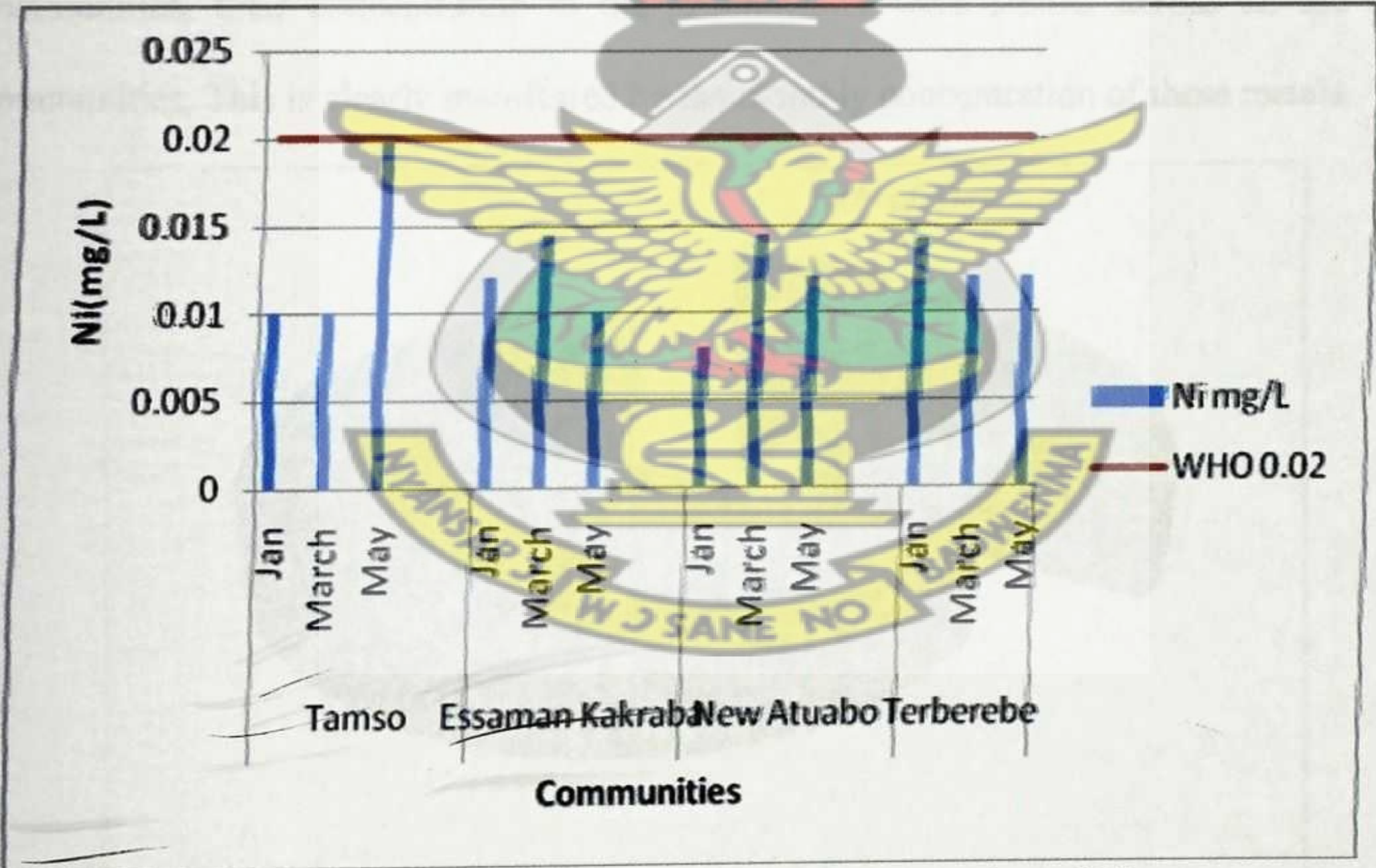


Figure 4.7: Mean monthly concentration of Ni

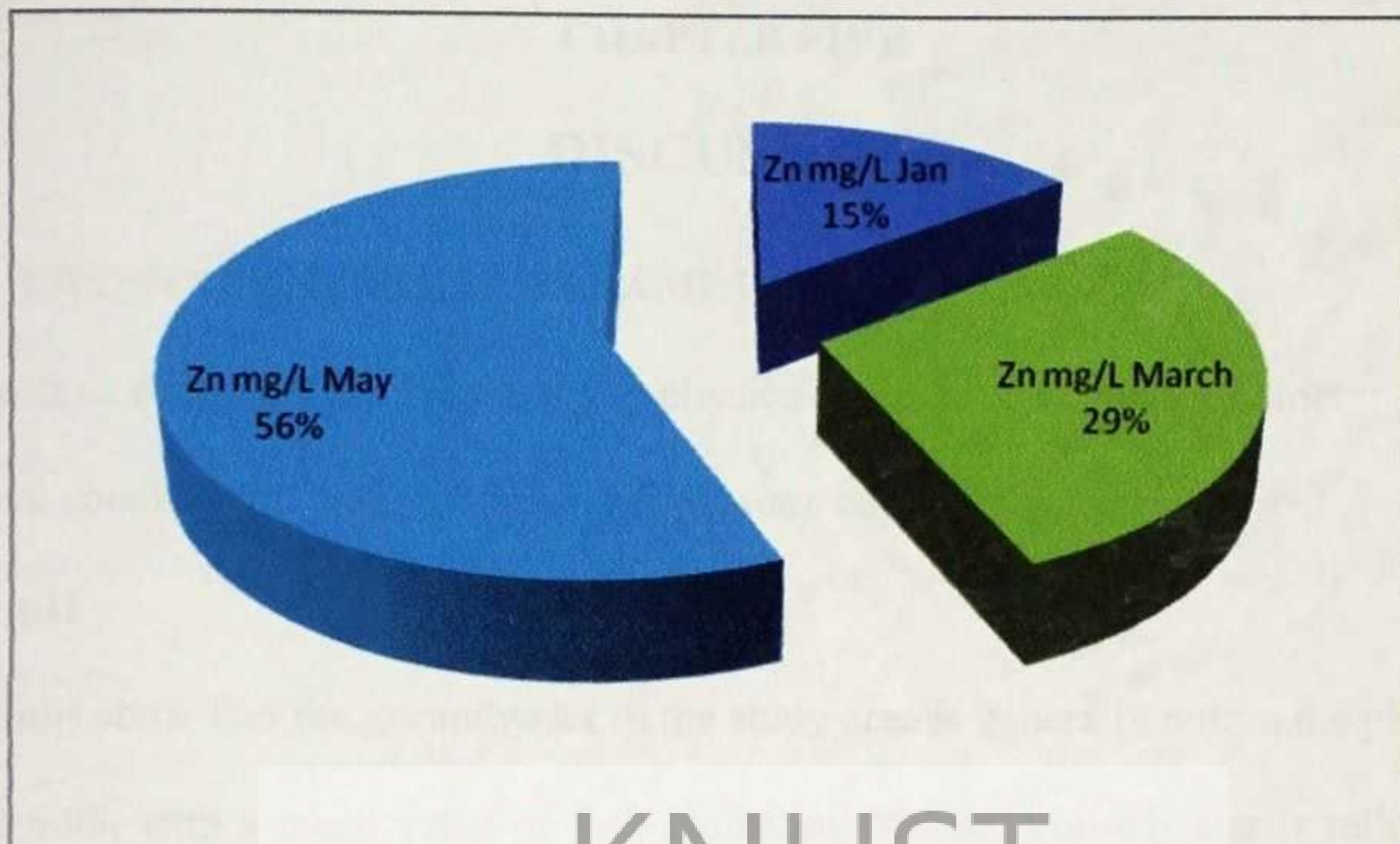


Figure 4.8: Mean monthly concentration of Zn

The results for both the Zn and Cu though did **not** exceed the WHO guideline in any of the communities, their concentration in the groundwater were similar across all the four communities. This is clearly manifested by the monthly concentration of these metals.

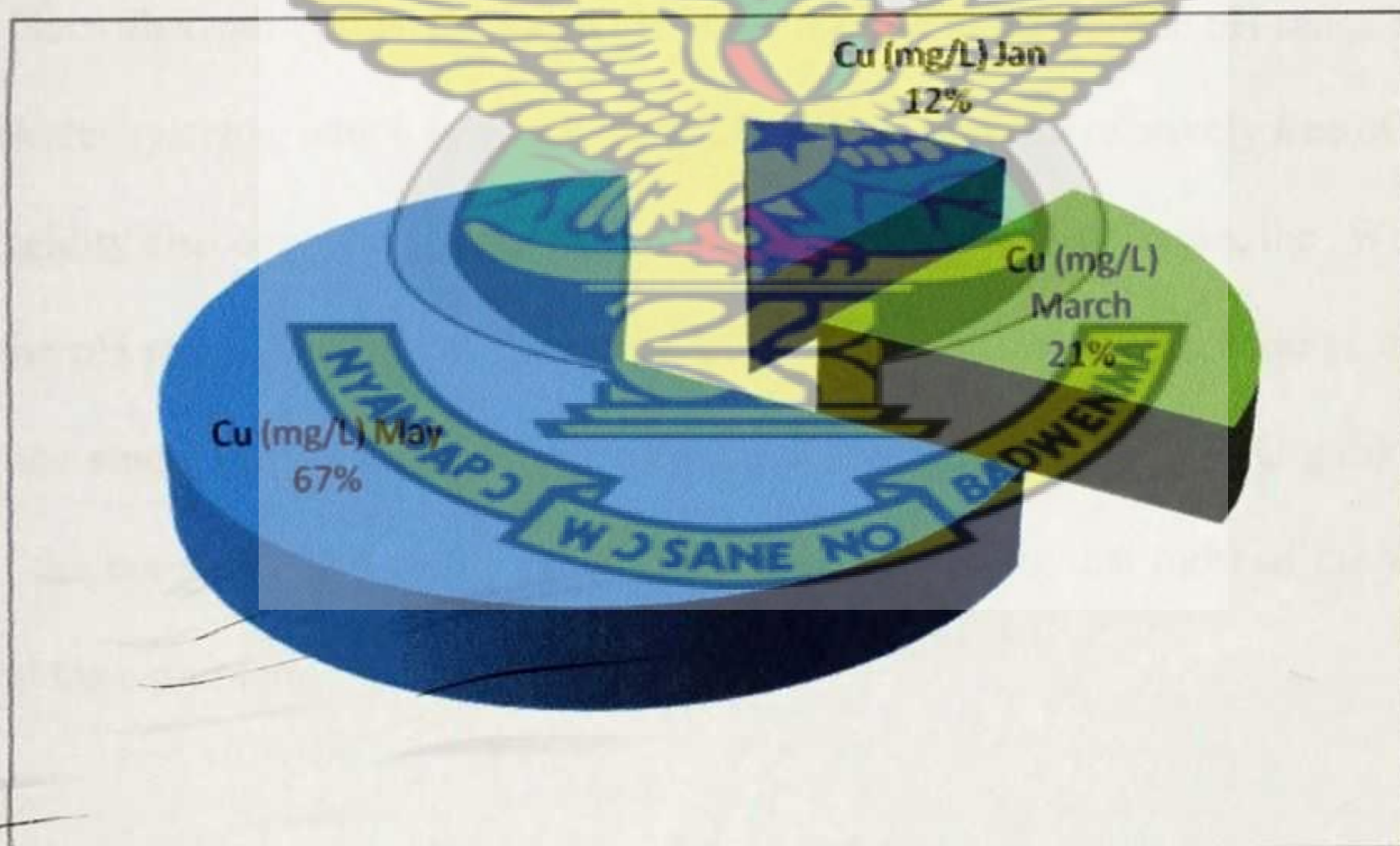


Figure 4.9: Mean monthly concentration of Cu

CHAPTER FIVE

DISCUSSION

5.1 PHYSICO-CHEMICAL PARAMETERS

This section discusses the result of the physico-chemical parameters namely; pH, TDS, electrical conductivity, total hardness, temperature and dissolved oxygen.

5.1.1 pH

The results show that the groundwater in the study area is generally within the pH range of 4.03 to 6.98, with a mean value of 5.49 indicating that the groundwater is mildly acidic. The acidic nature of the water is most likely generated from the geology of the aquifer containing the groundwater in the area. It is mainly metamorphic granitic schist, gneisses, volcanic rocks etc. CO₂ generated in the soil zone as a result of the oxidation of soil organic matter can also result in elevated acidic groundwater (Hounslow, 1995; Langmuir, 1997). Notwithstanding this, the mean pH value is close to the normal pH range for natural groundwater systems, which is mostly near 5.6; even if they are relatively free of pollution. Again acidity also contributes sour taste to water. For the reason of taste, the (WHO, 1993) limits the pH range for drinking water to 6.5–8.5. Out of the 60 pH readings determined during the study, only 3 readings representing 5% were within the WHO guideline, with 95% of the boreholes and wells outside this range suggesting that most of the wells have potential taste problem.

5.1.2 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) values ranged from 44-3005 mg/L for the area. The average value of TDS for the area is 152.85 mg/L, which is well below the WHO limit of 1000 mg/L. The highest TDS value was recorded at the Tamso area and may be due to dissolve minerals like manganese, lead and nickel, since these parameters recorded elevated

concentration in some wells in the Tamso area. The palatability of water with a TDS level of less than 600 mg/L is generally considered to be good. Drinking-water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/L (WHO, 1993). High levels of TDS may also be objectionable to consumers, owing to excessive scaling in household appliances; in the Tarkwa area however, this problem should not be expected from the groundwater since the TDS values were generally good and below the WHO guideline value for drinking water.

5.1.3 Electrical conductivity.

Electrical conductivity is the conducting capacity of water which is determined by the presence of dissolved ions and solids. The higher the ionizable solids, the greater the EC. The WHO permissible limit for EC in water is 300 $\mu\text{S}/\text{cm}$. Electrical conductivity values within the study area are generally low, in the range of 69.40-898 $\mu\text{S}/\text{cm}$, with a mean value of 246.09 $\mu\text{S}/\text{cm}$. About 25% of the EC readings exceeded the WHO permissible limit, indicating that the water in area is less contaminated. Since the E.C of water can be related to the total dissolved solids concentration, which can also be used as an indicator to determine the general quality of water especially the measure of the amount of dissolved ions in the water. From the mean monthly readings, the groundwater in the Tamso area may be vulnerable to the dissolved ions since elevated concentrations of EC were recorded within the period of March and May. This may be due to the high rainfall experienced during these periods-which can drain more water into the catchment, and thus result in the dissolution of ions and other solids inherent in the geology of the area.

5.1.4 Total Hardness

Total hardness is an essential parameter for ascertaining the suitability of water for domestic, drinking and industrial uses. It is a property of water which prevents lather

formation with soap and produces scales in hot water systems. It is mainly due to the metallic ions of Calcium (Ca^{2+}) and Magnesium (Mg^{2+}). Groundwater from the study area varies largely in total hardness from 18 to 210 mg/L. Analysis of the piper plot in Figure 4.10 showed that only Essaman Kakraba community had carbonate content exceeding 50%, whilst the remaining three communities had bicarbonate content of more than 50%. The hardness of the groundwater in the study area may therefore be derived mainly from bicarbonate sources.

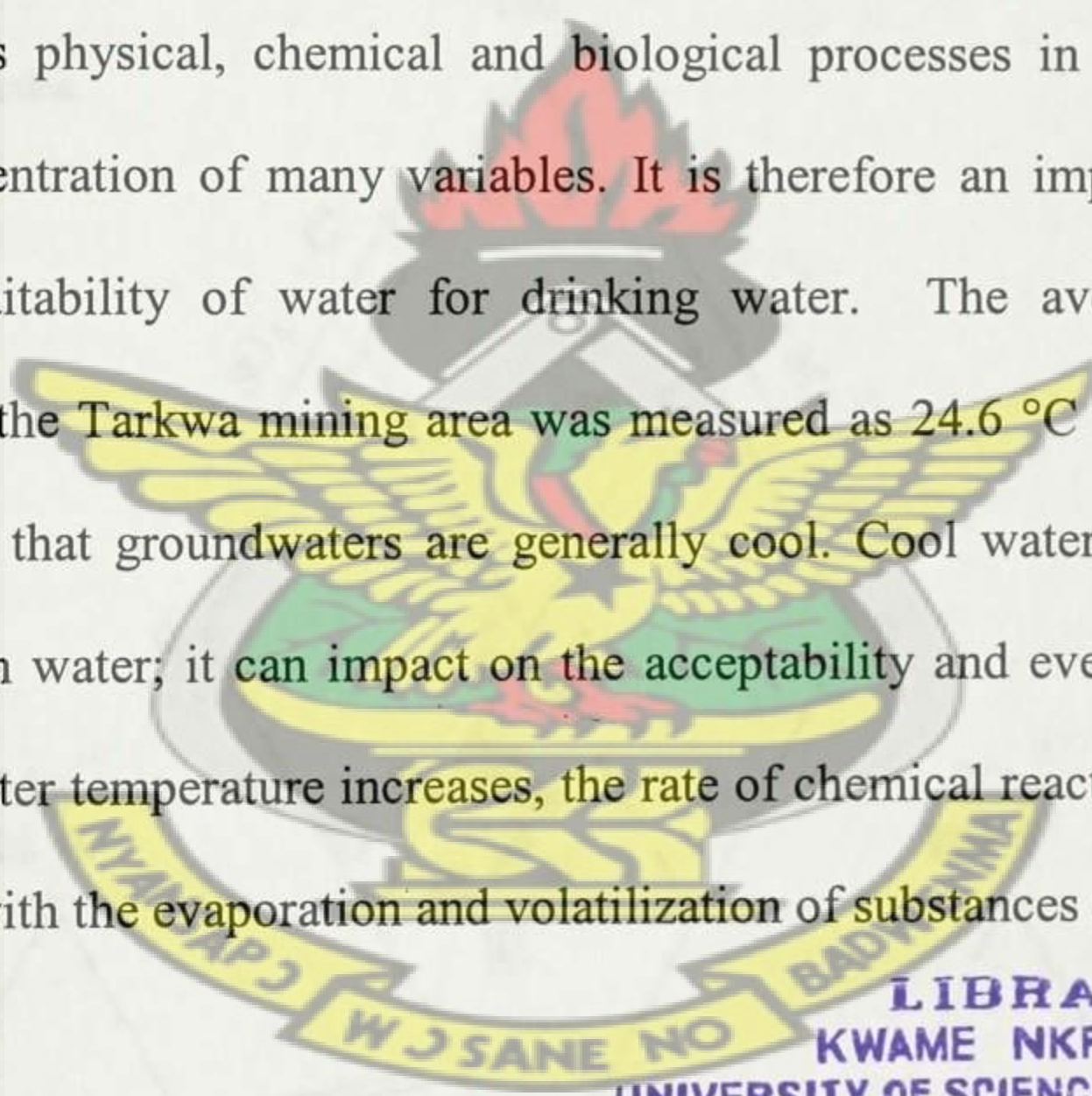
5.1.5 Temperature

Temperature affects physical, chemical and biological processes in water bodies and, therefore, the concentration of many variables. It is therefore an important criterion in ascertaining the suitability of water for drinking water. The average groundwater temperature within the Tarkwa mining area was measured as 24.6 °C ranging from 22.8-28.5 °C, indicating that groundwaters are generally cool. Cool water is generally more palatable than warm water; it can impact on the acceptability and even affect taste. It is also true that, as water temperature increases, the rate of chemical reactions also generally increases together with the evaporation and volatilization of substances from the water.

5.1.6 Dissolved Oxygen (DO)

The dissolved oxygen content of the groundwater within the Tarkwa mining area is in the range of 2.1-5.9 mg/L with a mean value of 3.61, indicating that the degree of contamination by organic matter is small. The mean DO of 3.6 mg/L is also enough to categorised the groundwater in the Tarkwa mining area as being of good quality. Since areas with less than 0.2 mg/L of dissolved oxygen indicates that the level of self-purification of the water is less (WHO, 2003). Again oxidisable minerals present in some

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The water types or the hydrological facies plotted on the Piper diagram were named per the abundance of the various constituents of the major cations and anions present in the water sample. Table 5.2 below gives the explanation to the various hydrological facies obtained from the diagram.

Table 5.2: Explanation to the various hydrological facies obtained from piper diagram.

Location	Water Type	Explanation
Tamso	Na+K, HCO ₃ , Cl	High Na+K andHCO ₃ , but also have a substantial quantity of the water mix (about 40%) emanating from intermediate chemical character.
Essaman Kakraba	Na+K, HCO ₃ +CO ₃	High Na+K and HCO ₃ +CO ₃ , but Carbonate content exceeds 50%. It may therefore be of temporary hardness since carbonate hardness exceeds 50%.
New Atuabo	Na+K, Ca, HCO ₃ , Cl	High Na+K and HCO ₃ , with about 20% of the water being the Ca and Cl type respectively. It is also of the non-carbonate hardness since HCO ₃ exceeds 50%.
Terberebe	Na+K, HCO ₃ ,Cl	High Na+K and HCO ₃ , but also have a substantial quantity of the water mix (about 30%) emanating from intermediate chemical character.

From the piper plot, most of the samples from New Atuabo and Essaman Kakraba communities had about 80% of Na + K of cations. The Tamso and Terberebe samples had about 70% and 60% of Na+K respectively. Again about 22.5% of the samples from the four communities were of no dominant type (that is water from an intermediate chemical character). Twenty percent of the water sampled from New Atuabo is also of the calcium type. Eighty two of the samples have CO₃ +HCO₃ as dominating anion whilst 17.5% is of Cl⁻ type with only about 0.5% of the total samples emanating from intermediate chemical character according to anion. A further study of the major ions for which recommended

permissible limits are available (sodium, sulphate and chloride) indicated that they were all within the WHO guidelines. When Na^+ exceeds the recommended limit of 200 mg/L, the water tastes salty. Similarly, maximum chloride concentration permissible in drinking water is 250 mg/L primarily because of taste. Likewise, sulphate concentration in drinking water must not exceed 250 mg/L otherwise the water will taste bitter. Higher SO_4^{2-} concentrations can even produce laxative effect. It is noticeable from (Table 4.1) that the major constituents Na^+ , Cl^- and SO_4^{2-} are generally low and well below the WHO recommended guideline maximum values for water potability. They, therefore, pose neither physiological nor aesthetic problem to groundwater usage for drinking or domestic purposes within the study area. Thus, with respect to major ions, the groundwater quality in Tarkwa is excellent.

Nitrate is the only ion that exceeds WHO's guideline. This even occurred at only one location in Tamso (Table 4.1). A further assessment of that location revealed an unprotected gutter which discharges foul water from various homes within the area. This gutter is sited about 45m away from the well. It is therefore believed that, the high nitrate content recorded by that particular well may originate from the nearby gutter.

5.3 HEAVY METAL CONCENTRATION

A total of 11 wells out of the 20 wells sampled across the four communities had at least one metal content higher than WHO's guidelines for drinking water. Lead, iron, manganese, nickel, and cadmium showed values exceeding WHO guideline values. Nickel exceeds the guideline at one location in Tamso 5. Manganese also exceeded the guideline at ten different locations in both toxic and alert levels, whilst lead exceeded in two locations at Tamso 1 & 3. Cadmium exceeded the guideline only at one location in Tamso

3. Essaman Kakraba 3, New Atuabo 1, Terberebe 5 and Tamso 3 also had iron content exceeding the WHO guideline. The mean values for the wells with elevated metal content are presented in Table 5.3

Table 5.3: Wells with elevated concentrations across the four communities.

PARAMETER	Fe	Pb	Mn	Ni	Cd
WHO GV	0.3 mg/l	0.01 mg/l	0.4mg/l	0.02 mg/l	0.003 mg/l
Location					
TAMSO 1		0.02	0.92		
TAMSO 2			0.48		
TAMSO 3	0.55	0.06			0.004
TAMSO 4			0.98		
TAMSO 5			1.22	0.02	
ESSAMAN KAK 1			0.26		
ESSAMAN KAK 3	0.53		0.32		
NEW ATUABO 1	0.30		0.27		
NEW ATUABO 5			0.44		
TERBEREBE 3			0.41		
TERBEREBE 5	0.31		0.26		

Locations marked bold indicate drilled wells

The principal contaminants across the communities are manganese and iron but lead, cadmium and nickel were also present in concentrations exceeding the WHO guideline values in some wells. The elevated concentrations of the manganese for instance, may be related to the presence of Mn-rich formations comprising manganiferous oxide minerals particularly in the Birimian rock terrains in the Nsuta area where manganese is mined. Manganese concentrations above 0.1 mg/l impart an undesirable taste to drinking water, however this same metal is believed to have a neurotoxin effect; a provisional health-based guideline value of 0.5 mg/l is proposed to protect public health (WHO, 1996). Out of the ten wells which recorded elevated concentrations of Mn, four of them were found at alert

levels of between 0.26-0.32; this would only have an undesirable taste on the wells when used as drinking water. The remaining six wells, also recorded Mn concentrations at toxic levels. Mn is indeed a problematic metal in the groundwater in the Tarkwa area.

The elevated levels of Fe on the other hand are also strongly believed to be influenced by the oxidation of pyrite and arsenopyrite in the rocks. This process may lead to the release of high concentrations of metals into groundwater (Smedley *et al.*, 1995). Fe, just like Mn also imparts metallic taste to water. The maximum permissible concentration of 0.3 mg/L (WHO, 1993) in drinking water is primarily for reasons of taste and avoidance of staining of sinks and clothes. The incidence of high iron concentration in some of the wells may result in complaints from people using the wells; this may ultimately lead to low patronage or total rejection of these wells.

Another reason for the elevated concentrations of the heavy metal loadings may result from the abandoned underground mining pits, (Figure 2.1). The outflow of water from such abandoned metal mines is normally associated with low pH down to about 3 (highly acidic) Kortatsi (2004). The acid nature of the underground mine decant can increase the capacity of the water to attack geological materials and leach toxic trace metals into the water making it potentially harmful for human consumption.

However, contrary to expectation from a town with a long history of gold and manganese mining, the heavy metal loadings particularly arsenic, copper, mercury, and zinc were low, with some occurring only at detection limits to values that are within the WHO drinking water guideline. The WHO (1993) permissible guideline limit for mercury (Hg) concentration in potable water is 0.001 mg/L. In the study area however, the concentration

of mercury in groundwater varies largely from detection limit to 0.002 ug/L. Mercury has not been detected in any of the rocks within the Tarkwa area (Kuma, 2004), however mercury is commonly used for small scale mining in the area and this may be the source of trace mercury found. Earlier studies have shown that the levels of Hg in the water resources fluctuated seasonally, low during dry seasons and high during rainy seasons (Kortatsi, 2004). Another reason for the low levels of some of the trace elements may be due to adsorption and absorption. Sorption processes are very important for attenuation of contaminants including heavy metal concentrations in soil. Sorption processes are probably very important for metal concentrations of the groundwater in the area. The transportation of metals with groundwater is normally affected by sorption to solid aquifer material (Appelo and Postma 1999). ~~Sorption can considerably lower the metal concentration in the groundwater.~~ The soil in the Tarkwa area also consists of clay, silts, sandy clays and clayey sands and is mostly the result of the weathering of both the Birimian and the Tarkwaian formations (Kuma and Younger, 2001). Heavy metals such as: Cu, Hg and Cd are therefore strongly bounded to these sites and this probably explains why many of the heavy metals displayed low values. The low heavy metal values displayed by some of the communities may also be associated with the minerals such Al/Fe oxides/hydroxides like goethite and montmorillonite associated with rocks in the area (Asklund and Eldvall, 2005).

5.3.1 Distribution of Heavy Metals across the Communities

High sulphate and low pH are known to contribute to the distribution of metals through the acid mine drainage phenomenon. From this study, AMD should be expected in the Tarkwa mining communities, since the pH levels of the groundwater were generally low. Notwithstanding this, a correlation matrix between pH, sulphate and the nine heavy metals

under investigation (Fe, Pb, Mn, Ni, As, Hg, Cu, Zn and Cd) revealed a trend which is not strong enough to draw a clear conclusion on the acid mine drainage phenomenon.

Table 5.4: Cross Correlation Matrix of Sulphate, pH and the Heavy metals.

Fe	Pb	Mn	Zn	Cu	Hg	As	Ni	Cd	pH	SO ₄	
1.0000	0.2669	-0.0024	0.2140	0.0135	0.3649	0.3589	0.1705	0.0606	0.0532	0.0158	Fe
	1.0000	0.1135	-0.0936	-0.1391	0.4931	-0.0980	0.2553	0.3510	0.0821	0.0972	Pb
		1.0000	-0.0125	-0.1807	0.2224	-0.0642	0.2477	0.1246	-0.1367	0.3081	Mn
			1.0000	0.0860	0.0410	-0.1077	-0.0642	-0.0712	-0.0242	-0.0938	Zn
				1.0000	-0.0802	-0.0430	-0.0358	-0.1099	-0.1410	-0.0630	Cu
					1.0000	-0.0629	0.2351	-0.0539	-0.0211	0.2063	Hg
						1.0000	-0.1132	-0.0252	0.3362	-0.1193	As
							1.0000	0.1256	-0.1959	0.2649	Ni
								1.0000	-0.0177	0.0472	Cd
									1.0000	0.2326	pH
										1.0000	SO₄

For the correlations in Table 5.4, Mn, Pb, Fe, Hg, Ni, and Cd showed a positive trend with sulphate, even though the trend is not very strong, it can still contribute to elevated concentration of metals originating from dissolution of minerals or from AMD, especially at reduced pH characteristic of the groundwater in the Tarkwa mining area. For certain areas particularly the Tamso community, the numerous abandoned mine pits in the area may collect and serve as underground point source for groundwater recharge, hence the elevated levels of some heavy metal loadings particularly in the Tamso area. Again, the correlation between Mn, Zn, Cu, Ni, and Cd revealed a negative trend with pH. This means that at a low pH, these metals increase in concentration, which also support acid

mine drainage. This observation was manifested in all four communities. The distribution of heavy metals across the Tarkwa mining communities may therefore be partly influenced by AMD.

5.3.2 Contaminant Loadings in the Deep and Shallow Wells

To be able to draw further conclusions on the groundwater chemistry and other dominating processes in the area the wells were classified into deep wells and shallow wells depending on whether they are drilled or hand dug. Within each community, at least two wells were identified as being deep. These groups have been investigated separately to come out with differences in parameters between deep and shallow wells using the piper diagram software.

From the piper plot in Figure 5.2, about 62% of the water emanating from the deep wells is of Na+K type, the shallow wells also had a similar water type but with a relatively higher percentage of Na+K (75%) according to cation. It was further observed from cations that about 37% of the water from the deep wells had no cation pair exceeding 50%. This is an indication of water from an intermediate chemical character. This observation also holds true for the shallow wells but had a smaller percentage (16.6% from intermediate chemical character). On the part of anions, both the deep and shallow wells had HCO_3 contents of 50% and 58% respectively, whilst that of Cl^- is 25% for the deep wells and 8.3% for shallow wells. Table 5.5 gives the water types for both the deep wells and shallow wells.

EXPLANATION

- Deep wells
- Shallow wells

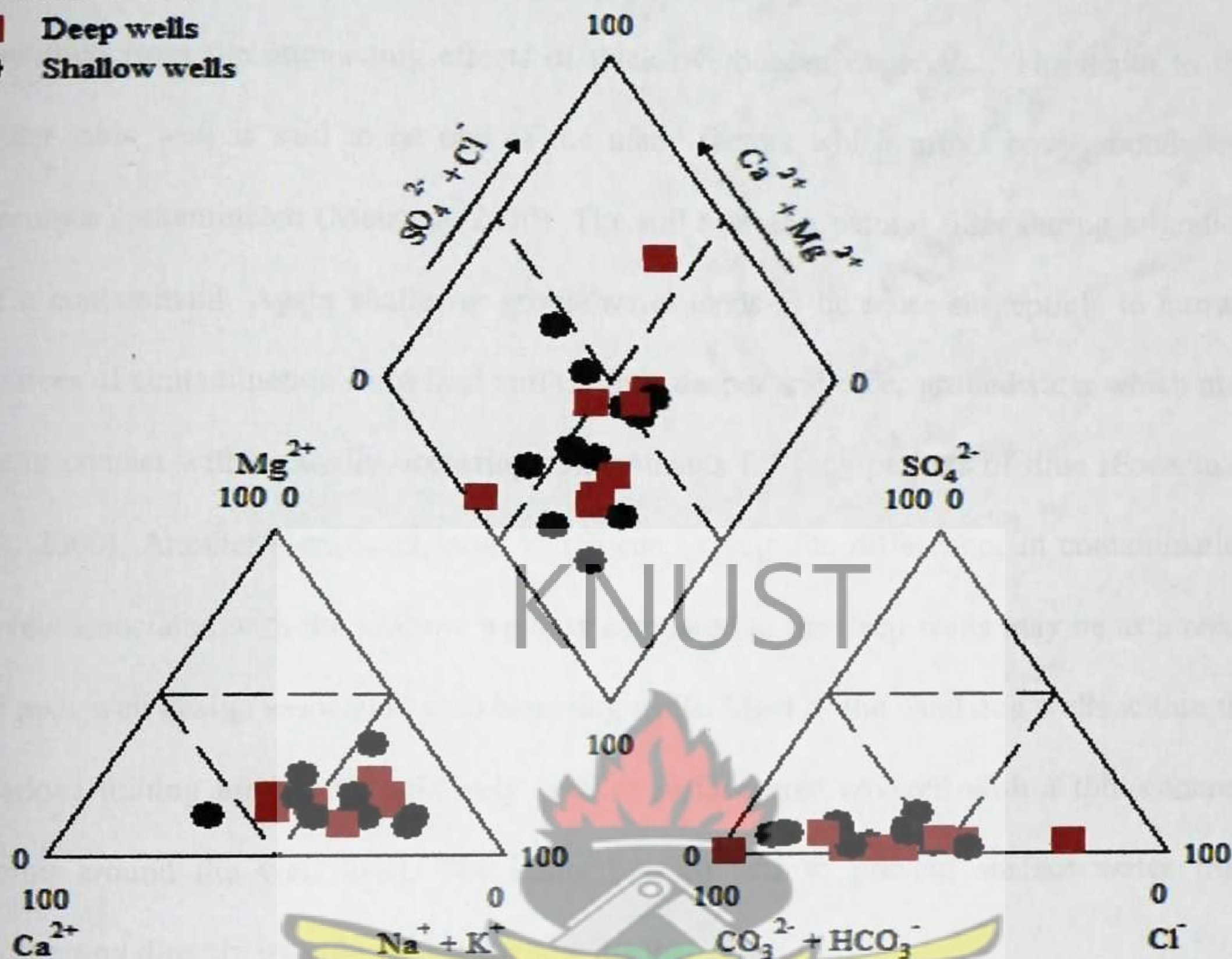


Figure: 5.2 Piper diagram showing the composition of deep and shallow wells

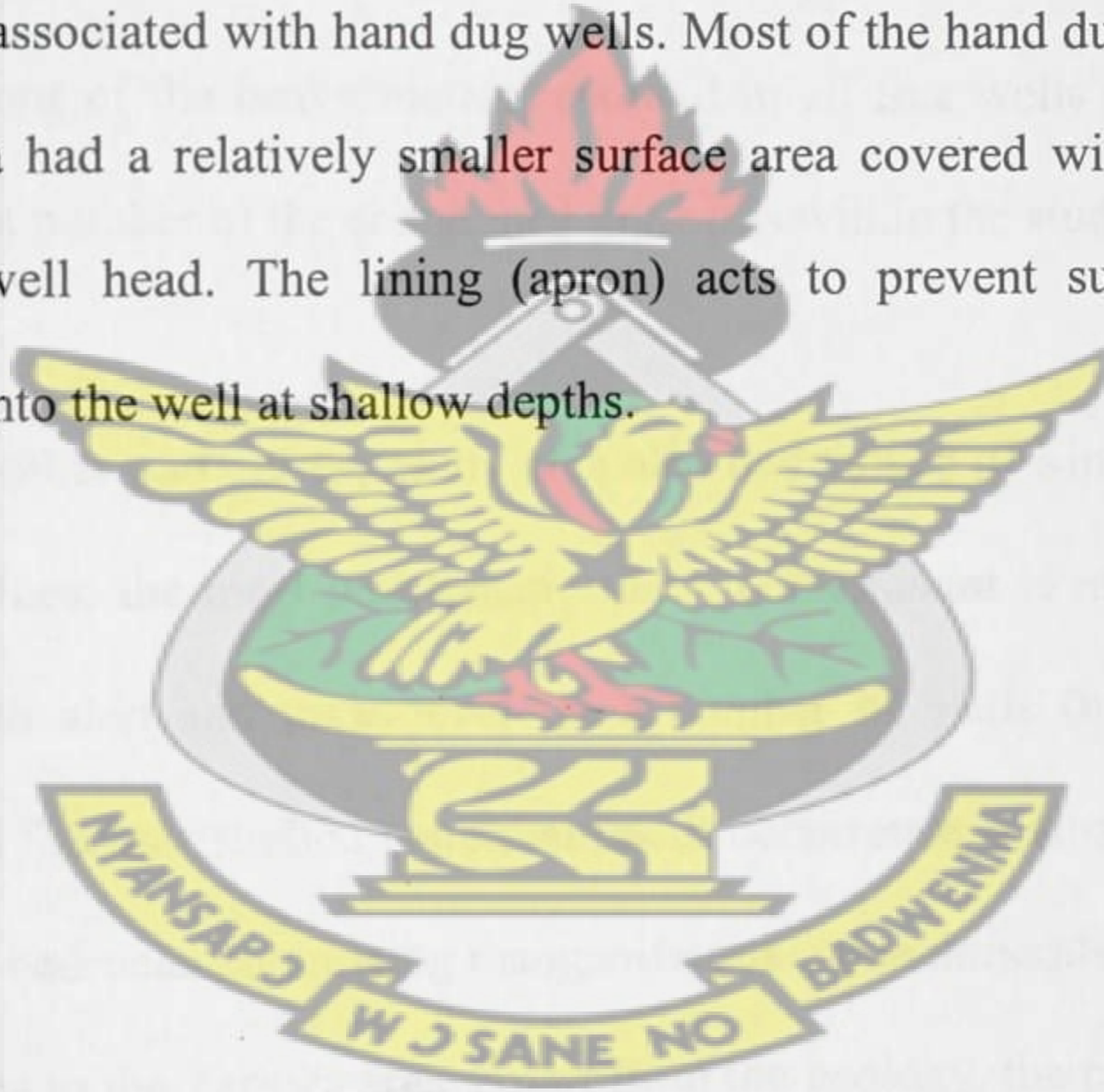
5.3.3 Heavy Metal Concentrations of Deep and Shallow Wells

From Table 5.3 only four drilled wells out of the eight categorised as deep wells had metal concentrations exceeding the WHO guideline values. Seven out of the 12 hand dug wells which were also categorised as shallow wells also had elevated concentrations of metals representing 58.3%. Indicating that the hand dug wells (shallow wells) are more prone to contamination in Tarkwa than the deep wells (boreholes or the drilled wells).

Table 5.5: The water types for both the deep wells and shallow wells

Well type	Water type
Deep wells	Na+K, HCO ₃ , Cl
Shallow wells	Na+K, Ca, HCO ₃ , Cl

This is expected since the hand-dug wells tap shallow groundwater, which may not have benefited from the attenuating effects of thick overburden materials. The depth to the water table well is said to be one of the many factors which affect how groundwater becomes contaminated (Metzege, 2010). The soil acts as a natural filter during migration of a contaminant. Again shallower groundwater tends to be more susceptible to current sources of contamination from land surface than deeper and older groundwater which may be in contact with naturally occurring contaminants for long periods of time (Focazio *et al.*, 2000). Another significant issue which can explain the differences in contamination levels associated with the shallow wells as compared to the deep wells may be as a result of poor well design associated with hand dug wells. Most of the hand dug wells within the Tarkwa mining area had a relatively smaller surface area covered with a thin concrete apron around the well head. The lining (apron) acts to prevent surface water from infiltrating directly into the well at shallow depths.



CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

Groundwater quality, especially in the Tamso mining area of the Tarkwa, is being threatened by heavy metal contaminants originating mainly from the abandoned underground mine pit in the area. An assessment of the hydrogeological environment of the study area revealed that the groundwater in the Tarkwa area is steadily being contaminated by the mine water decant from the abandoned underground mine pits which serve as an underground source for groundwater recharge. This is supported by the elevated concentrations of the heavy metals recorded in all five wells in the Tamso area which has the highest number of the abandoned mine pits within the study area.

The groundwater in other parts of the study area also had values of Mn and Fe exceeding WHO guidelines values; the most problematic metal contaminant is manganese, since it was recorded at both alert and toxic levels in a number of wells (both hand dug and boreholes) within all the four studied communities. Its occurrence is strongly related to the presence of Mn-rich bedrocks comprising manganiferous oxide minerals particularly in the Birimian rock terrains in the Tarkwa area. Apart from the geology, the processing methods used by the mining industries are also a contributing factor to the elevated concentrations displayed by some metal contaminant. For example, roasting of ore; can give rise to acidified rain. Indeed the current study produced pH values which were consistently acidic, the acid nature of the water will increase the capacity of the water to attack geological materials and leach toxic trace metals into the groundwater. The acid mine drainage phenomenon should therefore be expected, since manganese for instance showed

a positive correlation with sulphate which is a prerequisite for AMD especially at a reduced pH.

Despite the threat by the acid mine drainage phenomenon, parameters such as; Zn, As, Cu and Hg were generally low and did not exceed the guideline in any of the 20 sampling sites. Cd and Ni also exceeded the WHO guideline in Tamso 3 and Tamso 5 respectively. The concentrations of these metals cannot be described as one that can cause any eminent threat to groundwater usage within the Tarkwa mining communities, since their concentration in groundwater was general low except at Tamso which recorded elevated concentrations. It was observed further that only two wells (Tamso 1&3) exceeded the WHO guideline values for Pb. These findings were indeed contrary to expectations from a town with a long history of mining.

From the literature study, the possible reasons that can explain the relatively low levels of the metals, particularly Zn, As, Cu, Hg and even Cd in an intensive mining community may be due to sorption processes (adsorption and absorption), are very important for attenuation of contaminants including heavy metal concentrations in soil. Sorption can therefore lower the metal concentration in the groundwater. This is amply supported by the fact that, the soil in the study area is most likely to be of clayey soils which are derived mainly from both the Tarkwaian system and Birimian system. The soils therefore have a lot of adsorption and absorption sites due to their clay contents. Heavy metals such as: Cu, Hg and Cd are strongly bounded to these sites and this probably explains why many of the heavy metals displayed low values. For mercury the low levels may be attributed to the fact that, mercury has not been detected in any of the rocks within the Tarkwa area; the common use of mercury in gold recovery by the small scale mining activities may account

for the occurrence of mercury in the area. Even though the comparison between the shallow wells and the deep wells showed that more of the hand dug wells (shallow wells) are prone to contamination in Tarkwa than the deep wells (boreholes or the drilled wells), this should be interpreted with caution since the classification (of the wells) is not based on very detailed information.

The results of the physico-chemical parameters like: Ca^{2+} , K^{+} , Mg^{2+} , Na^{+} , Cl^{-} , SO_4^{2-} , HCO_3^{-} and NO_3^{-} in the groundwater in the study area are generally low and do not pose any quality problem for their use as drinking water. The dominating ions are sodium and bicarbonate. The result shows that the groundwater in the study area is generally within the pH range of 4.03 to 6.98 indicating that the water is mildly acidic. For the reason of taste, the WHO (1993) limits the pH range for water potability to 6.5–8.5. About 95% of the wells were outside this range suggesting that most of the wells have potential taste problem. The groundwater from the study area varies largely in total hardness from 18 mg/l to 210 mg/l. The waters were therefore categorized as being soft to moderately hard with only 15% of the boreholes having hard water. The average groundwater temperature was 24.6 °C ranging from 22.8–28.5 °C. The conductivity values are in the range 69.5–898 mS/cm with a mean 234.42 mS/cm suggesting that the groundwater is generally fresh. This shows that the physico-chemical qualities of the groundwater within the Tarkwa mining communities are generally acceptable.

6.2 RECOMMENDATIONS

Although the current study does not show a situation of gross contamination of the groundwater within the Tarkwa area, which has a long history of mining activities, further contamination is possible since mining in the area is still on going. In recent times, the

groundwater are even going to be more vulnerable to contamination since most of the abandoned mine pits are being reused mainly by *galamsey* operators who on daily basis pump out very huge (though unspecified) amount of the decant to surface waters.

- There is therefore a need for further in-depth investigations which would be geared towards estimating the exact quality and quantity of water in the old mines workings (abandoned mines) which serve as underground point source for groundwater contamination in the area. The investigation should include a cost benefit analysis approach which will help shed light on the viability or otherwise of collecting and containing of the mine water decant in holding (storage) facilities from where it would be pumped to a treatment facility for possible neutralization and iron removal.
- The Tamso community is indeed an interested location which requires a more comprehensive assessment of the groundwater. This is based on where this community is situated. It is located closer to both; Ghana Manganese Company (GMC) and AngloGold Ashanti Iduapriem Mine see geological map of Tarkwa (Figure 3.1). The findings/results of the current study also support this recommendation.
- Greater environmental compliance on part of the mining companies is also essential, if quality groundwater resources in the area are to be maintained. The processing methods of the mining companies, can contribute to reduced pH of groundwater.
- There is also the need to document enough data on the wells in the area, since it forms an integral part in groundwater quality assessment. Such data can give a better understanding of the processes governing the groundwater quality in the area. The current study did not make emphatic conclusions on the quality trend of

the shallow and deep wells in the area due to inadequate information on the depths of the wells in the area.

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REFERENCES

- Akabzaa, A. and Darimani, M. (2001), 'Impact of Mining Sector Investment in Ghana': A study of the Tarkwa Mining Region. A report prepared for SAPRI, January 2001.
- Anon, (2001), "Qualifying Report on the Bogoso-Prestea project, Ghana" Associated Mining Consultants Ltd. Report. 132pp.
- APHA: 1995, Standard methods for examination of water and waste water, 19th edn., American Public Health Association, Washington, D.C.
- Appelo, C.A.J. and Postma, D. (1999), 'Geochemistry, groundwater and pollution', A. A. Balkema, Rotterdam. McGraw-Hill Publishers, 247-281 pp.
- Armah, F. A., Obiri, S. Yawson, D. O., Pappoe, A. N. M., and Akoto, B. (2010), Mining and heavy metal pollution: Assessment of aquatic environments in Tarkwa (Ghana) using multivariate statistical analysis. Journal of Environmental Statistics, Volume 1, Issue 4. <http://www.jenvstat.org> (Accessed October 2010).
- Asklund, R. and Eldvall, B. (2005), 'Contamination of water resources in Tarkwa mining area of Ghana'. A Minor Field Study for Master of Science Thesis. Lund University.
- Brady, P.V., Brady, M.V., and Borns, D.J., (1997). 'Natural Attenuation': Cercla, RBCA's, and the Future of Environmental Remediation. Lewis Publishers, 147-171 pp.
- Chapman, D., (1996), "Water Quality Assessments". A guide to the use of biota, sediments and water in environmental monitoring. Second edition British Library Publication 620 pp.
- Charest, B (1998) Natural Attenuation: An Overview: <http://www.libraryindex.com>.
- Chilton, P.J., Lawrence, A.R. and Stuart, M.E. (1995). The impact of tropical agriculture on groundwater quality. In: H.Nash and G.J.H.McCall [Eds] Groundwater Quality, Chapman and Hall, London, 113-122.
- Columbia Water Center (2009) <http://water.columbia.edu>. "Learn More: Groundwater". Accessed 2009-09-15.
- Dawson, G. B., (2004), "Environmental Pollution". Chemistry: Foundation and Applications. The Gale Group Inc. Encyclopedia.com. <http://www.encyclopedia.com> (Accessed October 2009).
- Dickson, K. B. and Benneh, G. (1980), 'A New Geography of Ghana. Revised Edition.

- Dzigbodi-Adjimah, K. (1993), 'Geology and geochemical patterns of the Birimian gold deposits, Ghana, West Africa', *Journal of Geochemical Exploration*, vol. 47, Issue 1-3, pp. 305-320.
- Florida Department of Environment. (2008) Inorganic Contaminants. <http://www.dep.state.fl.us/water> (Accessed on November 2010).
- Focazio, M.J, Z. Szabo, T.F. Kraemer, A.H. Mullin, T.H. Barringer, and V.T. dePaul, (2000), 'Occurrence of selected radionuclides in ground water used for drinking water in the United States' A reconnaissance survey, U.S. Geological Survey Water-Resources Investigations Report 00-4273. 40 p.
- Freeze A. R. and Cherry J. A. (1979). *Groundwater*. Prentice-Hall Inc., Englewood Cliffs, New Jersey, 604pp.
- Freeze, R. A, Atwater, J. and Liebscher, H. (1985), 'Groundwater contamination': Occurrence, sources and transport of contaminants in groundwater. <http://www.wvlc.uwaterloo.ca/wat/gws>. Accessed November 2010.
- Fripp, J., Ziemkiewicz, P.F., and Charkavork, H. (2000). "Acid mine drainage treatment," EMRRP Technical Notes Collection (ERDC TN-EMRRPSR-14), U.S. Army Engineer Research and Development Center, Vicksburg, MS. www.wes.army.mil/el/emrrp Accessed August 2010.
- Hounslow A. W. (1995). *Water Quality Data Analysis and Interpretation*. Lewis Publishers, Boca Raton, New York, 109–111 pp.
- Jameel A. A and Sirajudeen J. (2006), 'Risk assessment of physico-chemical contaminants in groundwater of Pettavaithalai area, Tiruchirappalli, Tamilnadu' – *India Environmental Monitoring and Assessment* (2006) 123: 299–312 DOI: 10.1007/s10661-006-9198-5
- Karanth K. R. (1994). *Groundwater Assessment Development and Management*. Tata McGraw-Hill Publishing Company Limited, New Delhi, 122–128 pp.
- Kinniburgh, D.G. and Edmunds, W.M. (1986) *The Susceptibility of UK Groundwaters to Acid Deposition*. Hydrogeological Report 86/3, British Geological Survey, Wallingford, UK, 208pp
- Kortatsi, B.K. (2004), 'Hydrochemistry of groundwater in the mining area of Tarkwa-Prestea, Ghana', PhD thesis, University of Ghana, Legon-Accra, Ghana.
- Kuma, J. S. (2004), Is groundwater in the Tarkwa Gold Mining District of Ghana potable? *International journal of Geosciences- Environmental Geology*, 45pp 391-400.

- Kuma, J. S. (2007), 'Hydrological studies in the Tarkwa Gold Mining District, Ghana'. Bulletin of Engineering Geology and the Environment 66, pp. 89-99
- Kuma, J. S. and Ewusi, A. (2009), "Water Resources Issues in Tarkwa Municipality, Southwest Ghana", Ghana Mining Journal, Vol. 11, pp.37-46.
- Kuma, J. S. and Younger, P. L. (2001), 'Pedological Characteristics Related to Ground Water Occurrence in the Tarkwa Area, Ghana'. Journal of Africa Earth Sciences, 33, pp363-376.
- Langmuir D. (1997). Aqueous Environmental Geochemistry. Prentice Hall Upper Saddle River, New Jersey 07458. Longman, England, UK, 170 pp
- McCarty, P.L., 1996. "Biotic and Abiotic Transformations of Chlorinated solvents in Ground Water" in *Symposium on Natural Attenuation of Chlorinated Organics in Ground Water*, EPA/540/R-96/509.
- Metzege, M. R. (2010). 'Groundwater contamination, sources and prevention', <http://www.wapong.com> (Accessed November 2010).
- Naicker, K., Cukrowska, E., & McCarthy, T.S. (2003). 'Acid mine drainage from gold mining activities in Johannesburg', South Africa and environs. Environmental Pollution 122, 29-40.
- Obiri, S. (2007). 'Determination of heavy metals in boreholes in Dumasi in the Wassa West District of Western Region of the Republic of Ghana'. Environmental monitoring and assessment 130: 455-463
- Pradeep, J. K.: (1998), 'Hydrogeology and quality of ground water around Hirapur, District Sagar (M.P.)', Poll. Res. 17(1), 91-94.
- Safe Drinking Water Comm., (1980). Drinking water and health, Vol. 3. Nat. Acad. Press, Washington. 415 pp.
- Singh, T. B., Indu Bala and Devendra Singh: (1999), 'Assessment of ground water quality of Paonta Sahib (H.P.)', Poll. Res. 18(1), 111-114.
- Smedley P. L., Edmunds 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.
- Smedley, P.L. and Kinniburgh, D.G. 2001, 'A review of the source, behaviour and distribution of arsenic in natural waters', Applied Geochemistry, vol. 17, pp. 517-568.

TNMA, (2010). Municipal Profile, Ghana Districts, <http://www.ghanadistricts.com>
(Accessed October, 2010).

Todd, D.K. (1980), 'Groundwater Hydrology', 2nd edition, John Wiley, New York,
535 pp.

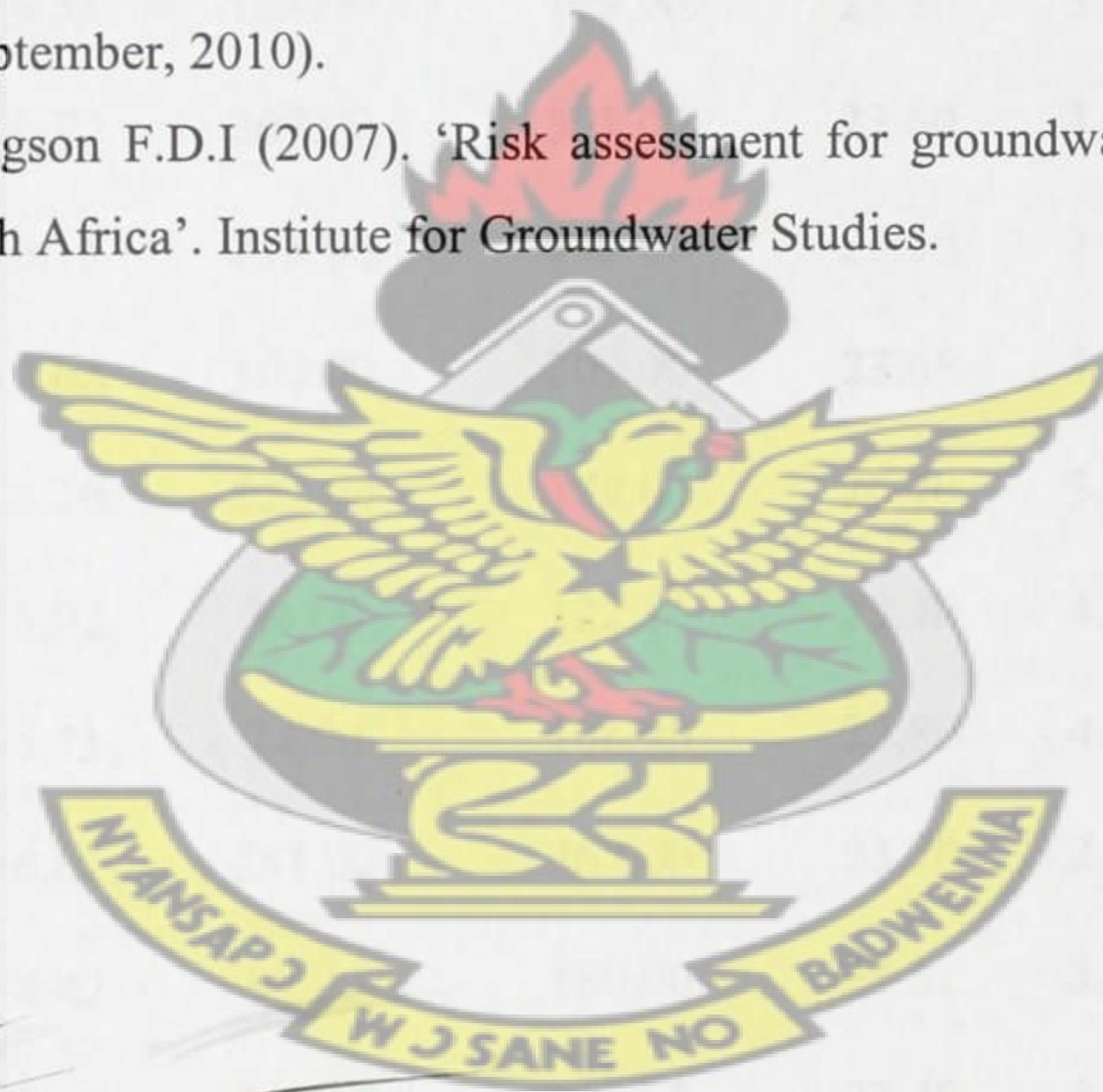
USGS (2008), Circular 1224 Assessing ground-water vulnerability to contamination:
<http://ga.water.usgs.gov/edu/watercyclegwstorage>. Accessed November 2010.

WHO, (1996). 'Guidelines for drinking-water quality', 2nd edition, vol 2, Health criteria
and other supporting information and addendum. World Health Organisation.
Geneva.

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

Xu, Y and Usher B.C. (2006). 'Groundwater Pollution in Africa'. <http://www.crcpress.com>
(Accessed September, 2010).

Zeelie, S. and Hodgson F.D.I (2007). 'Risk assessment for groundwater pollution from
mines in South Africa'. Institute for Groundwater Studies.



Appendix 1: Field measured parameters (January Sampling)

Sample ID	pH	TDS (mg/L)	EC (μS/cm)	Temp °C	DO	TH
Tamso - 01	4.14	248.00	360.00	28.28	3.90	45.67
Tamso - 02	4.23	126.00	182.50	27.75	3.40	33
Tamso - 03	5.84	62.00	90.40	28.18	4.10	37.33
Tamso - 04	6.40	201.00	401.90	27.29	3.70	207.7
Tamso - 05	5.61	305.00	209.00	23.68	3.80	100.7
Essaman K - 01	4.32	119.00	174.30	23.60	2.50	20.33
Essaman K - 02	6.31	103.00	149.90	23.50	3.20	55.67
Essaman K - 03	6.73	207.00	301.00	23.60	3.20	140.7
Essaman K - 04	6.15	215.00	312.00	23.50	2.50	136.7
Essaman K - 05	5.63	105.00	209.00	23.68	3.30	107.3
New Atuabo - 01	5.16	122.00	178.00	26.70	3.80	34.33
New Atuabo - 02	5.92	84.00	122.10	23.70	4.80	30.67
New Ataubo - 03	5.71	74.00	106.90	23.80	4.70	50.67
New Atuabo - 04	6.62	251.00	367.00	23.70	2.80	63.33
New Atuabo - 05	4.42	99.00	180.00	28.51	3.90	83.67
Teberebie - 01	5.58	260.00	379.00	27.40	3.90	49.67
Teberebie - 02	5.59	148.00	215.00	26.30	3.30	41.33
Teberebie - 03	5.89	119.00	172.70	23.30	3.20	76.67
Teberebie - 04	5.58	59.00	85.60	23.40	3.30	63.33
Teberebie - 05	5.32	150.00	233.00	26.40	3.70	77.67

Appendix 1: Continued (March Sampling)

Sample ID	pH	TDS (mg/L)	EC (μ S/cm)	Temp °C	DO	TH
Tamso - 01	4.18	219.00	347.00	23.40	3.30	41.33
Tamso - 02	4.37	101.00	158.70	23.80	3.70	69.4
Tamso - 03	5.51	50.00	77.90	24.10	3.80	57.33
Tamso - 04	6.21	391.00	612.00	22.80	3.60	218.3
Tamso - 05	5.22	431.00	490.00	23.40	3.50	90.54
Essaman K - 01	4.36	100.00	159.50	22.90	2.90	20.33
Essaman K - 02	5.84	44.00	69.40	24.50	3.10	46.67
Essaman K - 03	6.64	216.00	339.00	23.20	3.30	110.7
Essaman K - 04	6.21	110.00	172.60	23.50	2.70	144.7
Essaman K - 05	4.98	177.00	360.00	24.10	2.90	122.3
New Atuabo - 01	5.11	109.00	170.70	23.80	4.50	42.12
New Atuabo - 02	5.50	76.00	119.10	24.80	4.70	48.7
New Ataubo - 03	6.03	51.00	81.10	23.80	4.10	57.11
New Atuabo - 04	6.11	129.00	201.00	24.80	2.10	71.15
New Atuabo - 05	4.90	99.60	220.00	23.90	3.30	88.67
Teberebie - 01	5.70	129.00	204.00	24.20	3.30	59.56
Teberebie - 02	5.86	97.00	153.00	24.20	3.00	55.13
Teberebie - 03	5.93	68.00	107.50	24.10	3.60	76.79
Teberebie - 04	5.68	59.00	92.90	23.30	3.40	65.13
Teberebie - 05	5.11	127.00	211.00	24.40	3.10	82.44

Appendix 1: Continued (May Sampling)

Sample ID	pH	TDS (mg/L)	EC (μ S/cm)	Temp °C	DO	TH
Tamso - 01	4.31	211.00	346.00	24.70	3.90	55.78
Tamso - 02	4.17	105.00	171.40	24.60	3.70	59.77
Tamso - 03	5.34	53.00	83.50	24.70	3.90	67.33
Tamso - 04	5.84	551.00	898.00	25.70	3.80	247.7
Tamso - 05	5.11	563.00	721.00	25.40	3.90	110.83
Essaman K - 01	4.03	103.00	166.60	23.30	5.20	20.33
Essaman K - 02	5.72	118.00	188.60	23.30	3.40	62.67
Essaman K - 03	6.98	178.00	286.00	23.30	3.60	130.7
Essaman K - 04	6.22	260.00	419.00	23.80	3.40	146
Essaman K - 05	4.70	223.00	421.00	24.60	3.30	137.66
New Atuabo - 01	5.94	118.00	191.30	24.30	5.90	48.9
New Atuabo - 02	5.80	78.00	125.60	24.10	4.00	50.7
New Ataubo - 03	5.68	101.00	163.70	24.30	4.20	59.03
New Atuabo - 04	5.81	133.00	212.00	25.40	3.40	76.78
New Atuabo - 05	5.11	103.00	263.00	24.20	3.90	96.55
Teberebie - 01	5.84	157.00	254.00	26.60	4.10	63.33
Teberebie - 02	5.99	87.00	141.80	26.60	3.20	581.38
Teberebie - 03	5.81	148.00	241.00	24.80	3.50	79.23
Teberebie - 04	5.86	49.00	77.20	25.20	3.70	69.68
Teberebie - 05	4.82	109.00	219.00	25.50	3.70	87.53

Appendix 2: Physico-chemical Parameters (January Sampling)

Sample ID	Ca (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	Cl- (mg/l)	SO42- (mg/l)	NO ₃ ⁻ (mg/l)
Tamso - 01	7.631	0.384	0.997	6.701	61.4	4	101.3
Tamso - 02	13.778	1.076	2.843	18.633	13.1	<1	41
Tamso - 03	8.588	10.735	5.046	47.846	3.2	5	14.3
Tamso - 04	7.101	2.637	4.989	38.941	20.7	58	33.3
Tamso - 05	9.552	7.567	3.918	19.604	16	<1	27.2
Essaman K - 01	3.697	2.665	1.71	19.622	16	<1	53.9
Essaman K - 02	11.068	13.202	3.707	19.811	5.4	1	6.3
Essaman K - 03	16.556	1.594	4.117	17.014	2.5	1	16.3
Essaman K - 04	16.148	1.17	5.041	17.895	19	9	11.4
Essaman K - 05	7.779	3.921	14.66	41.161	37	11	37
New Atuabo - 01	13.466	4.165	16.478	82.966	19	3	33.1
New Atuabo - 02	13.158	1.882	7.676	56.345	13.5	<1	11.8
New Ataubo - 03	5.051	0.43	1.377	11.726	13	<1	19.4
New Atuabo - 04	7.494	3.776	2.478	32.253	24.8	16	13.2
New Atuabo - 05	22.169	2.34	1.771	5.109	33	7	20.4
Teberebie - 01	9.932	5.385	3.077	24.594	47.5	1	39.7
Teberebie - 02	2.571	0.413	1.222	7.816	28.1	<1	31.1
Teberebie - 03	2.029	0.471	0.788	7.185	16.6	7	13.3
Teberebie - 04	3.511	5.361	0.954	8.041	5.5	<1	25.2
Teberebie - 05	4.172	0.684	1.709	6.436	31.8	4	32.7

Appendix 2: Continue (March Sampling)

Sample ID	Ca (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	Cl- (mg/l)	SO ₄ ²⁻ (mg/l)	NO ₃ ⁻ (mg/l)
Tamso - 01	1.84	0.61	1.11	5.8	113	5	56.5
Tamso - 02	16.93	5.72	6.94	32.44	29.2	<1	39.4
Tamso - 03	2.85	2.6	0.72	9.88	13.5	5	8
Tamso - 04	17.54	29.81	6.71	20.92	193	30	41.2
Tamso - 05	2.37	2.05	1.43	13.35	22	1	65.8
Essaman K - 01	3.78	0.23	1.95	2.48	33.2	<1	38.8
Essaman K - 02	3.71	3.3	1.22	11.6	11.3	1	9.9
Essaman K - 03	2.52	0.4	1.2	2.95	9.2	3	3.2
Essaman K - 04	6.25	3.36	0.89	14.97	22.8	<1	1.3
Essaman K - 05	2.77	0.36	2.28	6.43	39	5	42.3
New Atuabo - 01	13.52	1.55	2.7	5.58	66.6	3	14.6
New Atuabo - 02	2.97	1.58	0.69	19.04	24.6	<1	11.4
New Atuabo - 03	9.75	1.61	1.3	7.66	16.6	<1	17.2
New Atuabo - 04	1.42	0.45	0.42	17.03	18.2	10	6.8
New Atuabo - 05	7.291	1.95	2.31	15.08	26.9	6	22.3
Teberebie - 01	10.33	9.18	1.92	23.89	47.6	<1	38.5
Teberebie - 02	3.623	0.197	1.395	6.367	45	3	17.3
Teberebie - 03	2.928	3.344	2.767	14.138	23	1	17.6
Teberebie - 04	9.835	6.211	1.121	11.347	21.4	1	28.4
Teberebie - 05	5.234	1.335	3.201	7.787	39.2	10	29.6

Appendix 2: Continue (May Sampling)

Sample ID	Ca (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	Cl- (mg/l)	SO42- (mg/l)	NO ₃ ⁻ (mg/l)
Tamso - 01	8.209	0.781	1.333	6.111	43.6	4	97.3
Tamso - 02	14.108	1.854	2.99	17.909	15	<1	38.9
Tamso - 03	9.103	12.011	4.107	48.132	3.6	4	16.5
Tamso - 04	7.709	2.334	5.117	39.101	106	54	34.3
Tamso - 05	10.201	7.898	4.013	19.301	57	8	26.5
Essaman K - 01	3.509	2.209	1.901	20.121	14	<1	54.4
Essaman K - 02	10.918	13.907	3.022	19.101	7.6	18	5.5
Essaman K - 03	16.958	2.223	4.222	17.414	3.7	2	18.7
Essaman K - 04	15.102	1.559	5.048	16.965	24.4	28	2.1
Essaman K - 05	8.101	4.101	14.221	41.764	26	16	34
New Atuabo - 01	13.921	4.233	17.178	83.261	30.2	4	23.6
New Atuabo - 02	13.903	1.309	8.171	51.125	13.8	<1	18.7
New Ataubo - 03	5.555	1.204	1.163	12.606	24.2	3	17.6
New Atuabo - 04	7.877	3.991	2.678	32.844	18.2	7	10.6
New Atuabo - 05	21.866	2.877	2.431	5.352	29.6	9.6	19.3
Teberebie - 01	9.311	5.575	3.231	24.699	40.2	2	40.5
Teberebie - 02	2.231	0.916	1.306	8.211	24	3	29.9
Teberebie - 03	1.902	1.211	1.104	7.886	20.6	17	12.9
Teberebie - 04	3.531	5.161	1.121	8.556	29.4	5	25.3
Teberebie - 05	4.928	0.984	1.877	6.755	33.6	8	32

Appendix 3: Heavy metal parameters (January Sampling)

Sample ID	Fe mg/L	Pb mg/L	Mn mg/L	Zn mg/L	Cu mg/L	Hg ug/L	As ug/L	Ni mg/L	Cd mg/L
Tamso - 01	0.18	0.00	0.88	0.08	0.01	<0.002	1.0	0.01	0.001
Tamso - 02	0.16	0.01	0.74	0.07	<0.01	0.002	1.0	0.01	0.001
Tamso - 03	0.44	0.00	0.14	0.04	<0.01	<0.002	<1.0	0.01	0.001
Tamso - 04	0.02	0.00	1.26	0.07	<0.01	<0.002	<1.0	0.03	0.001
Tamso - 05	0.04	0.01	0.81	0.07	0.04	0.002	1.0	0.01	0.002
Essaman K - 01	0.19	0.01	0.28	0.04	0.13	<0.002	<1.0	0.02	0.001
Essaman K - 02	0.21	0.00	0.07	0.04	0.14	<0.002	<1.0	0.01	0.001
Essaman K - 03	0.56	0.00	0.32	0.04	<0.01	<0.002	2.0	0.01	0.002
Essaman K - 04	0.16	0.00	0.05	0.04	0.01	0.002	<1.0	0.01	0.001
Essaman K - 05	0.15	0.00	0.08	0.07	0.06	<0.002	2.0	0.02	0.001
New Atuabo - 01	0.18	0.01	0.15	0.29	0.12	<0.002	<1.0	0.01	0.001
New Atuabo - 02	0.13	0.00	0.08	0.2	<0.01	<0.002	<1.0	0.01	0.002
New Ataubo - 03	0.25	0.00	0.01	0.06	0.04	<0.002	<1.0	0.01	0.001
New Atuabo - 04	0.11	0.00	<0.01	0.05	<0.01	<0.002	<1.0	0.02	0.001
New Atuabo - 05	0.28	0.00	0.04	0.11	0.19	0.002	<1.0	0.02	0.001
Teberebie - 01	0.15	0.00	0.01	0.09	<0.01	<0.002	<1.0	0.02	0.001
Teberebie - 02	0.05	0.00	0.1	0.08	0.01	<0.002	<1.0	0.02	0.001
Teberebie - 03	0.01	0.00	0.25	0.07	<0.01	<0.002	<1.0	0.01	0.001
Teberebie - 04	0.06	0.00	0.26	0.07	<0.01	<0.002	<1.0	0.03	0.001
Teberebie - 05	0.09	0.01	0.2	0.09	<0.01	0.002	1.0	0.03	0.001

Appendix 3: Continue (March Sampling)

Sample ID	Fe mg/L	Pb mg/L	Mn mg/L	Zn mg/L	Cu mg/L	Hg ug/L	As ug/L	Ni mg/L	Cd mg/L
Tamso 1	0.23	0.02	0.68	0.05	0.03	<0.002	<1.0	0.03	0.001
Tamso 2	0.25	0.01	0.46	0.04	0.01	0.002	1.0	0.03	0.001
Tamso 3	0.52	0.09	0.16	0.01	<0.01	<0.002	<1.0	0.02	0.01
Tamso 4	0.09	0.00	1.31	0.06	<0.01	0.002	<1.0	0.03	0.001
Tamso 5	0.05	0.00	1.23	0.06	0.03	0.002	<1.0	0.03	0.002
Essaman K 1	0.23	0.00	0.20	0.02	<0.01	<0.002	<1.0	0.02	0.001
Essaman K 2	0.29	0.01	0.05	0.01	<0.01	<0.002	<1.0	0.02	<0.001
Essaman K 3	0.51	0.00	0.30	0.03	<0.01	<0.002	2.1	0.01	0.001
Essaman K4	0.14	0.00	0.22	0.02	0.09	0.002	<1.0	0.01	0.001
Essaman K 5	0.17	0.01	0.32	0.02	0.01	<0.002	1.0	0.04	0.001
New Atuabo 1	0.12	0.00	0.12	0.23	0.03	<0.002	<1.0	0.01	0.001
New Atuabo 2	0.02	0.00	0.07	0.07	0.03	<0.002	<1.0	0.01	0.001
New Ataubo 3	0.23	0.00	0.01	0.02	0.01	<0.002	<1.0	0.02	0.001
New Atuabo 4	0.17	0.00	0.42	0.01	<0.01	<0.002	<1.0	0.01	0.001
New Atuabo 5	0.21	0.00	0.33	0.22	0.02	<0.002	<1.0	0.01	0.001
Teberebie 1	0.05	0.01	0.15	0.03	<0.01	<0.002	<1.0	0.01	0.001
Teberebie 2	0.07	0.00	0.07	0.02	<0.01	<0.002	<1.0	0.02	0.001
Teberebie 3	0.06	0.00	0.43	0.03	<0.01	<0.002	<1.0	0.01	0.001
Teberebie 4	0.08	0.00	0.02	0.06	0.01	<0.002	1.0	0.01	0.001
Teberebie 5	0.07	0.03	0.25	0.08	0.01	<0.002	<1.0	0.02	0.002

Appendix 3: Continue (May Sampling)

Sample ID	Fe mg/L	Pb mg/L	Mn mg/L	Zn mg/L	Cu mg/L	Hg ug/L	As ug/L	Ni mg/L	Cd mg/L
Tamso 1	0.31	0.03	1.19	0.09	<0.01	0.004	<1.0	0.04	0.001
Tamso 2	0.29	0.01	0.23	0.23	0.03	0.005	1.0	0.02	0.001
Tamso 3	0.69	0.06	0.91	0.04	0.01	0.009	<1.0	0.01	0.001
Tamso 4	0.19	0.00	0.29	0.10	<0.01	0.004	<1.0	0.02	0.001
Tamso 5	0.14	0.00	1.62	0.03	<0.01	0.002	1.0	0.02	0.01
Essaman K 1	0.12	0.00	0.11	0.08	0.04	<0.002	<1.0	0.02	0.001
Essaman K 2	0.31	0.00	0.13	0.13	0.07	<0.002	<1.0	0.02	0.001
Essaman K 3	0.51	0.00	0.35	0.06	<0.01	<0.002	2.0	0.01	0.001
Essaman K4	0.27	0.00	0.22	0.03	0.08	<0.002	<1.0	0.02	0.001
Essaman K 5	0.18	0.00	0.33	0.04	0.07	<0.002	1.1	0.03	0.001
New Atuabo 1	0.61	0.00	0.56	0.56	0.02	<0.002	<1.0	0.02	0.001
New Atuabo 2	0.01	0.00	0.12	0.07	0.02	<0.002	<1.0	0.01	0.001
New Ataubo 3	0.65	0.00	0.32	0.02	<0.01	<0.002	<1.0	0.01	0.001
New Atuabo 4	0.03	0.00	0.13	0.06	0.01	<0.002	<1.0	0.02	0.001
New Atuabo 5	0.01	0.00	0.94	0.09	<0.01	<0.002	<1.0	0.03	<0.01
Teberebie 1	0.08	0.01	0.17	0.08	<0.01	<0.002	<1.0	0.01	0.001
Teberebie 2	0.02	0.10	0.481	0.09	<0.01	<0.002	<1.0	0.04	0.001
Teberebie 3	0.02	0.00	0.165	0.08	0.07	0.002	<1.0	0.03	0.001
Teberebie 4	0.08	0.00	0.02	0.15	0.01	<0.002	<1.0	0.01	0.001
Teberebie 5	0.76	0.01	0.322	0.19	0.03	<0.002	<1.0	0.02	0.001

Appendix 4: Rainfall data (monthly means)

Month / Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	52.3	3.5	29.6	36.9	162.6	0.9	60.9	2.3	21	5.4	69.9
Feb	63.9	45	16.6	42.3	92.5	49.5	61.8	21.1	107.2	99.8	116.5
Mar	17	167	86.7	185.3	110.7	109.1	101.5	192.7	289.8	65	173.6
April	133.9	168	125.1	172.5	154.1	221.4	222.5	196.1	242.2	74.4	249.9
May	303.3	131	93.5	216.5	272.4	183.9	298.7	187.2	374.4	259.1	179
June	445.5	233	311.2	234.3	190.7	279.2	282.1	237	220.3	394.8	145.7
July	72.8	118	327.3	11.8	235.1	28.3	186.3	257.9	310.7	249.9	65.6
Aug	87.2	43.2	57.9	40.9	78.4	21.2	15.3	101.5	86.5	35.4	211.1
Sep	135.5	82	68.7	125.8	411.7	53.5	174.1	324.9	105.8	43.5	334.4
Oct	164.1	240	186.6	325.8	222.8	400	179.2	389	169	42.3	187.3
Nov	134.8	123	123.8	97.6	165.3	264.4	79.3	153	142.7	196.4	213
Dec	65.9	54.7	130.9	36.2	34.2	58	95.1	73.6	63	76.3	81.4

Appendix 5: GPS data

Location	Longitude	Latitude	Location	Longitude	Latitude
Essaman Kakraba 1	1°58'46"	5°20'15.16"	Tamso 1	2°00'05.8"	5°16'51.7"
Essaman Kakraba 2	1°58'49.3"	5°20'31.4"	Tamso 2	2°00'06.5"	5°16'43.6"
Essaman Kakraba 3	1°58'41"	5°20'11"	Tamso 3	2°00'08.3"	5°16'28.3"
Essaman Kakraba 4	1°58'34.5"	5°19'56.5"	Tamso 4	2°00'12.4"	5°15'36.4"
Essaman Kakraba 5	1°58'41.4"	5°19'56.1"	Tamso 5	2°00'08.6"	5°16'50.2"
New Atuabo 1	1°58'41"	5°19'26.5"	Terberebe 1	2°01'56.2"	5°16'10.5"
New Atuabo 2	1°58'35.3"	5°19'06.7"	Terberebe 2	2°01'57.2"	5°16'14.1"
New Atuabo 3	1°58'37.1"	5°18'57.8"	Terberebe 3	2°02'02.8"	5°16'16.5"
New Atuabo 4	1°58'40.9"	5°18'56.9"	Terberebe 4	2°01'51.6"	5°15'04.6"
New Atuabo 5	1°58'44.6"	5°18'58.2"	Terberebe 5	2°01'58"	5°16'08.0"