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DEPARTMENT OF THEORETICAL AND APPLIED BIOLOGY,

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EVALUATION OF ENVIRONMENTAL WATER MONITORING COMPLIANCE: A CASE
STUDY AT NEWMONT GHANA GOLD LIMITED (NGGL), AHAFO- KENYASI

BY

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DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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ABSTRACT

Surface and ground water monitoring data of the Newmont Ghana Gold Ahafo Mine Concession area were evaluated for the period 2007-2012. Data on some physico-chemical, nutrient and metal levels from 8 monitoring sites were studied. Results of the study revealed that many of the parameters studied were within the regulatory limits. However, turbidity and TSS recorded high values in some of the surface waters. pH of some of the sites were slightly acidic especially upstream groundwater number eight (GWC8S) but did not change significantly from the baseline data. Nutrients levels in some of the surface waters were naturally high. The research findings also made it abundantly clear that Arsenic and Iron were of concern in some of the surface and ground waters, but have not been affected significantly by the mine or deviated from the baseline and that the presence of these heavy metals could primarily be attributed to natural geological and climatological conditions but not from the mine. Mercury levels of all the water bodies under study were within the regulated limits (Ghana EPA and WHO guidelines) with the exception of few that were detected during the baseline and the operational period.

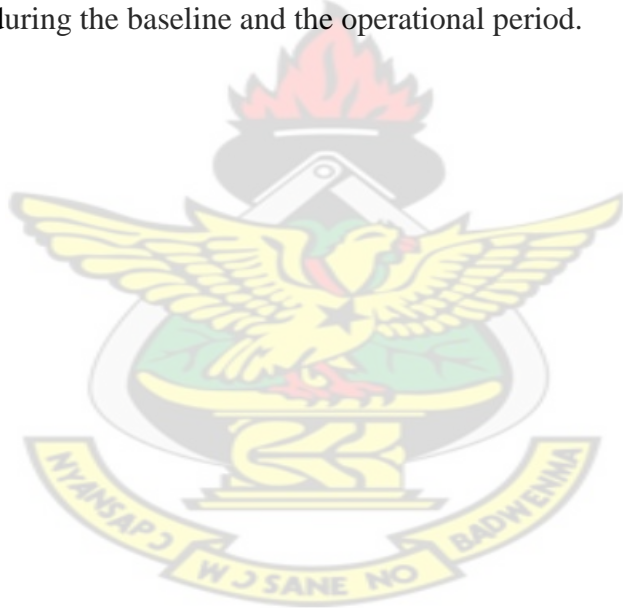


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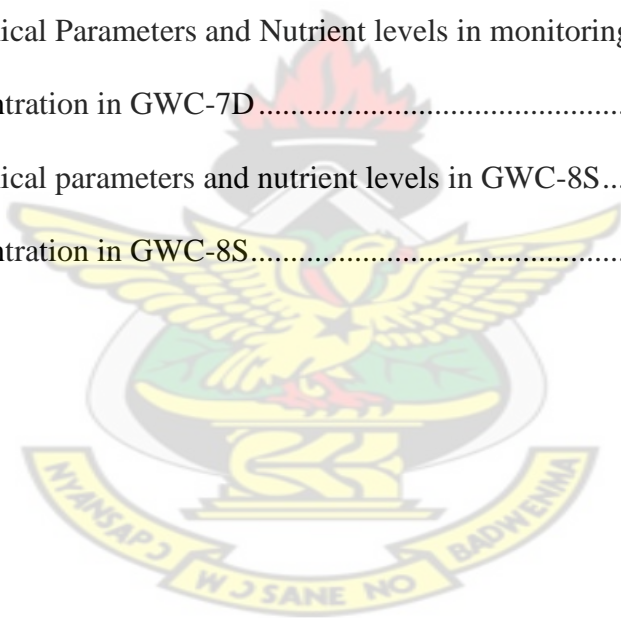
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CHAPTER ONE

1.1 INTRODUCTION

Surface and ground waters support a variety of human uses including drinking, irrigation of crops and landscape, industrial processes and recreation (Vickers, 1996). Water is an essential life-sustaining resource whose existence and availability for human use are often taken for granted. It is often utilized by people who are unaware of where the water originated and what happens to it after usage. Beyond meeting direct human use, water enables all living species to survive and flourish (USEPA, 2005).

The quality of freshwater bodies may be impacted negatively by a number of human activities. These include agriculture, mining and mineral processing, and many other industrial processes. Mining and mineral processing, for example, cause numerous environmental problems. During the course of mining and mineral processing, landscapes are altered and soils, rock and water are subjected to physical and chemical changes (UNESCO, 2006). Acid rock drainage may occur and heavy metals may be leached into the soil and water bodies. Mineral development also disturbs soil and rock in the course of construction and maintaining roads, open pits, and waste impoundments. In the absence of adequate prevention and control strategies, erosion of the exposed earth may carry substantial amounts of sediment into streams, rivers and lakes. Mining can even deplete surface and groundwater supplies (EMCBC, 2000). These changes associated with mining activities must be managed such that any resulting impacts are minimized. Failure to manage these impacts in an acceptable manner will result in the mining industry finding it increasingly difficult to obtain community and government support for existing and future projects (AMIC, 1997).

Water is integral to virtually all mining activities and typically the prime medium, besides air, that can carry pollutants into the wider environment. Hence, the impacts of mining on water bodies within the catchment of a mining activity cannot be completely avoided. Consequently, sound water management and practice are fundamental for most mining operations to achieve environmental best practice (Environment Australia, 2002).

Within the resources industry, the basic principles of water monitoring is to identify the receiving waters or natural resources which require protection from the existing or proposed mining and processing development. There is also the need to establish water quality objectives for these resources, collect and evaluate site specific data such as local climatic conditions, permeability of soil and underlying bedrock that has potential pathways for the migration of contaminants (Ahlers *et al.*, 1990). In water management, industries are required to prepare and implement a monitoring program for the region prior to the commencement of mining. This requirement includes the collection of rainfall data and background water quality data for all surface waters especially up and downstream of the operation. In the process of monitoring, emphasis should be placed on collecting representative samples of the medium being measured and an adequate number of duplicate and quality control samples (ARMCANZ, 2003). Mineral development disturbs soil and rock in the course of construction and maintaining roads, open pits, and waste impoundments. In the absence of adequate prevention and control strategies, erosion of the exposed earth may carry substantial amounts of sediment into streams, rivers and lakes. Mining can deplete surface and groundwater supplies.

Physical parameters such as temperature, turbidity, total suspended solids total dissolved solids, electrical conductivity, dissolved oxygen, alkalinity, etc. above or below certain limits in water is thought to have effect on humans, plants and aquatic organisms including fishes (Andrew *et al.*,

2005). Low dissolved oxygen, for example, has been attributed to the recent major fish kill in one of the mine water storage facilities at Newmont Ghana Gold Ltd at Ahafo-Kenyasi (NGGL, 2012).

1.2 STATEMENT OF THE PROBLEM

The Ahafo mine originally consisted of two projects: the Sefwi Gold Project and the Ntotroso Gold Project. These two projects were developed and permitted by Normandy Ghana Gold Limited in 1997. Newmont Ghana Gold Limited acquired the projects from Normandy in the year 2002. Prior to the development of the project into a mine, and in line with its objectives of protecting the immediate environment of its catchment area, Newmont Ghana Gold limited began a series of environmental baseline studies through field surveys and investigations. These were to serve as credits to support decisions regarding location and design of mine facilities, operational methods and closure or reclamation of disturbed areas associated with the proposed mine development. As part of these studies, the company began a comprehensive water quality studies in the year 2007 for both ground and surface waters in conjunction with Geomatrix Consultancy Service from the United States.

Since the beginning of its operations, there is the possibility of Newmont Ghana gold limited polluting the water bodies within the catchment area. This necessitates the monthly monitoring and compare with the baseline information (data) on water quality in order to assess its compliance with environmental standards.

1.3 OBJECTIVE OF THE STUDY

The main objective of the study was to evaluate the water quality monitoring data of the NGGL Ahafo Mine in order to assess its compliance with environmental standards.

The specific objectives were to:

1. Review some physico-chemical data (pH, turbidity, TSS, conductivity, TDS, nitrates and sulphates) at four surface water and groundwater monitoring sites at NGGL Ahafo-Kenyasi mine for both upstream and downstream sources for the period 2007 -2012.
2. Review the data on metal concentrations (mercury, iron & arsenic) at four surface water and groundwater monitoring sites at NGGL Ahafo-Kenyasi mine for both upstream and downstream sources for the period 2007 -2012.



CHAPTER TWO

LITERATURE REVIEW

2.1 WATER QUALITY AND FRESH WATER RESOURCES

Water is an essence of life on Earth that totally dominates the chemical composition of all organisms (Wetzel, 2001). Freshwater quality and availability is one of the most critical environmental and sustainability issues of the present century. Water quality is a generic term and is usually determined by the levels of various indicator substances. These indicators are generally selected on the basis of the type of water body in question. In an aquatic ecosystem, the density and diversity of organisms depend on availability and quality of water (USEPA, 1994).

Groundwater represents an important source of drinking water and its quality is currently threatened by a combination of over-abstraction and microbiological and chemical contamination (Aksu et al 2004). The presence of contaminants such as metals in groundwater can pose a significant threat to human health and ecological systems. Contamination of groundwater has severe implications for public health, particularly in small communities and developing countries where groundwater is often the preferred source of drinking water (Cynthia and David, 1997).

Because mines use large quantities of water, mostly in processing minerals and related activities, a mining company must demonstrate in its EIA that it has a comprehensive and accurate understanding of meteorological and hydrological conditions that determine the nature of water movement throughout the mine site (ELAW, 2010). The industry's role in water management is one of stewardship and not ownership. The operating philosophy should be based on the efficient use of water, implementation of the reduce, re-use and recycle concepts; avoidance or

minimization of contamination of clean streams and catchments; recognition and protection of downstream beneficial uses for both surface and ground waters and on relinquishment of title (Degens and Shand, 2009).

2.2 MINE WATER MANAGEMENT

Mine water management is a long-term process which may be simplified by: planning for the energy-efficient storage; transport and use of water; and modeling to quantify present and future water budgets. The thoroughness of the initial planning process determines the ease with, and the extent to which future changes to the water budget may be accommodated (USEPA, 1998). The planning process should consider the locations of potential sources and probable yields including surface water yields from rainfall and groundwater, identifying the locations of potential users of water and their likely demands (USEPA, 1998).

Impacts of mining on surface and groundwater water quality can occur during exploration, construction and operation of mines, as well as abandoned and rehabilitated mine sites. Uncontrolled drainage from mines can contribute potentially harmful materials to local waterways and may degrade water's suitability for domestic, agricultural or industrial uses, or be harmful to the ecology of the receiving environment (Bebbington, and Williams, 2008).

Comprehensive studies confirm that water quality can be adversely affected by pre-mining, mining and post mining activities associated with surface mining (NRC, 1981). During the pre-mining period exploration boreholes may intersect aquifers allowing communication of ground water which could result in deteriorating of deeper more pristine waters. Blasting activities during mining fragment rock materials thus expose fresh mineralized surfaces. In the post mining period, ground water recharge in the form of atmospheric precipitation, surface water and lateral

or vertical ground water flows may wet loosely consolidated overburden (Winter *et al.*, 1998). This process initiates chemical reactions with exposed minerals which could ultimately result in a serious deterioration of ground water quality. Contaminated aquifers that discharge to streams can result in long-term contamination of surface water; conversely, streams can be a major source of contamination to aquifers (Winter *et al.*, 1998).

Dissolved pollutants at a mine site are primarily metals but may include sulfates, nitrates, and radionuclides. These contaminants, once dissolved, can migrate from mining operations to local ground and surface waters (Wood C.R, 1996). Dissolved metals may include lead, copper, silver, manganese, cadmium, iron, arsenic, and zinc. Elevated concentrations of these metals in surface water and ground water may preclude their use as drinking water. Low pH levels and high metal concentrations can have acute and chronic effects on aquatic life/biota. While acid mine drainage (AMD/ARD) can enhance contaminant mobility by promoting leaching from exposed wastes and mine structures, releases can also occur under neutral pH conditions. Dissolution of metals due to low pH is a well-known characteristic of acid drainage. While low pH is not necessary for metals to be mobilized and to contaminate waters, there is increasing concern about neutral and high pH mobilization (Winter *et al.*, 1998).

Mining processes can result in the contamination of associated sediments in receiving streams when dissolved pollutants discharged to surface waters partition to sediments in the stream. In addition, fine grained waste materials eroded from mine sites can become sediments. Specifically, some toxic constituents like lead and mercury associated with discharges from mining operations may be found at elevated levels in sediments, while not being detected in the water column or being detected at much lower concentration (Lee and Risley, 2002). The sedimentation can also result in the filling of downstream reservoirs reducing the capacity for

both flood control and power generation. The sedimentation can also cause the channel to widen and become shallower, which may increase the frequency of overbank flow (Gerritsen and Burton, 2003).

2.3 WATER QUALITY MONITORING

2.3.1 Physico-chemical Parameters

The pH is a measure of the level of activity of hydrogen ions in a solution, resulting in its acidic or basic quality. Each stream organism is adapted to a specific pH range. The pH in most rivers that is unaffected by humans ranges from 6.5 to 8.0. The pH range of survivability of most freshwater organisms ranges from about 4.5 to 9.0. The pH of freshwater ecosystems can fluctuate considerably within daily and seasonal timeframes, and most freshwater animals have evolved to tolerate a relatively wide environmental pH range (Boyd and Tucker, 1998). Animals can, however, become stressed or die when exposed to pH extremes or when pH changes rapidly, even if the change occurs within a pH range that is normally tolerated. In addition to the direct effects of pH on aquatic animals, the hydrogen ion concentration affects aqueous equilibria involving ammonia, hydrogen sulfide, chlorine and dissolved metals (Ludwig *et al.*, 2007).

The interactions of pH with these variables are often more important than the direct effects of pH on aquatic organisms. Humans contribute to elevated pH primarily in the form of nutrient runoff; most commonly fertilizer, which leads to increased algae growth and higher pH. Low pH can be especially harmful to aquatic organisms (Mandal and Boyd 1980). Low pH affects physiological functions of aquatic life through the reduction of enzyme activity and effectiveness. Low pH can cause the release of toxic elements and compounds from sediments into the water where they may be taken up by aquatic animals or plants (Mischke and Wise, 2008).

Suspended solids are particles of sand, silt, clay, and organic material moving with the water or along the bed of the stream. Suspended solids usually are measured as a concentration in milligrams per liter (mg/l). High levels of suspended solids can cause problems for aquatic organisms both as the solids travel through the water and after they are deposited on the streambed. Suspended solids can reduce visibility, making it hard for fish to find prey. Solids also can clog the gills of fish and suffocate macro invertebrates such as insects (APHA, 1998).

Turbidity measures water clarity or the ability of light to pass through water. Turbidity is a measure of the amount of particulate matter and dissolved substances that are suspended in water. Water that has high turbidity appears cloudy or opaque. The composition and concentration of particulate matter in the aquatic environment is affected by the source and pathway of sediment input (Eisma, 1993; Webster *et al.*, 1990).

High turbidity can cause increased water temperatures because suspended particles absorb more heat and can also reduce the amount of light penetrating the water. High levels of turbidity make it difficult for fish to find prey and indicate high levels of suspended solids. Long-term changes in the composition and concentration of suspended solids can have potential cumulative effects on aquatic ecosystems in a multitude of ways (Newcombe and MacDonald, 1991). Stone and Droppo (1994) suggested that, suspended solids probably act as the primary transport mechanism for pollutants and nutrients in streams through flocculation, adsorption and colloidal action. Turbidity often is measured as a way to estimate amounts of suspended solids. Turbidity is an optical property and does not directly reflect the amount or types of solids; thus it must be used carefully. Turbidity is measured in Nephelometric Turbidity Units (NTU). Water color due to dissolved solids and temperature, as well as the shape, size and mineral composition of particles can significantly affect a turbidity reading (Packman *et. al*, 1999).

Total dissolved solids (TDS), measured in milligrams per liter (mg/l) is the amount of dissolved materials in the water. Ions such as potassium, sodium, chloride, carbonate, sulfate, calcium, and magnesium all contribute to the dissolved solids in the water. In many instances, resource agencies use the terms TDS and salinity interchangeably, since these ions are typically in the form of salts (Mahananda *et al.*, 2010). Measuring total dissolved solids is a way to estimate the suitability of water for irrigation and drinking. High TDS may result in a 'salty' taste in drinking water. Groundwater often has higher levels of dissolved solids than it is for surface water because of its contact with aquifer geologic material and more time to dissolve rock and mineral materials. Mine discharge waters often have elevated levels of TDS and aquatic biodiversity is often low in waters with elevated levels of TDS (Bauer and Burton, 1993).

Electrical conductivity is the ability of a substance to conduct an electrical current, and it is measured in micro Siemens per centimetre ($\mu\text{S}/\text{cm}$). Ions such as sodium, potassium, and chloride give water its ability to conduct electricity. Conductivity is an indicator of the amount of dissolved salts in water. The conductivity of water depends upon the concentration of ions and its nutrient status. Based on electrical conductivity values the water quality can be classified as poor, medium or good (Pandey and Tiwari, 2009). Conductivity often is used to estimate the amount of total dissolved solids (TDS) rather than measuring each dissolved constituent separately.

2.3.2 Chemical Parameters

Heavy metal pollution is caused when such metals as arsenic, cobalt, copper, cadmium, lead, silver and zinc contained in excavated rock or exposed in an underground mine come in contact with water. Metals are leached out and carried downstream as water washes over the rock surface. Where they occur, heavy metals are pollutants of considerable concern because they are not usually eliminated from aquatic ecosystems by natural processes. Instead, they are either accumulated in sediments or biota, or transported to other ecosystems (e.g., from the land to streams by storm water runoff). Thus, metals such as arsenic, cadmium, chromium, copper and mercury frequently accumulate in aquatic plants and in river and lake sediments and some of these elements can be remobilized and incorporated into food webs (Harding *et al.*, 2004).

Some metals such as mercury (Hg) can bioaccumulate within food webs (Goodyear and McNeill, 1999), and affect the physiology, growth and reproduction of organisms at multiple trophic levels (Kelly, 1988). In contrast, other metals such as aluminium (Al) and iron (Fe) do not seem to bioaccumulate up food chains, as found by Winter Bourn *et al.* (2000). In some instances, mercury (Hg) contamination of groundwater is more diffuse, perhaps coming from multiple point sources. Somasundaram *et al.* (1993) reported that mercury contamination of the surficial alluvial aquifer in urban Madras, India was suspected to have been introduced by industrial and wastewater discharges to groundwater aquifer. The report of mercury concentrations of 1.0 to 18 mg/l in water from wells near the Cooum River in the Madras urban area mainly exceeded the Indian drinking water standard of 1.0 mg/l. In some instances, Hg released from industrial operations results in contamination of soils at the site, but the soil characteristics are such that the Hg is sequestered or attenuated and does not leach to groundwater (Saether *et al.*, 1997). At a site in southern Germany where “cyanizing” (mercuric

chloride (HgCl_2) used to preserve wood from decay) was performed in groundwater in a 1.3km long plume was found to be contaminated with Hg at concentrations that reached 230 mg/l (Bollen *et al.*, 2008). The effects of metals in water range from beneficial through troublesome to dangerously toxic. Some metals are essential to plant and animal growth while others may adversely affect water consumers, wastewater treatment systems, and receiving waters. The benefits versus toxicity of some metals depend on their concentration. Lead, mercury and cadmium, and the metalloid arsenic have all caused major human health problems in various parts of the world (Waldron, 1973).

Extreme toxicity of some species of mercury and its ability to bioaccumulate in particular in fish meat, and the known cases of lethal poisoning by mercury have drawn particular attention to this element's presence in the natural environment (Stein *et al.*, 1996). Due to the relatively long time of its presence in the air, elemental mercury can be transported over large distances; hence the presence of mercury of anthropogenic origin is detected practically all over the world. Mercury has long been identified as an element that is injurious (or even lethal), to living organisms. Exposure to its inorganic form, mainly from elemental Hg vapor can cause damage to respiratory, neural, and renal systems (USEPA, 2012; WHO, 2012). The organic form, methylmercury (CH_3Hg^+ ; MeHg), is substantially more toxic than the inorganic form (Fitzgerald and Lamborg, 2007).

Arsenic is a common contaminant in the natural environment that can enter the water column through geologic weathering and volcanic action, or by various anthropogenic practices including smelting and use in gasoline (WHO, 1995). Contamination of water through anthropogenic practices is the primary cause of lead poisoning in fish (Sorensen, 1991). Although metals can become mobile in neutral pH conditions, leaching is particularly

accelerated in the low pH conditions such as that created by Acid Mine Drainage (APHA, 1992). Like many other substances, heavy metals can lead to serious impact when dispersing into environment and into human food sources, and consequently can endanger human health and hygiene (Shokrzadeh *et al.*, 2010).

Mining techniques such as hydraulic fracturing, mobilize arsenic in groundwater and aquifers due to enhanced methane transport and resulting changes in redox conditions (Brown *et al.*, 2010; Murcott, 2012). Arsenic contamination of ground water is found in many countries throughout the world, including the USA (Smedley, 2002). Smedley and Kinniburgh (2002) point out that whether released arsenic remains at problematic levels in groundwater depends not only on whether there are biogeochemical reactions that retard the transport of arsenic but also upon the hydrologic and hydrogeologic properties of the aquifer, such as flow velocity and dispersion.

If the kinetics of Arsenic release are slow, and groundwater residence time is short, then arsenic concentrations may not increase to the point where groundwater would be considered contaminated. Conversely, if reactions that mobilize arsenic are rapid and residence time is long, then arsenic can accumulate in groundwater such that concentrations become hazardous as seen in Bangladesh, for example. Consuming water contaminated by arsenic can cause skin and bladder cancer, as well as cardiovascular disease (Jaymie *e*, 2008). Most arsenic in drinking water comes from natural rock formations. Water that encounters rock formations can dissolve arsenic and carry it into underground aquifers, streams, and rivers that may be used as drinking water supplies. Arsenic deposited on the ground from industrial or agricultural uses tends to remain in the top few feet of soil for a long time and is not likely to have a significant impact on

most aquifers. When dissolved in water, arsenic has no smell, taste, or color, even at high concentrations (Twarakavi *et al.*, 2006).

Iron can also be a troublesome chemical in water supplies. Making up at least 5 percent of the Earth's crust, iron is one of the earth's most plentiful resources. Rainwater as it infiltrates the soil and underlying geologic formations dissolves iron, causing it to seep into aquifers that serve as sources of groundwater for wells. Although present in drinking water, iron is seldom found at concentrations greater than 10 mg/l. However, as little as 0.3 mg/l can cause water to turn a reddish brown color. Iron is mainly present in water in two forms: either the soluble ferrous iron or the insoluble ferric iron (Bradley, 2003).

In surface waters, such as rivers and lakes, dissolved iron is hardly ever found, because it reacts with oxygen, forms insoluble compounds and sinks out of the water. However, in ground water such as wells and springs, iron is the most common dissolved chemical. Although not considered to cause health problems in humans, its presence in potable water is rather unpleasant due to the bad odours it spreads, its rusty taste and colour, its feel on skin and hair, and its tendency to stain clothing (Ityel, 2011).

2.3.3 Nutrients

The term nutrient refers collectively to elements and compounds which are essential to sustaining adequate biological function. The most common nutrients which may affect the water management of a mining operation are nitrogen and phosphorus. There are various forms of nitrogen such as ammonia, nitrite, nitrate, and organic nitrogen. Phosphorus can be found in the form of orthophosphate, total phosphorus and organically bound phosphates. The form of the nutrient has an integral role in its function and fate in the aquatic environment. Biological

productivity may be limited by the availability of either nitrogen or phosphorus, which is often referred to as the growth limiting nutrients. Silica has also been identified as a limiting nutrient in some aquatic systems (USEPA, 1994).

Some nutrients form part of the water's TDS, whereas others, such as ammonia, are found dissolved completely into solution. At high levels, however, they are considered contaminants. High levels of nutrients can cause increased growth of algae beyond what is normal. Decaying algae mats can cause foul odors and tastes. When an algae produce energy or decay, they remove dissolved oxygen from the water. Both nitrogen and phosphorus are affected by chemical and biological processes that change their form and transfer them to or from water, soil, decaying organisms, and the atmosphere. In nature, both nitrogen and phosphorus come from the soil and decaying plants and animals (USEPA, 2005). However, if algae grow too wildly, oxygen levels will be reduced and fish will die. Nitrates can be reduced to toxic nitrites in the human intestine, and many babies have been seriously poisoned by well water containing high levels of nitrate-nitrogen. The U.S. Public Health Service has established 10 mg/l of nitrate-nitrogen as the maximum contamination level allowed in public drinking water (USEPA, 2005).

2.4 EVALUATION OF ENVIRONMENTAL MONITORING PLAN

Every promise in an EIA runs the risk of being an illusion unless the EIA sets out measures by which mining companies and responsible government officials will monitor performance of the mining project and its impact on the environment (Australia EPA, 1995).

Monitoring programme should be a part of a company's overall environmental management system, and should respond directly to the environmental issues identified in the EIA performed before operations began. The monitoring programme should be developed using a set of

objectives, the commitments of the company and existing conditions (USEPA, 1995). Monitoring programs begin with baseline sampling performed to characterize the pre-development environment. Environmental issues addressed in and managed by the plan generally relate to issues such as land-clearing and topsoil, water, waste rock, tailings, hazardous wastes, biological species, health risks, biodiversity, dust, noise and transportation (MINEO Consortium, 2000).

The Environmental Monitoring Plan (EMP) needs to provide more than details about where, when, what, and how often a mining company will monitor the quality of water, air, and soil in the vicinity of the mining project. The Environmental Monitoring Plan must also specify how information will be provided to government decision-makers and to the general public in a manner that enables decision-makers and the general public to ascertain if the mining company is complying with all of its promises and relevant environmental regulations and standards (USEPA, 1998). Therefore, it is important that the Environmental Monitoring Plan specifies that it will report all monitoring data promptly to the public in a user friendly format. It is also important to insure monitoring and the extent to which water quality is changing within a mine site for the protection of water quality. An adequate water quality monitoring programme can insure that a mining company is fulfilling promises in its Environmental Monitoring Plan and is responding to water quality problems before it is too late (USEPA, 1998).

Monitoring of mine site water quality is an essential part of the environmental management of a mining and mineral processing operation. It enables water quality and chemical containment performance to be assessed. Undesirable impacts can thus be detected at an early stage and remedied (Environment Australia, 2002).

Focus should be placed on toxic substances that are contaminants of concern (e.g., arsenic, lead, cadmium and mercury) but should include other substances that may have harmful effects, e.g. electrical conductivity, pH and total dissolved solids (USEPA, 1998).

If a mining project includes a proposal to divert surface water, then the Environmental Impact Assessment (EIA) should include a thorough assessment of the impacts. This includes how the proposed diversion would affect the quality and availability of other surface and groundwater resources (a diverted stream might be a source of groundwater replenishment) and the aquatic species that might rely on existing conditions in the stream proposed to be diverted (WHO, 2006).

Citizens from affected communities are part of any teams assembled to monitor a mining company's environmental performance. These monitoring teams might be compromised if they include only industry and or government agency representatives (Bebbington and Williams, 2008).

Bores are normally required upstream and downstream in the direction of groundwater flow to monitor changes in water level and quality across a site and to monitor the performance and stability of tailings facilities. In hard rock areas, bores must be located within geological features that are most likely to transmit groundwater (National Wildlife Federation, 2000).

CHAPTER THREE

METHODOLOGY

3.1 THE STUDY AREA

3.1.1 Location

The Ahafo Kenyase Gold Project which was developed by Newmont Ghana Gold Limited (NGGL) is located at Ahafo Kenyase in the Asutifi South District of the Brong Ahafo Region of Ghana (Figure 1).

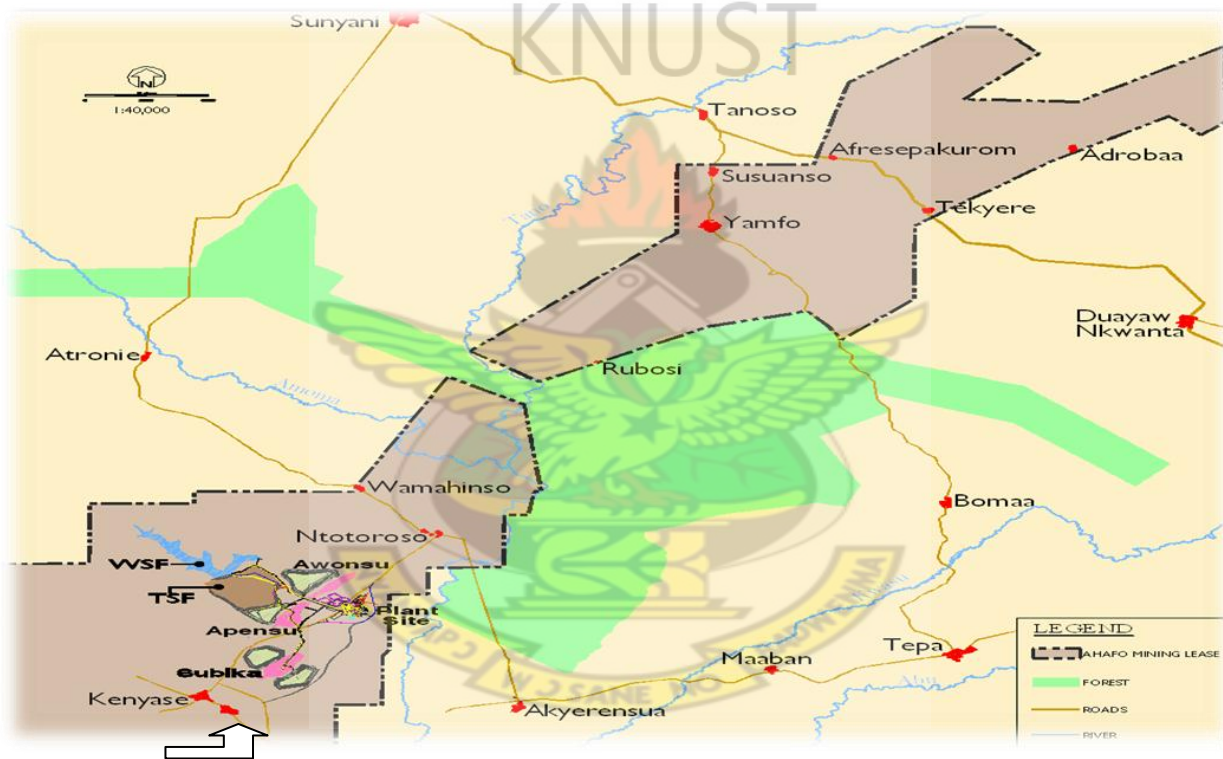


Figure 1 Map of Ghana showing location of the study area (NGGL)

3.1.2 Climate

The study area falls within the wet semi-equatorial climatic zone of Ghana. It is characterized by an annual double maxima rainfall pattern occurring in the months of May to July and from September to October. Mean monthly temperature within the area ranges between 23.9^o C and 28.4^o C. In general, March is the hottest month of the year while August is the coldest month (Walker, 1962).

3.1.3 Hydrogeology

The type of geological formation found in the study area is Metasediments and Granitoids. There is no primary porosity and ground water occurrence is linked only to fractured and weathered zones. The typical aquifer system is composed of low permeability weathered zones drained by the fractures underneath (NGGL, 2005).

The study area is drained by a number of seasonal streams and perennial rivers which feed into the upper basin of the Tano River. The seasonal streams and rivers divide the project area into a number of smaller sub-basins. Sub-basins within the project area include: the Awonsu, Subika, Ntotroso and Amoma (NGGL, 2005). The Tano River is a vital source of potable water for the Brong Ahafo Region and people from Sunyani and several small towns located within and around the study area. Water from the river is pumped and treated through small to medium size treatment plants operated by the Ghana Water Company Limited (GWCL). The various mining pits and proposed infrastructure are situated within different sub-basins of the study area. Two of the proposed pits namely, Subika pit and the Awonsu pit fall within the Subri Sub-basins and partly within the Awonsu Sub-basin (NGGL, 2005).

3.1.4 Floral Environment

The study area lies within the semi-deciduous agro-ecological zone of Ghana and belongs to the Celtis-Triplochiton Association. The forest Reserves of the study area contain remnants of the Eastern Guinean Forest that at one time covered extensive areas of central Ghana. Typically, the forest communities are characterized by a three-story canopy structure with emergent tall trees often exceeding 50m in height, with the uppermost canopy having a mixture of evergreen and deciduous species. Dominant species include *Nesogordonia papaverifera*, *Celtis mildbraedii*, *Argomuerella macrophylla*, *Sterculia rhinopetala*, *Aframomum stanfieldii*, *Ricinodendron heudelotii* and *Masonia altissima*. (NGGL, 2005).

3.1.5 Soil Environment

The soil associations identified within the study area are the Bekwai, Hwidiem, Kumasi and Birim-Kyekyewere associations. Human activities including farming within the study area have greatly influenced the nature of the soils resulting in nutrient depletion, soil erosion, pan formation and land degradation (NGGL, 2005).

3.1.6 Socio-economic Environment

Agricultural production is the main economic activity in the district and is practiced mainly on subsistence level with a few farmers engaged in plantation agriculture. Agriculture accounts for about 65% of the labour force. This reflects the agrarian nature of the local economy. Manufacturing and processing activities in the district, though practiced on a small scale, represent important economic activity (NGGL, 2006).

3.1.7 Potentially Relevant Standards of the Ahafo Mine

The Ghana Environmental Protection Agency approved the Environmental and Social Impact Statement (EIA&S). The water storage facility of the Ahafo mine was constructed and operated in accordance with relevant sections of the Ghana Minerals and Mining Law, 1986, Ghana Mining Environmental Guidelines, and IFC operational Policy 4.37 Safety of Dams. The Mine must comply with the recommendations in the EIA&S and the IFCs standards. The required discharge locations are: pit discharge, tailings discharge, waste dump, oil-water separator, water storage facility, mining and surface disturbance management, sediment control, noise and vibration, air quality, and water quality and chemical management.

The discharge samples must meet Ghana EPA, the Ghana Minerals and Mining Law effluent standards, IFC and WHO standards and must be monitored monthly (GEOMETRIX, 2007). A list of the potentially relevant standards is contained in Table 1. Since Ghana has guidelines for water quality standards for natural waters based on beneficial use, the EIA&S of the Ahafo mine stipulated that, surface water and groundwater quality sampling results should be examined for permanent concentration trends in reference to the water quality limits. Water quality standards for surface water and groundwater should address possible uses, for example, habitat for aquatic biota, drinking water, agricultural use, and livestock watering (GEOMETRIX, 2007).

Table 1. NGGL Legal Discharge Compliance Limits.

Parameters	UNITS	IFC ⁽¹⁾	Ghana EPA ⁽²⁾	Ghana Mines ⁽³⁾	NGGL Compliance Requirements ⁽⁴⁾
pH		6-9	6 - 9	6-9	6 - 9
Temperature	degrees C	<3	Ambient < 3	<3oC	Ambient < 3
TSS	mg/l	50	50	50	50
TDS	mg/l	-	1000	1000	1000
Conductivity	micro S/cm	-	1500	-	1500
Color	TCU	-	20	150	20
Turbidity	N.T.U.	-	75	75	75
Ammonia as N	mg/l	-	1.0	-	1
Aluminum	mg/l	-	5.0	-	5
Antimony	mg/l	-	1.5	-	1.5
Arsenic, Total	mg/l	1	0.5	-	0.5
Arsenic Dissolved	mg/l	-	0.1	-	0.1
Barium	mg/l	-	0.7	-	0.7
Beryllium	mg/l	-	-	-	-
Boron	mg/l	-	-	-	-
Cadmium	mg/l	0.1	0.1	0.1	0.1
Chloride	mg/l	-	250	-	250
Chlorine, Free	mg/l	-	-	-	-
Chlorine, Total Residual	mg/l	-	300	-	300
Chromium (VI)	mg/l	0.05	0.1	0.1	0.05
Chromium, Total	mg/l	1	0.5	-	0.5
Cobalt	mg/l	-	-	-	-
Copper	mg/l	0.3	2.5	-	0.3
Fluoride	mg/l	-	10.0	-	10
Iron	mg/l	2	-	-	2
Lead	mg/l	0.6	0.1	-	0.1
Manganese	mg/l	-	0.1	-	0.1
Mercury	mg/l	0.002	0.005	-	0.002
Molybdenum	mg/l	-	-	-	-
Nickel	mg/l	0.5	0.5	-	0.5
Nitrate,	mg/l	-	75.0	-	75 (16 NO ₃ as N)
Nitrites, as N	mg/l	-	-	-	-
Phosphorus, Total	mg/l	-	2.0	2	2
Selenium	mg/l	-	1.0	-	1
Silver	mg/l	-	0.1	-	0.1
Sulfate	mg/l	-	300	-	300
Sulfide as H ₂ S	mg/l	-	1.5	1.5	1.5
Thallium	mg/l	-	-	-	-
Tin	mg/l	-	5.0	-	5
Zinc	mg/l	-	5.0	-	5
Cyanide (Free)	mg/l	0.1	0.2	-	0.1
Cyanide, Weak Acid Dissociable	mg/l	0.5	0.6	-	0.5
Cyanide, Total	mg/l	1	1.0	-	1
Coliform, Total	MPN/100mL	-	400	400	n/a ^b
Coliform, Faecal	MPN/100mL	-	10	-	n/a ^b
E-Coli	MPN/100ml	-	-	10	n/a ^b
BOD	mg/l	50	50	50	n/a ^b
COD	mg/l	-	250	250	n/a ^b
Phenol	mg/l	-	1.0	2	1
Oil & Grease	mg/l	20	10	10	10
Total Metals (for all metals)	mg/L	-	10.0	-	10
Total Toxic Metals	mg/L	-	5.0	-	5

3.2 SAMPLING SITES

A total of 8 sampling sites, which included four (4) surface and four (4) ground water monitoring points were selected for the study (Table 2). The selection was based on the potential and predicted impact they may have during the operation of the Ahafo mine as stipulated in the ESIA and the environmental management plan drawn by the Environmental Department of NGGL and approved by the Environmental Protection Agency (EPA) of Ghana for water quality monitoring programmes. The sampling sites are shown in Figure 2.

Table 2: Selected water quality sampling locations

Monitoring Points	Type of water source	Description
KSW13	Surface	Subika Stream on Kenyasi-Ntotroso road. Further upstream of ECD6 and NSW6.
KSW16	Surface	Located upstream of TSF
NSW6	Surface	Downstream of Subika Pit and ECD6. On Subika Stream just before joining Subri River.
NSW8	Surface	Downstream of Mine. Further downstream of ECD4 on Subri River. To the Subri River and Subika River confluence.
GWC-3S	Groundwater	Downstream of subika pit
GWC-4D	Groundwater	Upstream of subika pit
GWC-7D	Groundwater	Downstream of subika and Apensu pits
GWC-8S	Groundwater	Upstream of Apensu pit

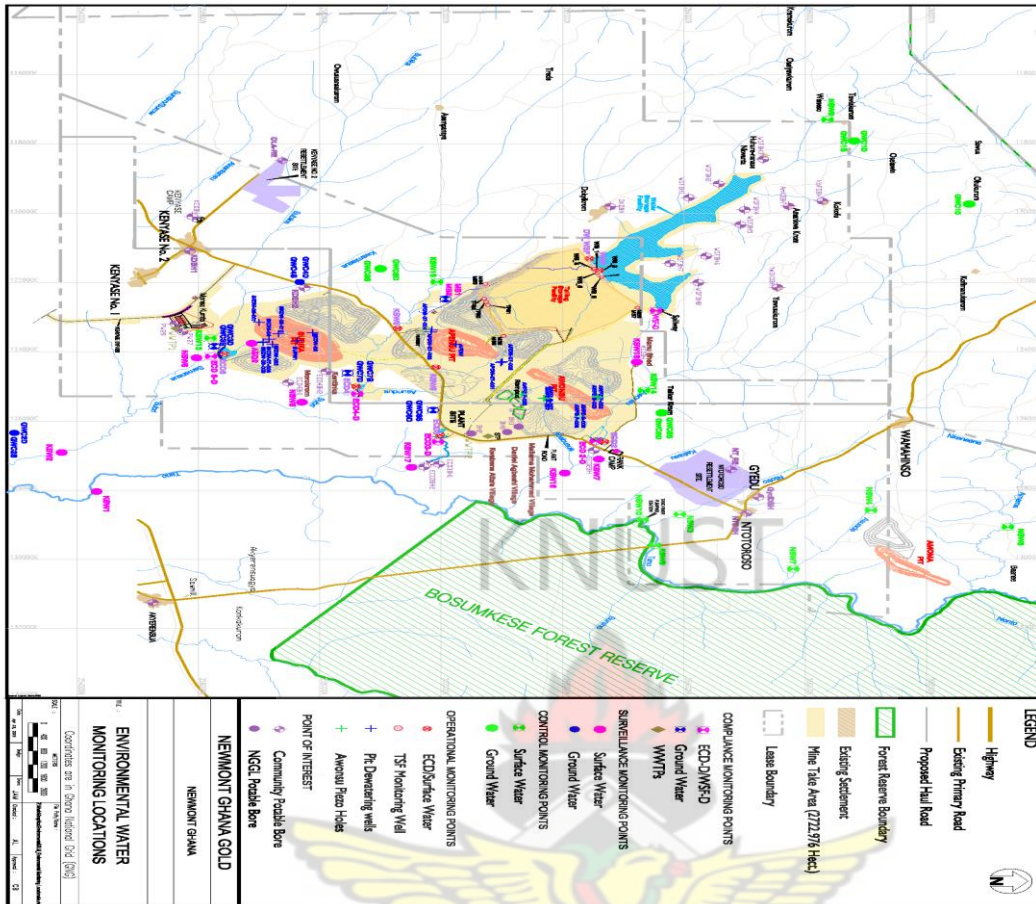


Figure 2: Map showing the Ahafo mine water quality monitoring points and other facilities

3.3 DATA COLLECTION

Secondary data was collected from the Environmental Department of the Newmont Ghana Gold Ltd. at Ahafo Kenyase. Data collected spanned the years 2007 to 2012. The data was gathered with the help of the Environmental Manager and the data entry personnel of the Environmental Department of the company. Other information were also gathered from the field sampling and monitoring crew.

3.4 STATISTICAL ANALYSES

In order to establish variations between and within the baseline data and the operational data of the water bodies under investigation, a two sample t-test with equal variances were used using STATA 10 software which also employs the use of classical test of hypothesis. This test provided information on variation within each sample data and the standard deviations in order to predict the quality of water for future use.



CHAPTER FOUR

RESULTS

4.1.1 Physico-chemical parameters and nutrients levels in samples from site KSW13

Mean pH at sampling site KSW13 ranged from 7.0 ± 0.1 in the year 2007 (baseline) to 7.4 ± 0.3 in the year 2012 (Table 3). All values recorded for the pH were within the Ghana EPA recommended range of 6-9. The differences in pH for KSW13 during operation were not statistically significant from the baseline ($p > 0.05$) (Appendix 1a) with the exception of 2012 where statistically, significant difference existed between the baseline and the operational data ($p < 0.05$) (Appendix 1a).

The mean turbidity levels at KSW13 during baseline studies were 44.6 ± 16.6 mg/L while the operational values ranged from 13.70 ± 4.7 to 69.55 ± 12.2 mg/L (Table 3), and were within the Ghana EPA limit of 75 mg/L (Table 3). Variations in turbidity values between the baseline and the operational values were only significant for the year 2008 ($p < 0.05$) (Appendix 1a). Mean Total Suspended Solids (TSS) at site KSW13 was 31.3 ± 14.3 mg/L in the year 2007 and ranged from 15.00 ± 5.9 to 59.50 ± 3.3 mg/L during operations (Table 3). The mean TSS at this site exceeded the Ghana EPA recommended level (50 mg/L) in 2009 and 2010 (Table 3). Except for the year 2009, no significant differences existed among the values and the baseline (Appendix 1a). Nitrate concentrations ranged between 0.2 ± 0.1 to 0.5 ± 0.1 mg/L while sulphate was from 0.2 ± 0.1 to 3.7 ± 2.5 mg/L over the period (Table 3). Both concentrations were within the respective regulatory limits of 75 mg/L and 250 mg/L by the Ghana EPA. Statistically, no significant differences existed between the baseline and the operational nitrate concentrations ($p > 0.05$) (Appendix 1a). For sulphate, significant statistical differences existed between the baseline data and some of the years (Appendix 1a).

Table 3: Physico–chemical parameters and nutrient levels of Subika stream at KSW13

Years	pH	Turbidity (mg/L)	TSS(mg/L)	Nitrate(mg/L)	Sulphate (mg/L)
2007	7.0±0.1	44.6±16.6	31.3±14.3	0.3±0.2	3.7±2.5
2008	7.0±0.2	13.7±4.7	15.0±5.9	0.3±0.5	1.0±0.01
2009	7.2±0.4	69.6±12.2	59.5±3.3	0.5±0.1	1.0±0.01
2010	7.0±0.4	57.1±49.0	58.0±52.4	0.4±0.4	1.0±0.1
2011	7.3±0.3	40.7±19.7	39.3±23.7	0.2±0.1	4.0±6.03
2012	7.4±0.3	31.2±17.7	19.3±15.9	0.2±0.2	0.2±0.1
Gh EPA	6-9	75	50	75	250

4.1.2 Concentrations of metals at site KSW13

The concentrations of the metals iron and mercury at monitoring site KSW13 for the period 2007–2012 are presented in Table 4. The mean concentrations of iron, mercury and arsenic were 2.7±0.3-6.7±4.1mg/L and 0.0019±0.0004-0.0025±0.0019mg/L (Table 4) respectively whereas the mean concentration of arsenic which is a metalloid was between 0.0002±0-0.0015±0.0009 mg/L (Table 4). Iron concentrations recorded for the period were higher than the Ghana EPA recommended limit of 0.1mg/L. Mercury and arsenic were within the respective values recommended by the Ghana EPA necessary for surface water discharge.

Table 4: Metal concentrations at monitoring site KSW13

Years	Iron (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
Baseline (2007)	6.7±4.1	0.0025±0.0019	0.0010±0
2008	3.8±1.4	0.0020±0.0014	0.0015±0.0005
2009	6.4±2.9	0.0027±0.0022	0.0015±0.0009
2010	3.6±2.0	0.0023±0.0006	0.0004±0.0004
2011	3.1±1.0	0.0019±0.0005	0.0002±0
2012	2.7±0.3	0.0019±0.0004	0.0002±0
Ghana EPA	0.1	0.002	0.01

4.2 MONITORING SITE KSW16

4.2.1 Physico-chemical and nutrient levels

Table 5 presents the results of the physico-chemical analysis of the surface water samples in monitoring well KSW16. The pH ranged from 6.7 ± 0.2 - 7.3 ± 0.4 (Table 5), whereas the range for turbidity and TSS were 25.3 ± 17.0 - 89.7 ± 57.0 mg/L and 12.25 ± 12.8 - 89.25 ± 51.0 mg/L respectively (Table 5). The pH values were all within the Ghana EPA standard of 6-9. Generally, the turbidity and TSS values were within the respective limits by the Ghana EPA, with the exception of the year 2009 where these limits were exceeded (Table 5). The mean nitrate concentrations during the period under study saw a slight reduction from the baseline value of 0.8mg/L to 0.4mg/L in 2012 (Table 5). In a similar fashion, sulphate levels decreased from 4.4mg/L in 2007 to 1.0mg/L in 2012 (Table 5). Both concentrations were several orders of magnitude lower than the Ghana EPA recommended limits for drinking water. Statistically there were no significant differences among the baseline data and the operational data ($p > 0.05$) (Appendix 3a) for both nutrients.

Table 5: Physico-chemical and nutrient levels at KSW16

Years	pH	Turbidity (mg/L)	TSS(mg/L)	Nitrate (mg/L)	Sulphate(mg/L)
Baseline (2007)	6.7±0.2	25.3±17.0	26.5±32.4	0.8±1.5	4.4±8.5
2008	7.1±0.4	42.0±15.5	42.0±10.9	0.8±1.0	2.2±4.1
2009	6.8±0.4	89.7±57.8	89.25±51.0	0.7±0.6	1.1±1.3
2010	7.1±0.3	49.6±8.8	27.5±12.8	0.4±0.2	1.0±0.001
2011	7.3±0.4	40.3±11.5	25.25±13.5	0.2±0.1	1.0±0.001
2012	7.0±0.5	17.8±9.4	12.25±12.8	0.4±0.5	1.0±0.001
Ghana EPA	6-9	75	50	75	250

4.2.2 Metal concentrations

The mean concentrations for iron, mercury and arsenic at the monitoring site KSW16 over the period were between; 2.6±1.3-6.9±6.2mg/L, 0.0002±0.0001-0.0038±0.0020mg/L and 0.0013±0.0005-0.0018±0.0005mg/L, respectively (Table 6). Iron concentrations exceeded the Ghana EPA limit of 0.1mg/L, whereas arsenic values were within the recommended limit (0.01mg/L). Mercury levels were generally within the Ghana EPA recommended value (0.002mg/L). However mercury levels for 2008 monitoring year recorded values higher than the Ghana EPA limit (Table 6). Statistically arsenic concentrations over the years did not differ significantly from the baseline ($p>0.05$) (Appendix 4a). For mercury, significant statistical differences existed between the baseline values and before operations ($p<0.05$) (Appendix 4a).

Table 6: Metal concentrations at monitoring site KSW16

Year	Iron (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
Baseline (2007)	5.1±2.0	0.0008±0.0004	0.0013±0.0005
2008	4.3±1.4	0.0038±0.0020	0.0013±0.0005
2009	4.7±1.7	0.0013±0.0001	0.0018±0.0005
2010	6.5±5.5	0.0004±0.0004	0.0019±0.0006
2011	2.6±1.3	0.0002±0	0.0017±0.0007
2012	6.9±6.2	0.0002±0.0001	0.0018±0.0005
Ghana EPA	0.1	0.002	0.01

4.3 MONITORING SITE NSW8

4.3.1 Physico-chemical parameters and nutrient levels

The mean concentrations of physico-chemical and nutrients levels recorded at site NSW8 are presented in Table 7. Levels of pH ranged between 7.2±0.1 and 7.7±0.1 (Table 7), and were within the Ghana EPA value of 6-9. Mean turbidity ranged between 7.20±3.4 and 24.3±10.8 mg/L (Table 7). The operational data recorded a range lower than the baseline value of 35.3±29.7 mg/L (Table 7). All the turbidity values recorded compared favourably with the Ghana EPA recommended value of 75 mg/L. No significant differences existed between the baseline and operational data ($p > 0.05$) (Appendix 5a). The mean TSS during the period was 5.3±3.9 to 25.3±12.4 mg/L while a value of 31.8±20.7 mg/L was recorded during the baseline studies. All the values recorded were within the Ghana EPA value of 50 mg/L (Table 7).

Mean nitrate and sulphate levels at this site generally increased from the respective baseline values (Table 7). Nitrate values for all the years were far less than the Ghana EPA limit

(75mg/L). Sulphate concentrations ranged from 71.6±42.9 to 392.50±162.6mg/L. Average sulphate concentrations exceeded the Ghana EPA limit (250mg/L) in 2011 and 2012 (Table 7).

Table 7: Physico-chemical and nutrient levels at site NSW8

Years	pH	Turbidity (mg/L)	TSS (mg/L)	Nitrate (mg/L)	Sulphate (mg/L)
Baseline (2007)	7.3±0.2	35.3±29.7	31.8±20.7	1.1±1.4	137.9±161
2008	7.6±0.1	7.2±3.4	5.3±3.9	1.5±1.3	71.6±42.9
2009	7.5±0.1	20.4±9.0	12.0±8.5	4.5±3.1	138.3±66.2
2010	7.2±0.1	24.3±10.8	25.3±12.4	3.5±1.8	152.0±90.4
2011	7.5±0.2	24.0±40.5	21.0±23.7	9.5±8.4	312.7±209.6
2012	7.7±0.1	8.1±3.9	16.2±11.8	12.6±7.7	392.5±162.6
Ghana EPA	6-9	75	50.0	75	250

4.3.2 Metals Concentrations at NSW8

The concentrations of chemicals recorded at monitoring site NSW8 for iron, mercury and arsenic respectively ranged between 0.3±3.9-1.60±29.7mg/L, 0.0002±0.001-0.002±0.001mg/l and 0.001±0-0.003±0.002mg/L (Table 8). From Table 8, NSW8 had elevated levels of iron which exceeded the compliance limit of 0.1 mg/l approved by Ghana EPA. These differences, however, were not statistically significant ($p > 0.05$) (Appendix 6a). There were no exceedances in mean mercury levels during the operations compared to Ghana EPA recommended value of 0.002 mg/l. However, the baseline data exceeded the Ghana EPA compliance level for water quality discharge. There were no significant statistical difference ($p > 0.05$) (Appendix 6a) between the baseline data and the operational data. All the values recorded for arsenic compared favourably with the Ghana EPA value of 0.01 mg/l. Statistically, there were significant differences between the mean arsenic concentrations of the baseline and the operational data ($p < 0.05$) (Appendix 6a).

Table 8: Metal concentrations at monitoring site NSW8

Years	Iron (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
Baseline (2007)	1.6±29.7	0.007±0.010	0.001±0
2008	0.5±3.5	0.002±0.001	0.002±0.001
2009	0.7±9.1	0.0002±0.001	0.003±0.002
2010	1.4±10.7	0.001±0	0.002±0.001
2011	1.0±40.4	0.001±0	0.001±0.001
2012	0.3±3.9	0.001±0	0.001±0
Ghana EPA	0.1	0.002	0.01

4.4 MONITORING SITE NSW6

4.4.1 Levels of physico-chemical parameters and nutrients

Table 9 presents the results for the physico-chemical parameters and levels of nutrients at monitoring site NSW6. The results indicate that pH, TSS, turbidity as well as nitrates and sulphates were within the respective levels recommended by the Ghana EPA (Table 9).

Also, the variations in the mean values between the baseline (2007) data and the operational data were not statistically significant ($p>0.05$) for pH, turbidity and TSS as well as nitrates and sulphates (Appendix 7a).

Table 9: Physico-chemical and nutrient levels at site NSW6

Years	pH	Turbidity (mg/L)	TSS (mg/L)	Nitrate (mg/L)	Sulphate (mg/L)
Baseline (2007)	7.3±0.4	27.7±24.7	26.0±20.7	0.2±0.12	115.4±171.4
2008	7.4±0.1	42.9±14.4	39.7±11.0	0.1±0.1	1.0±0
2009	7.2±0.1	51.8±27.2	45.5±26.6	0.4±0.3	1.0±0
2010	7.0±0.5	29.7±10.7	28.5±9.7	0.2±0.1	1.0±0.15
2011	7.5±0.3	14.8±8.0	19.2±4.4	0.5±0.4	32.2±24.5
2012	7.6±0.3	27.2±12.4	18.2±3.5	0.3±0.1	11.7±16.1
Ghana EPA	6-9	75	50	75	250

4.4.2 Metals Concentrations at NSW6

Mean iron concentration at NSW6 during operations ranged between 2.0 ± 0.5 and $2.7\pm1.1\text{mg/L}$ which shows a slight increase from the baseline value of $1.5\pm0.9\text{mg/L}$ (Table10). All the values recorded for iron at this monitoring site exceeded the EPA regulatory limit of 0.1mg/L . The baseline data however, was statistically not significant ($p<0.05$) from the operational data (Appendix 8a).

Mercury concentrations ranged from 0.0002 ± 0 to $0.002\pm0.001\text{mg/L}$, and were within Ghana EPA recommended value of 0.002 mg/L (Table10). The differences between the baseline values and the operational ones were significant ($p<0.05$) (Appendix 8a).

The mean operational data recorded for arsenic were between 0.002 ± 0 and $0.003\pm0.002\text{mg/L}$ whereas the mean baseline value was $0.001\pm0\text{mg/L}$ (Table10). All the values compared favourably with the Ghana EPA guideline value of 0.01mg/L . Arsenic concentrations showed significant difference among the years all the years under review ($p<0.05$) (Appendix 8a).

Table 10: Concentrations of Metals at NSW8

Years	Iron (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
Baseline (2007)	1.5±0.9	0.001±0.000	0.001±0
2008	2.0±0.5	0.002±0.001	0.001±0.002
2009	2.6±0.7	0.0002±0	0.002±0
2010	2.7±1.1	0.001±0.001	0.002±0
2011	2.1±0.5	0.001±0	0.002±0
2012	2.2±0.5	0.001±0	0.003±0.002
Ghana EPA	0.1	0.002	0.01

4.5 MONITORING SITE GWC-4D

4.5.1 Physico-chemical and nutrient levels

Table 11 indicate that the mean values of pH, TDS, conductivity, nitrates and sulphates at monitoring site GWC-4D were within the Ghana EPA recommended limit for all the parameters under review.

Table 11: Physico-Chemical Parameters and Nutrient levels at site GWC-4D

Years	pH	TDS (mg/L)	Conductivity (µS/cm)	Sulphate (mg/L)	Nitrate (mg/L)
Baseline (2007)	6.9±0.3	295.0±19.7	612.8±41.1	6.1±0.6	0.1±0.1
2008	7.1±0.1	341.0±128.7	691.0±251.4	7.5±0.8	0.1±0.01
2009	7.2±0.2	345.0±52.8	606.5±30.1	9.0±0.8	0.1± 0.02
2010	7.2±0.3	315.3±77.0	610.7 ± 41.1	13.0±4.2	0.2±0.2
2011	7.2 ±0.2	278.8±22.8	567.3±44.6	9.3±0.5	0.1±0.00
2012	7.3 ±0.1	315.3±57.5	594.5 ±39.0	9.5 ±1.0	0.1±0.00
Ghana EPA	6-9	1000	1500	250	75

4.5.2 Concentration of Metals at GWC-4D

The mean concentrations for iron, arsenic and mercury were: iron (0.4 ± 0.2 - 1.0 ± 0.7 mg/L), arsenic (0.04 ± 0 - $0.09\pm$ mg/L) and mercury (0.0002 ± 0 - 0.001 ± 0 mg/L) (Table 12) with iron and arsenic recording values higher than the recommend value by the Ghana EPA throughout the monitoring period. Mercury recorded values that were below the recommended limit for water quality discharge (Table 12).

Table 12 Concentrations of Metals in samples from site GCW-4D

Years	Iron (mg/L)	Arsenic (mg/L)	Mercury (mg/L)
Baseline (2007)	0.7 ± 0.4	0.04 ± 0	0.001 ± 0
2008	0.4 ± 0.2	0.07 ± 0	0.001 ± 0
2009	0.7 ± 0.5	0.08 ± 0	0.0002 ± 0
2010	1.0 ± 0.7	0.06 ± 0	0.0002 ± 0
2011	0.6 ± 0.5	0.07 ± 0	0.0002 ± 0
2012	0.6 ± 0.4	0.09 ± 0	0.0002 ± 0
Ghana EPA	0.1	0.01	0.002

4.6 MONITORING SITE GWC-3S

4.6.1 Physico-chemical and nutrient levels

Table 13 shows the mean values of nutrients and the physico-chemical parameters studied. The range for pH was 6.8 ± 0.3 - 7.1 ± 0.2 ; TDS ranged from 612.5 ± 168.2 - 915.2 ± 124.7 mg/l while the range for conductivity was 1018.8 ± 466.3 - 1742.5 ± 254.5 μ S/cm. Nitrates ranged from 0.02 ± 0.01 to 2.2 ± 4.2 mg/l with sulphates ranging from 27.3 ± 12.0 - 413.8 ± 73.4 mg/l. The baseline and the operational data for the above parameters did not show any significant statistical difference ($p>0.05$) (Appendix 3b).

Table 13: Physico-Chemical Parameters and Nutrient levels at site GWC-3S

Year	pH	TDS (mg/L)	Conductivity (μ S/cm)	Nitrate (mg/L)	Sulphate (mg/L)
Baseline (2007)	6.8 \pm 0.3	850.0 \pm 106.2	1742.5 \pm 254.5	0.06 \pm 0.03	293.7 \pm 24.5
2008	6.9 \pm 0.0	718.0 \pm 55.9	1465.75 \pm 114.0	0.02 \pm 0.01	311.8 \pm 38.2
2009	7.0 \pm 0.2	915.2 \pm 124.7	1620.0 \pm 200.4	0.03 \pm 0.03	413.8 \pm 73.4
2010	6.9 \pm 0.1	631.8 \pm 54.1	1347.5 \pm 97.9	0.5 \pm 0.4	259.7 \pm 114.4
2011	7.0 \pm 0.1	612.5 \pm 168.2	1250.3 \pm 342.6	1.4 \pm 1.9	315.0 \pm 139.6
2012	7.1 \pm 0.2	703.5 \pm 268.3	1018.8 \pm 466.3	2.2 \pm 4.2	27.3 \pm 12.0
Ghana EPA	6-9	1000	1500	75	250

4.6.2 Metals Concentration in GWC-3S

Table 14 indicates that iron concentrations in the shallow groundwater (GCW-3S) over the monitoring period exceeded the Ghana EPA regulated value of 0.1mg/L while arsenic and mercury levels were within the respective limits.

Table 14 Metal concentrations at site GWC-3S

Years	Iron (mg/l)	Arsenic (mg/l)	Mercury (mg/l)
Baseline (2007)	0.2 \pm 0.1	0.001 \pm 0.00	0.001 \pm 0.00
2008	0.1 \pm 0.03	0.0015 \pm 0.00	0.0017 \pm 0.00
2009	7.8 \pm 11.4	0.002 \pm 0.00	0.0017 \pm 0.00
2010	1.1 \pm 0.8	0.0008 \pm 0.00	0.002 \pm 0.00
2011	2.3 \pm 2.3	0.0014 \pm 0.00	0.002 \pm 0.00
2012	2.7 \pm 2.8	0.0012 \pm 0.00	0.002 \pm 0.00
Ghana EPA	0.1	0.002	0.01

4.7 MONITORING WELL GWC-7D

4.7.1 Physico-chemical parameters and nutrient levels in GWC-7D

Table 15 shows the mean values of nutrients and some physico-chemical parameters studied. All the parameters under review were compliant with the baseline data and the Ghana EPA approved limit for groundwater quality.

Table 15: Physico-chemical Parameters and Nutrient levels in monitoring well GWC-7D

Years	pH	TDS (mg/l)	Conductivity (μS/cm)	Nitrate (mg/l)	Sulphate (mg/l)
Baseline 2007	6.8±0.3	326.5±45.0	664.8±98.1	0.05±0.03	19.1±7.2
2008	6.7±0.6	334.7±15.5	682.5±30.5	0.02±0.01	20.8±0.8
2009	6.8±0.1	504.5±231.2	861.8±280.3	0.3±0.01	19.9±1.8
2010	6.6±0.1	322.2±71.9	654.0±422.1	2.8±4.70	14.5±11.7
2011	6.4±0.2	212.8±27.4	434.3±55.6	0.04±0.03	21.5±2.6
2012	6.9±0.1	166.8 ±14.5	340.0±29.5	0.2±0.20	23.8±1.3
Ghana EPA	6-9	1000	1500	75	250

The range for pH was 6.4±0.2 -6.9±0.1; TDS was from 166.8±14.5-504.5±231.2mg/L, while the range for conductivity was 340.0±29.5 - 861.8±280.3μS/cm(Table 15 above). Nitrates ranged from 0.02±0.0- 2.8±4.70mg/L with sulphates having a range of 14.50±11.7-23.8±1.3mg/L (Table15 above).

4.7.2 Metals concentration in well GWC-7D

Mean levels of iron, arsenic and mercury in the monitoring site GWC-7D over the period 2007-2012 are presented in Table 16 below. The table indicates that the the mean values for iron, arsenic and mercury were 0.08±0.01-0.28±0.16mg/L, 0.0009±0-0.0035±0.002mg/L and 0.0002±0-0.0017±0mg/l, respectively (Table 16 below). Values for iron generally exceeded the

Ghana EPA regulated value of 0.1mg/L. However, values for arsenic and mercury were found to be within the respective guideline value.

Table 16: Metals concentration in GWC-7D

Years	Iron (mg/L)	Arsenic (mg/L)	Mercury (mg/L)
Baseline 2007	0.21±0.03	0.0035±0.004	0.001±0
2008	0.24 ±0.04	0.0015±0.001	0.0015±0
2009	0.17±0.1	0.0035±0.002	0.0017±0
2010	0.08±0.01	0.0009±0	0.0002±0
2011	0.45±0.30	0.0009±0	0.0003±0
2012	0.28±0.16	0.0012±0	0.0002±0
Ghana EPA	0.1	0.002	0.01

4.8 MONITORING SITE GWC-8S

4.8.1 Physico-chemical parameters and nutrient levels of GWC-8S

This site exhibited acidic pH (5.4 ± 0.2 - 5.7 ± 0.6) over the period (Table 17). The range for conductivity was 71.9 ± 3.0 - 110.6 ± 41.8 $\mu\text{S/cm}$, and TDS also ranged between 40.0 ± 7.0 - 65.4 ± 15.4 mg/l. The difference in means between the baseline and the operational data for pH and conductivity were statistically insignificant ($p>0.05$). However, the differences were statistically significant for the TDS values ($p<0.05$) (Appendix 7b).

Nitrate and sulphate concentrations measured over the period at this site were far below the Ghana EPA recommended value (Table 17). Statistically, no significant difference existed between the baseline and the operational data for nitrate ($p>0.05$). However, sulphate showed significant statistical differences in mean values between the baseline and the operational data ($p<0.05$) (Appendix 7b).

Table 17: Physico-chemical parameters and nutrient levels in GWC-8S

Years	pH	Conductivity ($\mu\text{S}/\text{cm}$)	TDS (mg/l)	Nitrate (mg/l)	Sulphate (mg/l)
Baseline 2007	5.4 \pm 0.2	90.9 \pm 30.8	44.7 \pm 15.4	0.3 \pm 0.1	1.1 \pm 0.1
2008	5.7 \pm 0.05	93.9 \pm 5.6	46.3 \pm 2.6	0.5 \pm 0.1	1.2 \pm 0.2
2009	5.4 \pm 0.3	83.1 \pm 12.4	45.5 \pm 13.5	0.9 \pm 1.3	1.3 \pm 0.5
2010	5.5 \pm 0.3	110.6 \pm 41.8	65.4 \pm 15.4	0.8 \pm 0.4	1.0 \pm 0.0
2011	5.5 \pm 0.1	81.3 \pm 14.2	40.0 \pm 7.0	0.4 \pm 0.1	1.0 \pm 0.0
2012	5.7 \pm 0.6	71.9 \pm 3.0	41.4 \pm 11.2	0.4 \pm 0.0	1.0 \pm 0.0
Ghana EPA	6-9	1000	1500	75	250

4.8.2 Metal concentrations in GWC-8S

Mean levels of iron, arsenic and mercury in the downstream deep groundwater (GW-C8S) are presented in Table 18 below. The table indicates that the ranges for the mean values for iron, arsenic and mercury were 0.1 \pm 0-1.1 \pm 1.0mg/L, 0.0009-0.04mg/L and 0.0002-0.002mg/L, respectively (Table 18). Values for iron generally exceeded the Ghana EPA regulated value of 0.1 mg/L, while arsenic were found to be within the respective guideline value of 0.01mg/L.

Table 18: Metals concentration in GWC-8S

Years	Iron (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
Baseline (2007)	0.56 \pm 0.3	0.001 \pm 0.00	0.026 \pm 0.04
2008	0.2 \pm 0.1	0.002 \pm 0.001	0.008 \pm 0.01
2009	1.1 \pm 1.0	0.002 \pm 0.001	0.042 \pm 0.06
2010	0.2 \pm 0.3	0.0002 \pm	0.002 \pm 0
2011	0.1 \pm 0.1	0.0002 \pm 0	0.001 \pm 0
2012	0.1 \pm 0	0.0002 \pm 0	0.001 \pm 0
Ghana EPA	0.1	0.002	0.01

CHAPTER FIVE

DICISSIONS

5.1 SURFACE WATER MONITORING SITES

5.1.1 PH

Before the start of mining operations in 2007, the average pH values measured at the upstream surface water monitoring sites KSW13 and KSW16 were 7.0 ± 0.1 and 6.7 ± 0.2 , respectively, whereas a value of 7.3 ± 0.2 was recorded at both downstream sites NSW6 as against a pH of 7.3 ± 0.4 at NSW8. This trend indicates that the water samples were nearly neutral at the start of mining operations. Even though these neutral pHs were maintained, the values appeared to have increased slightly from the baseline value. In particular the increase appeared to be consistent from the year 2011 at both sites (i.e. KSW13 and KSW16). Nonetheless, these values were still within the Ghana EPA recommended range (6-9).

The trends exhibited by the upstream surface waters were similar to those of the downstream surface water monitoring sites (NSW6 and NSW8). The values at both sites appeared to have increased slightly, but consistently from the baseline (year 2007) to the year 2012.

A change in pH can alter the behavior of other chemicals in water for example; ammonia is relatively harmless to fish in water that is neutral or acidic. However, as the water becomes more basic (the pH increases) ammonia becomes increasingly toxic (Mesner and Geiger, 2010). There has been an increase in pH of the upstream surface water since the operation of the Ahafo mine. Buffered nature of stream water can be attributed to the fact that, running waters normally are influenced by the nature of deposits over which they flow (Hynes, 1970). The upstream pH of the Mine was gradually approaching neutral. However, from literature, acid mine drainage (AMD/ARD) can enhance contaminant mobility by promoting leaching from exposed wastes and mine structures and releases can also occur under neutral pH conditions. Dissolution of

metals due to low pH is a well-known characteristic of acid drainage. Low pH is not necessary for metals to be mobilized and to contaminate waters; there is increasing concern about neutral and high pH mobilization (Winter *et al.*, 1999). Even moderately acidic water (low pH) may reduce the hatching success of fish eggs, irritate fish and aquatic insect gills, and damage membranes (Mesner and Geiger, 2010).

Turbidity

The values for turbidity in all the surface water samples (both upstream and downstream) at the start of operations were below the 75 NTU set by the Ghana EPA for water discharge. The turbidity value at KSW13 dropped sharply from 44.6 ± 16.6 NTU (baseline) to 13.7 ± 4.7 NTU in 2008. This sharp decrease in value could be attributed to the fact that the stream takes its course from an area which had been acquired by the company to use as resettlement site. No construction activities had begun at the time, and also other disturbances such as farming were restricted within the catchment area.

However, in 2009 the company had begun the construction of houses to resettle the communities that were inundated as a result of the mine land take and eventual excavation caused increase in the sedimentation of the stream characterized by runoffs. Hence, the high value of turbidity (69.576 ± 12.2 NTU) observed in the year 2009 at site KSW13.

On the other hand the mean turbidity during baseline studies at KSW16 which is also located at the upstream of the mine was 25.3 ± 17.0 NTU. There was a sharp increase in turbidity during the first two years (2008 and 2009) of operation due to vigorous constructional activities and earthworks in preparation for the tailings storage facilities and the water storage facility. Those facilities are located at the upstream of site KSW16 and continuous rainfall could increase the sediment load.

Comparatively, monitoring sites NSW6 and NSW8, which are located downstream, had mean turbidity that were lower than those of the upstream water samples. This is an indication of no discharge or runoffs from the mine into the receiving stream. Whereas turbidity levels were not higher than the Ghana EPA standard of 75 NTU at KSW13, there was exceedance at KSW16 in 2009 with a value of 89.7 ± 57.8 NTU. The US EPA (2005) reiterate that human activities that disturb land, such as construction, mining and agriculture can lead to high sediment levels entering water bodies during rain storms due to storm water runoff. Anderson *et al.* (1996) explain that, turbidity is caused by suspended matter or impurities that interfere with the clarity of water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble coloured organic compounds, and plankton and other microscopic organisms (Fox, 1995).

5.1.3 TOTAL SUSPENDED SOLIDS (TSS)

TSS values for the upstream surface water monitoring sites (KSW13 and KSW16) showed trends similar to what was observed for turbidity. At site KSW13, the value decreased from 31.3 ± 14.30 mg/l to 15.0 ± 5.9 mg/l in 2008, and increased again to 59.5 ± 3.3 mg/l in 2009. They then steadily reduced to 19.3 ± 15.9 mg/l in 2012. The year 2009 exceeded the Ghana EPA discharge standard (50 mg/l), and this is, again, attributed to the construction activities. Construction and excavation activities loosen soil particles, and increase the total surface area per unit mass of particle. The smaller the particle size, the higher the pollutant load that is likely to be carried. Loosened soil particles are also more likely to be carried by runoff water into streams and rivers.

The TSS levels recorded at KSW16 during operation of the mine were between 12.25 ± 12.8 mg/l to 89.25 ± 51.0 mg/l whereas the baseline value was 26.50 ± 32.4 mg/l. The values steadily

increased to 42.0 ± 10.9 mg/l in 2008 and further to 89.25 ± 51 mg/l in 2009, indicating noncompliance with the Ghana EPA discharge guidelines and reaffirms the continuous earth works during operation of the mine. However, from 2010 there was a steady decline to the lowest value of 12.25 ± 12.8 mg/l in 2012.

The TSS values recorded at the downstream sites (NSW6 and NSW8) were also within the Ghana EPA limit of 50 mg/l. Generally, steady decline were observed at both sites. Suspended solids reduce visibility and absorb light, which can increase stream temperatures and reduce photosynthesis (USEPA, 2005).

NITRATE LEVELS

Nitrate levels are monitored as nitrogen in water samples at the mine site. The upstream surface water monitoring sites (KSW13 and KSW16) showed values similar to the baseline data. Likewise, the corresponding downstream data (NSW6 and NSW8) showed very low levels of nitrates. The low values are an indication of no industrial discharges of organic, sewage or nutrient rich pollutants from the mine into the downstream waters. The relatively little amount of nitrates found in natural waters is of mineral origin (WHO, 1993). Bacterial oxidation and fixing of nitrogen by plants can both produce nitrates.

However, the upstream surface waters of the Mine during the baseline studies and the operational data showed a much more deficit in this nutrient. According to APHA (1992), such low levels of nitrate (less than 1 mg/l) are typical of surface waters. The low levels are also indicative of low level of agricultural runoff into the water bodies (WHO, 1993). Nitrates from land sources end up in rivers and streams more quickly than other nutrients like phosphorus. This is because they dissolve in water more readily than phosphates, which have an attraction for soil

particles. As a result, nitrates serve as a better indicator of the possibility of a source of sewage or manure pollution during dry weather (USEPA, 2012).

5.1.5 SULPHATE LEVELS

The sulphate levels of the upstream surface waters (KSW13 and KSW16) were found to be generally low and all falling below the Ghana EPA trigger limit of 250mg/L. Sampling site KSW13 exhibited a baseline value of 3.7 ± 2.5 mg/L and KSW16 showing baseline value of 4.4 ± 8.5 mg/L. The levels of sulphate declined steadily from the baseline value throughout the period. Though sampling site NSW6 recorded high sulphate level during the baseline studies, it was within the Ghana EPA recommended limit of 250 mg/l. The relatively high value may be attributed to the high agricultural activities around the water bodies before the land was acquired for the mine. The operational levels were however, far below the baseline data since a large number of the farmers were resettled away from the banks of the stream.

The sulphate values for downstream NSW8 were consistently higher compared to the upstream during and after the baseline studies. With the exception of the year 2008, the monitoring values from 2009 to 2012 exceeded the baseline data, with 2011 and 2012 levels exceeding the Ghana EPA standard. This particular stream takes its major inflows from one of the Mine's Environmental Control Dams (ECD4). This dam is a reservoir for all runoffs and sediments from the mine site hence it could be a sink for the source of high sulphate levels in NSW8. Human activities in watersheds can increase nutrient loads carried into surface waters by runoff and enhance primary production (Sharpley and Menzel, 1987).

5.1.6 METALS IN THE SURFACE WATER

The upstream surface water sampling points at KSW13 and KSW16 recorded 6.7 ± 4.1 mg/L and 5.1 ± 2.0 mg/L iron concentrations respectively during the baseline studies. Iron concentrations did not show a uniform in these surface waters. There were instances (2010 and 2012) where higher values of iron were observed compared with the baseline. All the mean values of iron exceeded the Ghana EPA recommended limit (0.1mg/L) for surface water quality discharge. However, it has been found that, documentation of heavy metal concentrations in water is frequently difficult as levels often fluctuate rapidly making the detection of spikes problematic (Harding, 2005). Although the iron concentrations of the downstream surface waters (NSW6 and NSW8) were lower than the upstream waters, both baseline and the monitoring period iron levels of all the surface waters exceeded the approved EPA limit of 0.1 mg/L. Surface waters around the Ahafo mine operational area are reported to be rich in iron. Iron is among the most abundant metals accounting for about 5% in the Earth's crust. Suspended solids have the ability to bind iron together and release it into waters at higher temperatures and rainfall. Iron is not hazardous to health, but it is considered a secondary or aesthetic contaminant (IDPH, 2010). According to Harding (2005), the primary sources of anthropogenic metal contamination in our waterways are from drainage associated with mining activities, storm water from urban and industrial areas and seepages from landfills.

Mercury concentration of the upstream surface waters of the Ahafo mine were generally within the tolerable limit of 0.002mg/L for both streams with the exception of the year 2008 where mercury level of 0.003 ± 0.002 mg/L was detected in KSW16. The ability mercury to bioaccumulate in particular in fish meat and the known cases of lethal poisoning have drawn particular attention to this element's presence in the natural environment. Due to the relatively

long time of its presence in the air, elemental mercury can be transported over large distances; hence the presence of mercury of anthropogenic origin is detected practically all over the world. (Boszke et al, 2002).

Levels of mercury in NSW8 and NSW6 (downstream sampling sites) were also within the tolerable limit (0.002 mg/L) with the exception of the year 2007 (baseline) a value (0.007±0.01 mg/L) higher than the tolerable limit was detected in NSW8.

Metals such as mercury frequently accumulate in aquatic plants and in river and lake sediments and can be remobilized and incorporated into food webs. Metals such as mercury (Hg) can bioaccumulate within food webs (Goodyear and McNeill, 1999), and affect the physiology, growth and reproduction of organisms at multiple trophic levels (Kelly, 1988).

Since the Ahafo Mine does not make use of mercury in any of its operational activities, the source of this mercury is unlikely to be from the mining, rather could be from natural sources. BMEPC (1987) asserts that data on the concentration of mercury in natural waters are unreliably diverse not only as a consequence of the natural variation of the species and concentrations of this metal in water but also because of analytical difficulties. Mercury occurs in water in the dissolved phase as well as in the colloidal and suspended phases. The contribution of mercury in these two phases varies both in time (seasonal changes) and in space (Cossa *et al.*, 1996).

Most environmental arsenic problems are the result of mobilisation under natural conditions, but man has had an important impact through mining activity, combustion of fossil fuels, the use of arsenical pesticides, herbicides and crop desiccants and the use of arsenic as an additive to livestock feed, particularly for poultry.

Both upstream surface water sampling points recorded arsenic values that were generally within the Ghana EPA limit (0.01 mg/L). Baseline arsenic levels of 0.001 ± 0 mg/l and 0.0013 ± 0.0005 mg/l were recorded in KSW13 and KSW16, respectively. These showed slight variations during the operation of the mine. Arsenic is a naturally occurring element found in the Earth's crust that is found almost everywhere. It occurs naturally in rocks and soil, water, air, plants and animals. Arsenic is mobilised in the environment through a combination of natural processes such as weathering reactions, biological activity and volcanic emissions as well as through a range of anthropogenic activities (Smedley and Kinniburgh, 1999). Smedley(1996), found high arsenic concentrations in soils in Obuasi(Ghana) close to the mine's treatment works. Some high concentrations have also been reported in river waters close to the mining activity. Arsenic is now recognised as the most serious inorganic contaminants in drinking water on a worldwide basis (Smedly, 2001). Higher levels of arsenic tend to be found more in ground water sources than in surface water sources (USEPA, 2005).

5.2 GROUNDWATER MONITORING SITES

5.2.1 pH

The mean pH levels of the upstream groundwater characterization well (GWC-4D) in the Ahafo Mine area increased from the baseline value of 6.9 to 7.3 ± 0.1 in 2012. From the same upstream of the mine, the shallow well (GWC-8S) had a baseline value which was slightly acidic (5.4 ± 0.2) and continued to have slightly acidic values (5.4 ± 0.3 to 5.7 ± 0.6) throughout the operational period. Dissolution of metals due to low pH is a well-known characteristic of acid mine drainage, and therefore, the high levels of acidity exhibited by water samples from GWC-8S can leach metals into nearby aquifers. The pH of groundwater will vary depending on the composition of the rocks and sediments that surround the travel pathway of the recharge water infiltrating into

the ground water (American Well Owner, 2003). Groundwater chemistry will also vary depending on how long the existing ground water is in contact with a particular rock (The American Well Owner, 2003). The low pH is mainly due to oxygen in infiltrating waters reacting with high concentrations of dissolved iron. In aquifers with no neutralizing minerals like carbonates; this results in pH remaining low.

The pHs of GWC-3S and GWC-7D were all within the Ghana EPA approved limit. While low pH is not necessary for metals to be mobilized and to contaminate waters, there is increasing concern about neutral and high pH mobilization (Winter *et al.*, 1999). Environmental Law Alliance affirms that, acid drainage and contaminant leaching is the most important source of water quality impacts related to metallic ore mining. Acidity can occur if iron sulfide minerals especially pyrite are abundant in water and there is an insufficient amount of neutralizing material to counteract the acid formation (ELAW, 2010).

5.2.2 TOTAL DISSOLVED SOLIDS

Total Dissolved Solid (TDS) in the upstream groundwater GWC-4D of the mine ranged between $278.8 \pm 22.8 \text{ mg/l}$ to $345.0 \pm 52.8 \text{ mg/L}$ during operations compared with a baseline value of $295 \pm 19.7 \text{ mg/l}$. Although there was slight increase of TDS over the period, the values recorded did not exceed the Ghana EPA recommended limit of 1000 mg/L . Samples from GWC-3S recorded TDS values that compared favourably with the baseline data and complied with the Ghana EPA limit of 1000 mg/L as well.

Samples from GWC-7D (downstream) of the catchment area also maintained TDS concentrations within the approved EPA limit but exceeded the baseline value in the year 2009. There were however, a reduction in the mean TDS values of the operational data for GWC-8S from $46.3 \pm 2.6 \text{ mg/L}$ in year 2008 to $40.0 \pm 7.0 \text{ mg/L}$ in year 2011. TDS value for the year

2010 at GWC-8S exceeded the baseline data. Dissolved solids in water supplies may originate from industrial wastewater, sewage, urban and agricultural runoffs. Concentrations of TDS in water vary owing to different mineral solubilities in different geological regions (Hem, 1989).

5.2.3 CONDUCTIVITY

The mean electrical conductivity of the upstream groundwater wells (GWC-4D and GWC-8S) of the Ahafo mine were below the Ghana EPA limit of 1500 $\mu\text{S}/\text{cm}$. The values also compared favourably with the baseline value. According to APHA (1992), waters that run through areas with granitic bedrock tend to have lower conductivity because granite is composed of more inert materials that do not ionize.

However, the downstream groundwater (GWC-3S and GWC-7D) exhibited high mean conductivity values compared with the Ghana EPA standards. Monitoring site GWC-3S recorded baseline value of $1742.5 \pm 254.5 \mu\text{S}/\text{cm}$ with operational values ranging from $1018.8 \pm 466.3 \mu\text{S}/\text{cm}$ recorded in 2012 to $1620 \pm 200.4 \mu\text{S}/\text{cm}$ recorded in 2009. Shallow (alluvial) wells may easily trap anions such as chloride, nitrate, sulfate, and phosphate or cations such as sodium, magnesium, calcium, iron, and aluminum to increase ionic levels in water (APHA, 1992). Again, the baseline electrical conductivity data of GWC-7D also compared favourably with its corresponding operational values and the Ghana EPA regulatory limit for groundwater quality.

SULPHATE

The sulphate levels of the sampling site GWC-4D and GWC-8S were found to be generally low and were below the Ghana EPA limit of 250 mg/L. Sulphate data during the monitoring period on both wells also compared favourably with the baseline data. The concentrations of sulphate in the downstream groundwater (GWC-7D) during monitoring by the mine were found to be within the approved EPA limit with no deviation from the baseline. In practice sulphate levels of

the downstream ground water has not been impacted by the mine's operations. However, the sulphate concentration of the downstream well (GWC-3S) showed higher concentrations exceeding the approved Ghana EPA limit. In the year 2012 sampling site GWC-3S recorded very low sulphate level ($27.3 \pm 12.0 \text{ mg/L}$) compared with a baseline value of $293.7 \pm 24.5 \text{ mg/L}$.

Low concentrations ($< 0.5 \text{ mg/L}$) of sulfate can encourage algal growth, however, sulfate concentrations greater than 250 mg/L can cause water to have a salty taste and may cause pipe and fixture corrosion (USEPA, 1994). Sometimes sulfate concentrations increase rapidly with depth but other times they remain relatively low in the deeper part of the aquifer. This variability suggests that sulfate concentrations and sources vary both vertically and laterally in the aquifer (Lawrence and Upchurch, 1982).

5.2.5 NITRATE

Nitrate levels in both upstream groundwater wells (GWC-4D and GWC-8S) during operations showed no deviation from the baseline data and the Ghana EPA approved level of 16 mg/L required for groundwater discharge. Generally, the downstream groundwater wells (GWC-3S and GWC-7D) also showed low levels of nitrate concentrations. This may imply that there were no discharges of organic materials and other pollutants from the mine that could seep or infiltrate into the aquifers to contaminate the groundwater. According to APHA (1992), levels of nitrate in natural groundwater is typically low ($< 1 \text{ mg/L}$), and can be attributed to low level of agricultural and other anthropogenic inputs (WHO, 1993).

5.2.6 METALS IN GROUND WATER OF AHAFO MINE

Iron concentration in the groundwater well (GWC-4D) located at the upstream of the Ahafo mine were higher exceeding the recommended Ghana EPA regulatory limit of 0.1mg/L. The monitoring data ranged between 0.4 ± 0.2 - 1.0 ± 0.7 mg/L and were below the baseline value of 0.7 ± 0.4 mg/L. The monitoring year 2010 recorded value that exceeded the baseline value.

Sampling site GWC-8S (found upstream of the mine) also recorded iron values that exceeded the Ghana EPA limit (0.1 mg/L). The exceedances in iron concentration were not limited to the upstream groundwater wells alone but also the downstream wells (GWC-7D and GWC-3S) recording values that were higher than the Ghana EPA limit (0.1mg/L). Iron is most commonly found in nature in the form of its oxides (Elinder C.G., 1986, Knepper, 1981). The extent to which iron dissolves in ground water depends on the amount of oxygen in the water and to a lesser extent, the degree of acidity. Metals such as iron and aluminium are common in mine drainages; however, in general neither seems to bioaccumulate (Winterbourn *et al.*, 2000).

Mercury concentration of the upstream groundwater wells of the Ahafo mine were generally within the EPA recommended limit of 0.002 mg/L for both GWC-4D and GWC-8S. There were however, increase in mercury concentrations in downstream GWC-3S during the operational years; 2010, 2011 and 2012 compared to the baseline data but these increases were within the regulatory limit. Relatively, there were no deviation in mercury concentrations from both the base line and the operational data at GWC-7D (found downstream). Mercury in groundwater can be due to dissolution of minerals and ores, and industrial effluents. Relatively low levels of mercury (Hg) is mobilized in groundwater than in surface water because, Hg can be attenuated by sorption to clays, iron oxides, and residual soil organic matter (Barringer *et al.*, 2012).

Past agricultural use of mercurial pesticides and atmospheric deposition are two likely sources of Hg in water (Barringer, & Szabo, Z. 2006).

Arsenic concentration of groundwater in the upstream of the mine (GWC-4D) during the operation of the mine and the baseline data were all higher than the tolerable limit of 0.01 mg/l. Barringer *et al.* (2010) posits that, natural fluctuations can affect the fate and transport of arsenic within groundwater systems. Seasonal fluctuations in recharge during periods of high precipitation brings dilution to shallow groundwater, but also transport surficial derived materials to aquifer. Effects of mining on soils and waters in other African countries (Ghana and Zambia) have been studied only recently and arsenic contamination of groundwater has been reported in Ghana (Bowell, 1994; Nakayama *et al.*, 2011; Smedley and Kinniburgh, 2002).

The downstream groundwater wells (GWC-3S and GWC-7D) on the contrary had arsenic values which were within the approved EPA limit. These results are a representation of the existing characteristics of groundwater environment of the study area. Many instances, arsenic concentrations in groundwater that far exceed standards have been reported throughout much of the world (Smedley, 2008) and the number of countries in which groundwater is found to be contaminated by arsenic has increased substantially over the past 80 years (Barringer *et al.*, 2012). Disposal of mining wastes has caused Arsenic contamination of groundwater in numerous places, including; Thailand, Ghana, and Turkey (Gunduz *et al.*, 2010; Smedley and Kinniburgh, 2002; Smedley, 2008).

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The current evaluation of water quality monitoring compliance at Newmont Ghana Gold Ltd Ahafo Mine has revealed that most of the parameters studied generally met the Ghana EPA recommended limits. But notwithstanding that, there were elevated levels of iron both in the surface and ground waters during baseline studies and the operational monitoring period of the Ahafo-Kenyasi mine. These elevated levels of iron exceeded the Ghana EPA approved limit of 0.01mg/l but were comparable with the baseline data. It can be attributed to that fact that iron is naturally abundant metal in the geology of the study area. In view of the findings on iron levels Newmont Ghana gold has not complied with the Ghana EPA limit for the year under review. The operational data is however, compliant with the baseline findings.

Comparatively, some of the groundwaters; thus, GWC-4D and GWC-8S all at upstream of the mine were found to contain some levels of arsenic higher than the Ghana EPA limit of 0.1mg/l but were compliant with the baseline studies. The higher levels of arsenic revealed during the period under review can be attributed to the geology and bedrock formation of the area.

Also, high levels of sulphate were detected in the downstream sampling point (NSW8) during the baseline studies and the operational data which can be attributed to the historical high agricultural practices in the area.

Some of the ground waters especially upstream GWC-8S exhibited slightly acidic behavior with a pH levels ranging between 5.41-5.65 exceeding the Ghana EPA approved limit of 6-9. The lowest pH occurred during the baseline studies.

Constructional activities also affected parameters like the turbidity and the total suspended solids of some of the downstream surface waters.

Mercury levels of the groundwater conformed to the EPA standards, though there were some instances where levels increased above the baseline value.

Generally, Newmont Ghana Gold limited is in compliance with its environmental water monitoring in relation to the baseline studies since the operational data correlated with the baseline data in most of the parameters. However, in comparison with the regulatory limits, some parameters failed to meet the Ghana EPA standard. Some of the parameters especially the pH of some of the groundwater, the sulphates, iron (critical) and arsenic levels were of high concern and could lead to future pollution of Newmont Ghana Gold Ltd Ahafo-Kenyasi catchment area if these levels consistently fails to meet the EPA standards.

6.2 Recommendations

- All monitoring data should be publicly made available in electronic format
- The groundwater, surface water, and discharge monitoring systems should be expanded. Groundwater monitoring wells should be expanded so that a reliable estimate of groundwater elevations and flow directions can be established. More surface water monitoring points are needed upstream and more immediately downstream of mine facilities.
- Thorough research should be conducted to ascertain the cause of high level of iron in the area under study.
- In-depth research must be conducted to find out the cause of acidity in GWC-8S.

- Any surface water and groundwater areas that may be adversely affected by discharges from waste rock piles and the open pit of the mine should be investigated as part of an independent study of the site.
- There should be an in-depth research and experiment on acid rock drainage(ARD) at the upstream groundwater sampling point GWC-8S to mitigate any potential generation of acid mine drainage.

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APPENDIX A:

A1: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE KSW13

	pH	Turbidity	TSS	Nitrate	Sulphate
	Ha: diff	Ha: diff	Ha: diff	Ha: diff	Ha: diff
	$\neq 0$	$\neq 0$	$\neq 0$	$\neq 0$	$\neq 0$
Years	Pr(T > t)	Pr(T > t)	Pr(T > t)	Pr(T > t)	Pr(T > t)
Baseline(2007)					
2008	0.6436	0.0117	0.0805	0.9245	0.0761
2009	0.3047	0.0521	0.0085	0.1416	0.0761
2010	0.8416	0.6522	0.3624	0.6819	0.0761
2011	0.1298	0.7725	0.5848	0.7539	0.9236
2012	0.0376	0.3124	0.3052	0.5512	0.0313

A2: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE KSW13

	Iron	Arsenic	Mercury
	Ha: diff	Ha: diff	Ha: diff
	$\neq 0$	$\neq 0$	$\neq 0$
Years	Pr(T > t)	Pr(T > t)	Pr(T > t)
Baseline(2007)			
2008	0.2254	0.6891	0.1340
2009	0.9139	0.8701	0.2675
2010	0.2253	0.8491	0.0240
2011	0.1430	0.5522	0.00
2012	0.1026	0.5795	0.00

A3: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE KSW16

	pH	Turbidity	TSS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.1226	0.1980	0.3989	0.9667	0.6549
2009	0.6282	0.0766	0.1144	0.9139	0.4637
2010	0.0945	0.0447	0.9560	0.6153	0.4519
2011	0.0347	0.1962	0.9455	0.4341	0.4519
2012	0.2113	0.4713	0.4439	0.6747	0.4519

A4: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE KSW16

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.5094	1.0000	0.0308
2009	0.7672	0.1696	0.2095
2010	0.6706	0.1370	0.2070
2011	0.0751	0.3465	0.0240
2012	0.6168	0.1647	0.0240

A5: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE NSW8

	pH	Turbidity	TSS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.1540	0.1095	0.0453	0.6843	0.4589
2009	0.2156	0.3760	0.1276	0.0887	0.9976
2010	0.3792	0.5148	0.6093	0.0736	0.8848
2011	0.2637	0.6691	0.5198	0.0978	0.2352
2012	0.0161	0.1195	0.2408	0.0259	0.0685

A6: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE NSW8

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.3002	0.1340	0.3446
2009	0.4055	0.0924	0.3652
2010	0.8515	0.0748	0.2641
2011	0.6318	0.3961	0.2511
2012	0.2308	0.0001	0.2511

A7: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE NSW6

	pH	Turbidity	TSS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.8354	0.3290	0.2852	0.5614	0.2302
2009	0.4307	0.2372	0.2919	0.3699	0.2302
2010	0.2753	0.8848	0.8343	0.6336	0.2305
2011	0.6630	0.3622	0.5473	0.2067	0.3737
2012	0.4147	0.9751	0.4883	0.2608	0.2737

A8: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE NSW6

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.3723	0.2142	0.0240
2009	0.0990	0.0000	0.000
2010	0.1580	0.0177	0.0240
2011	0.2986	0.0157	0.000
2012	0.2703	0.1036	0.000

APPENDIX B:

STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT
LEVELS AT 95% CONFIDENCE INTERVAL OF GROUND WATER SAMPLING SITE
GWC 4D

	pH	Conductivity	TDS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.27	0.5616	0.51	0.3272	0.0299
2009	0.15	0.8144	0.13	0.2621	0.0012
2010	0.20	0.9474	0.63	0.2593	0.0183
2011	0.15	0.1846	0.32	0.3022	0.0002
2012	0.09	0.5435	0.53	0.3437	0.0011

B2: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF GROUND WATER
SAMPLING SITE GWC 4D

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.2478	0.4258	0.00
2009	0.9421	0.1451	0.0240
2010	0.4627	0.4954	0.00
2011	0.7761	0.0821	0.00
2012	0.7010	0.0333	0.00

B3: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF GROUND WATER SAMPLING SITE GWC 3S

	pH	Conductivity	TDS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.4823	0.0944	0.0702	0.0697	0.7602
2009	0.2982	0.4781	0.4560	0.2729	0.1142
2010	0.4075	0.0274	0.0106	0.0852	0.6805
2011	0.2474	0.0605	0.0542	0.2039	0.8167
2012	0.1713	0.0344	0.1287	0.3435	0.0026

B4: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE GWC3S

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.0770	0.1340	0.1340
2009	0.2269	0.000	0.0240
2010	0.0745	0.0278	0.00
2011	0.1236	0.4096	0.00
2012	0.1349	0.3980	0.00

B5: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF GROUND WATER SAMPLING SITE GWC7D

	pH	Conductivity	TDS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.6956	0.7414	0.7407	0.1572	0.6566
2009	0.8445	0.2329	0.1815	0.3559	0.8368
2010	0.2798	0.9066	0.9234	0.2804	0.2645
2011	0.0694	0.0064	0.0050	1.0000	0.5520
2012	0.4539	0.0007	0.0005	0.1408	0.2498

B6: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE GWC7D

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.2569	0.3365	0.1340
2009	0.5336	1.0000	0.0240
2010	0.0002	0.2229	0.00
2011	0.1541	0.2229	0.0004
2012	0.4056	0.2828	0.0000

B7: STATISTICAL ANALYSIS (STATA 10) OF THE PHYSICO- CHEMICAL AND NUTRIENT LEVELS AT 95% CONFIDENCE INTERVAL OF GROUND WATER SAMPLING SITE GWC8S

	pH	Conductivity	TDS	Nitrate	Sulphate
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years					
Baseline(2007)					
2008	0.1452	0.8581	0.8444	0.0580	0.3903
2009	0.8103	0.6517	0.9347	0.4172	0.3991
2010	0.7550	0.4773	0.1049	0.0573	0.3559
2011	0.7960	0.5880	0.6019	0.7165	0.3559
2012	0.6746	0.2639	0.4513	0.4971	0.3559

B8: ANALYSIS OF METALS AT 95% CONFIDENCE INTERVAL OF SURFACE WATER SAMPLING SITE GWC8S

	Iron	Arsenic	Mercury
	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)	Ha: diff != 0 Pr(T > t)
Years			
Baseline(2007)			
2008	0.0508	0.5112	0.1340
2009	0.3737	0.6890	0.0240
2010	0.1351	0.3735	0.00
2011	0.0426	0.3541	0.00
2012	0.0263	0.3573	0.00