KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF SCIENCE



FACULTY OF BIOSCIENCE DEPARTMENT OF THEORETICAL AND APPLIED BIOLOGY AND ENVIRONMENTAL SCIENCE

ACID MINE DRAINAGE

EFFECT OF ACID MINE DRAINAGE ON WATER AND SOIL RESOURCES WITHIN THE BOGOSO/PRESTEA MINE RESOURCE. (BOGOSO CONCESSIONAL AREA)

A THESIS SUBMITTED TO THE DEPARTMENT OF APPLIED & THEORITICAL BIOLOGY, FACULTY OF BIOSCIENCE, COLLEGE OF SCIENCE, KWAME NKRUMAH UNIVERSITY OF SCIENCE & TECHNOLOGY, KUMASI IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE. (ENVIRONMENTAL SCIENCE)

BY

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DECLARATION

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DEDICATION

This thesis is dedicated to the entire family of Debrah; Mr. & Mrs. Debrah, Charity, Gifty, Lawrence, Gladys, Leticia, Patrick, Junior Kwame and Roberta. More especially my wife Mrs. Abena Serwaa Afriyie -Debrah

It is also dedicated to the entire children in the communities in mining area whose livelihood depends on the environment.



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ABBREVIATIONS

- **AMD**: Acid Mine Drainage
- **ARD**: Acid Rock Drainage
- AMIC: Australia Mining Industry Country
- UNDESA: United Nation Department of Economic and Social Affairs
- UNEP: Nation Environmental Programme Industry and Environment
- BPGL: Bogoso/ Prestea Gold Limited
- **GSR**: Gold Star Resources
- PGR: Prestea Gold Resources
- **BGL**: Bogoso Gold Limited
- SAP: Structural Adjustment Programme
- MEND: Mine Environmental Neutral Drainage
- **RGW-** Researched Groundwater sampling sites
- **RSW** Researched Surface water sampling sites

SANG CANA

ABSTRACT

Heavy metals contamination (As, Fe, Cu, Zn, Mn and Cd) and other physico-chemical changes (pH, temperature, EC, DO, alkalinity, SO_4^{2-} , free CN) in underground and surface water, and carbonate carbon and sulphate sulfur in soil samples due to the effect of acid mine drainage (AMD) were assessed around Golden Star Resource Mine (Bogoso concession). Underground and surface water samples were collected from seven different sites and soil samples from three different sites within Golden Star Resources Mine (Bogoso concession) between November, 2006 and April, 2007. Atomic Absorption Spectrometry (AAS) was used to determine the heavy metal concentrations whilst the physico-chemical parameters were determined using standard methods. Average total levels of arsenic, iron, copper, zinc, manganese and cadmium were 0.0313, 3.7675, 0.0518, 0.0382, 0.8102 and 0.008 (mg/l) and average dissolved levels were 0.0104, 0.6737, 0.0356, 0.0256, 0.6998 and < 0.005 (mg/l) in surface water respectively. In underground water, average total levels of arsenic, iron, copper, zinc, manganese and cadmium were 0.0058, 5.8220, 0.1676, 0.0339, 0.2521 and 0.0065 (mg/l) whilst average dissolved levels were 0.0050, 4.3496, 0.1219, 0.0215, 0.2239 and 0.006 (mg/l) respectively. Iron and manganese levels in surface and underground waters exceeded Ghana Environmental Protection Agency standards for mining effluent. Differences in pH, temperature, E.C. alkalinity, SO_4^{2-} , iron, Cu, Zn and Mn levels in the seven water samples were statistically significant (p \leq 0.05). Surface water samples recorded values of EC and SO₄²⁻ ions higher than in underground water samples which exceeded acceptable limits. Carbon and sulfur in soil samples varied from 0.1922 to 1.8247 % and 0.0237 to 1.5830 % respectively. The results of the study showed high impact of AMD on water quality in Bogoso mining area. This effect could be attributed to the release of metals as a result of oxidation of metal-bearing sulphides in the mine dumps and pits at the selected sampling sites. The study showed that addition of lime as a treatment option has not been effective. Hence new conventional methods should be considered in the treatment of acidic water (AMD) in the mining area.

CHAPTER ONE

1.0 INTRODUCTION

Majority of materials and metals extracted from the earth by mining occur naturally as sulphide ores or are associated with sulphide minerals. During the extraction process, those sulphides which are not part of the ore material are dumped in waste rock dumps with other rocks. Sulphides containing valuable material (either metals, or in the case of a pyrite mine, sulphide itself) are processed, and the residue dumped in slimes (tailings) dams. The tailings contain large amounts of sulphide, which are either unwanted or were not extracted (Lupankwa *et al.*, 2004a). This results in more of the sulphides being exposed to the surface environment, where they are unstable. Thus spontaneous chemical weathering takes place, releasing acid, metals and sulphate into surface water and groundwater (Bigham and Nordstrom, 2000). This process, whereby sulphide minerals break down in the presence of oxygen water and catalyzing bacteria, is known as acid mine drainage (AMD).

The oxidation of sulphidic mine waste, and the consequent release of acid drainage is one of the main strategic environmental issues facing the mining industry as it exposes large amounts of pyrite and other sulphides to the effects of water and oxygen. Mining operations can greatly accelerate the oxidation process by providing flow paths that allow the release of levels of pollutants in surface and groundwater at rates far greater than the downstream environment can sustain without significant ecological effects (AMIC, 1994).

Acid mine drainage thus includes all processes whereby the inadvertent oxidation of sulphides following mining leads to the release of pollutants including seepages from waste rock, tailings, underground workings and open pit wall where the contaminants are produced by the oxidation of sulphides (AMIC, 1994).

1

Australia has a number of historic closed mines where acid mine drainage caused and, in many cases, still causes major pollution problems. Examples include the Rum Jungle mine site in the Northern Territory, Captains Flat mine sites in New South Wales and Brukunga in South Australia. Other well known sites where acid drainage is a major problem are the mountain Lyell in Tasmania and the mountain Morgan mine in Queensland (AMIC, 1994).

Once started, the release of pollutants from the oxidation of sulphides is a persistent and potentially severe source of pollution from mine sites. It is the long – term nature of acid mine drainage which creates the environmental problems for mine operators. During mine operations, treatment of polluted surface waters is usually a minor addition to mining cost. However, acid drainage can continue to be a major source of pollution long after mining ceases (AMIC, 1994).

Acid mine and acid rock drainage can cause major long - term environmental problems at many types of mine sites if appropriate management strategies are not adopted. Acid mine drainage is a potential problem at many base metal mines where recoverable metals occur as metal sulphides, at some coal mines where pyretic coal seams are mined and at some uranium and gold mines where the ore is associated with sulphidic materials. The ubiquitous nature of pyrite in many valuable mineral deposits means that control of sulphide oxidation is important if mine owners are to avoid long - term liability when the site is released at the end of mining (AMIC, 1994).

Mining in Zimbabwe most often takes place in the agriculturally productive source areas of trans boundary river systems. This gives rise to conflicts between the mines, which need to dispose of large volumes of waste and wastewater on one hand, and the water quality needs of the environment, agriculture and other water users (Ashton *et al.*, 2001; Lupankwa *et al.*, 2004a; 2004b; Musiwa *et al.*, 2004; Ravengai *et al.*, 2004a; 2004b).

Mining can be a potential source of wealth in developing countries, a point emphasized in the 1990s by the adoption of new, or modified mining policies and legislation in more than 75 countries worldwide. These changes have, for the most part, been undertaken to promote foreign investment and the creation of stable fiscal and regulatory practice attractive to the international mining community. But in addition to generating wealth, mining can also be a major source of degradation to the physical and social environment unless it is properly managed (UNDESA and UNEP, 1994).

Mining can have adverse effect on surrounding surface and groundwater if protection measures are not exercised. The result can be unnaturally high concentrations of some chemical elements over a significantly large area of surface or subsurface. Gold mining releases approximately twenty toxic chemicals, of which 85% is said to be managed on site (Morrison, 1992). In well regulated mines, hydrologists and geologists take careful measures to mitigate any type of water contamination that is caused by mines. In America, mining operations must under federal and state law, meet standards for protecting surface and groundwater from contamination, including acid mine drainage (AMD) (Hedin *et al.*, 1994). To mitigate these problems water is continuously monitored at gold mines. The five principal technologies used to control water flow at mine sites are: Diversion systems, Containment ponds, Groundwater pumping systems, Subsurface drainage systems and Subsurface barriers. In the case of AMD, contaminated water is generally pumped to a treatment facility that neutralizes the contaminants (Baird, 1995). Golden Star Resources (Bogoso/Prestea) Limited (BPGL) a gold mining company in Ghana owns and operates Bogoso/Prestea an open pit mine which is located in the Wassa West District of the Western Region of Ghana. BPGL is a 90% owned subsidiary of Golden Star Resource Limited (GSR) with the Ghanaian Government holding the remaining 10 % (GSR Technical Report, 2004). The gold ore found at Bogoso/Prestea is made up of the metal and the combined forms of pyrites (FeS₂) and arsenopyrite (FeAsS) which is called sulphur - base minerals and gangue materials. These sulphide base minerals when exposed to air and water are oxidized to sulphate and hydrogen ion or sulphuric acid which leads to Acid Mine Drainage (AMD) (Kesse, 1985).

1.1 PROBLEM OF STATEMENT

There are a number of major environmental problems caused by acid mine drainage. It disrupts growth and reproduction of aquatic plants and animals, diminishes valued recreational fish species, degrades outdoor recreation and tourism, contaminates surface and groundwater drinking supplies, and causes acid corrosion of infrastructure like wastewater pipes (Baird, 1995).

Mine drainage is a complex of elements that interact to cause a variety of effects on aquatic life that are difficult to separate into individual components. Toxicity is dependent on discharge volume, pH, total acidity and concentration of dissolved and total metals. pH is the most critical component, since the lower the pH, the more severe the potential effects of mine drainage on aquatic life. The overall effect of mine drainage is also dependent on the flow (dilution rate), pH, and alkalinity or buffering capacity of the receiving stream. The higher the concentration of bicarbonate and carbonate ions in the receiving stream, the higher the buffering capacity and the greater the protection of aquatic life from adverse effects of acid mine drainage (Kimmel, 1983). Alkaline mine drainage with low concentrations of metals may have little discernible effect on receiving streams. Acid mine drainage with elevated metals concentrations discharging into headwater streams or lightly buffered streams can have a devastating effect on the aquatic life.

Communities within the Bogoso/Prestea Mines continue to complain about the negative impact of mining on their water and soil resources. This includes the colorization of most surface water and low yield production of crops on their farms as a result of chemicals leach onto the soil and most lands taken by the company for the construction of tailing dams and other activities. Communities within the Bogoso/Prestea concession complain of the inability to use more especially surface water resource for both domestic activity and farming where it serves as drinking water for livestock or irrigation. Fish farming have become a risky business due to incidence of cyanide spillage which has the ability to kill aquatic life.



1.2 GENERAL OBJECTIVES OF RESEARCH

This study investigated the effects of acid mine drainage on selected soil, surface and groundwater resources in the Bogoso Mine concession area.

1.3 SPECIFIC OBJECTIVES

- To determine concentrations of some heavy metals like Arsenic, Iron, Copper, Zinc, Manganese and Cadmium and other acid mine drainage parameters such as pH, Conductivity, Temperature, Alkalinity, Dissolved Oxygen, Free Cyanide and Sulphate in surface water and underground water resources.
- To compare concentrations of the heavy metals which include Arsenic, Iron, Copper, Zinc, Manganese and Cadmium and other acid mine drainage parameters such as pH, Conductivity, Temperature, Alkalinity, Dissolved Oxygen, Free Cyanide and Sulphate at both the upstream and downstream sites in the mining area.
- Determine the effect of acid mine drainage on soil resources using the principle of acid /base accounting.
- To compare the upstream and downstream activity parameters with the GEPA and other world international standards.
- To make recommendations based on the information collected to improve the understanding of acid mine drainage in Ghana.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 ACIDIC MINE DRAINAGE

Acidic leachate from waste rock and tailings from metallic mining and beneficiation of sulfide-rich ores, often referred to as acid mine drainage (AMD), poses a threat to groundwater and surface water at mine sites worldwide. AMD is formed when sulfide-rich mine wastes oxidize in the presence of water and is characterized by low pH and elevated concentrations of metals, some of which are toxic. The most common elements found in AMD from metallic mine wastes are sulfur, iron, copper, zinc, silver, gold, cadmium, arsenic, and uranium (Gustafson, 1997).

Acidic drainage has been identified as the largest environmental liability facing the mining industry and to a lesser extents the public through abandoned mines. This liability is estimated to be over billions of dollars, depending on the sophistication of treatment and control technology used. There are numerous examples throughout the world where elevated concentrations of metals in mine drainage have adverse effects on aquatic resource and prevent the reclamation of mined land. Metals leaching problems can occur over an entire range of pH conditions, but are commonly associated with acid drainage (MEND, 2000).

The primary requirements for acid generation are:

- \succ sulfide minerals in the overburden
- ➢ water or a humid atmosphere
- \blacktriangleright an oxidant (usually oxygen in the form of O₂)

Acid drainage may originate from a variety of natural and man made source. Potential natural source can include

- Run off from rock faces and
- ➢ Groundwater seeps

Man-made source can include

- Mines and associated facilities
- Road cuts and fill
- > Quarries and
- > Other construction fills.

Waste rock dumps from mining activities

- ➢ Mill tailings
- Ore tailings
- Effluent from mining operations
- Ore piles from heap operations which eventually drain into streams and bore holes in mining environment (Williams *et al.*, 1982).

Mines are the major source of acidic drainage primarily because sulphide minerals are concentrated in geological environment containing ore deposit. In addition, rock removal and processing occurs on a large scale and the methods involved (from blasting to processing) result in particle size reduction.

At active mine sites (and many inactive mine sites), systems are operated to collect and treat effluents and seepage and prevent downstream environmental impact. In some instances, acid generation may persist for hundreds of years following mine closure. The operation of treatment plants for periods of time is clearly not desirable. In addition, conventional water treatment technologies produce sludge's with low solid content. In some extreme case, the volume of sludge produced from the acidic drainage effluent can exceed the volume of tailings and/or waste rock storage capacity could become an issue for decommissioned mine site.

Wastes that have the potential to generate acid as a result of metal mining activity include mined material such as spent ore from heap leach operations, tailings, and waste rock units, including overburden material. While not wastes or waste management units, pit walls in the case of surface mining operations, and the underground workings associated with underground mines and sub grade ore piles, also have the potential to generate Acid Rock Drainage.

As mineralogy and size variables change, the ability to accurately predict the acid potential becomes quite difficult (Brodie *et al.*, 1991).Waste rock piles and sub grade ore piles, when left onsite, are both characterized by wide variation in mineralogy and particle size. Changes in these variables appear to influence drainage water quality (Doepker *et al.*, 1993). Coarse grain material allows air circulation; however, fine grain material exposes more surface area to oxidation (Ferguson and Erickson, 1998).The results reflect the diurnal and seasonal fluctuations in drainage quality as well as variation in mineralogy and particle size common to waste rock piles. In contrast, drainage from tailing impoundments is more likely to carry a more uniform contaminant load due to their more uniform mineralogy and texture as showed in Table 2.0.

Table 2.0 Comparison of Acid Rock Drainage Factors in Waste Rock Piles and

Acid Generation	Waste Rock Piles	Tailings Impoundment
Factors Affecting		
Sulphide Source	• Variable in concentration and	• Conditions uniform, often with
	location.	very high sulphide content.
	• Conditions may vary from sulphide	
	rich to basic over short distances.	T
Particle Size	• Average rock size typically greater	• Tailings may be 100% less than
	than 20 cm (but highly variable).	0.2 mm.
pH Variation	• Highly variable conditions over	• Fairly uniform conditions with a
	short distances.	few major horizontal zones.
Initiation Of	• Usually starts immediately after first	• Usually starts after tailings
Rapid Oxidation	rock is placed (in "trigger" spots).	placement ceases at end of mine
		life.
Oxygen Entry	• pid along preferential flow paths.	• Seepage slow and uniform.
	• Seasonal variations in flow path	• Reduced flow path variation and
	"flushes" out stored products resulting	stored product "flushing."
	in concentration peaks.	
ARD Releases	• Large infiltration resulting in large	• Large early top surface ARD
	seepage from toe and to groundwater.	runoff.
	• Rapid release following generation,	• Lower infiltration.
	sometimes with both neutralized and	• Gradual transition in seeps from
	acid ARD seeps.	process water to neutralized ARD
		to low pH ARD

Tailings Impoundments

Source: (Brodie et al., 1991).

Compares acid rock drainage factors of waste rock piles and tailings impoundments. In examining this table, it is important to note that diffusion of oxygen into water is slow and, therefore, oxidation of iron sulfide is inhibited until the water level drops, which can occur periodically or seasonally in some cases (Brodie *et al.*, 1991).

2.2 OXIDATION OF METAL SULFIDES

Acid is generated at mine sites when metal sulfide minerals are oxidized. Metal sulfide minerals are present in the host rock associated with most types of metal mining activity. Prior to mining, oxidation of these minerals and the formation of sulfuric acid is a function of natural weathering processes. The oxidation of undisturbed ore bodies followed by release of acid and mobilization of metals is slow. Discharge from such deposits poses little threat to receiving aquatic ecosystems.

Extraction and beneficiation operations associated with mining activity increase the rate of these same chemical reactions by exposing large volumes of sulfide rock material with increased surface area to air and water.

The oxidation of sulfide minerals consists of several reactions. Each sulfide mineral has a different oxidation rate. For example, marcasite and framboidal pyrite will oxidize quickly while crystalline pyrite will oxidize slowly (Manahan and Stanley, 1991). For discussion purposes, the oxidation of pyrite (FeS_2) will be examined. Other sulfide minerals are identified in Table 2.1.

Mineral	Composition
Pyrite	FeS ₂
Marcasite	FeS2
Chalcopyrite	CuFeS ₂
Chalcocite	Cu ₂ S
Sphalerite	ZnS
Galena	PbS
Millerite	NiS

Table 2.1 Partial List of Sulfide Minerals

Pyrrhotite	Fe _{1-x} S (where 0 <x<0.2)< th=""></x<0.2)<>
Arsenopyrite	FeAsS
Cinnabar	HgS

(Source: Ferguson and Erickson, 1988)

2.3 THE CHEMISTRY AND BIOLOGY OF ACID GENERATION PROCESS FROM SULPHIDE MINERAL

Acid drainage can and does occur naturally at specific sites. It happens when sulfide minerals are exposed to weathering and react with water and oxygen to produce sulfuric acid, which is carried away in runoff. This process is called acid rock drainage (ARD). In mining, however, the scale and impact of the acid generation (here usually called acid mine drainage) can be pushed far beyond natural limits.

Acid generation results from exposure to air and water. This means that the more surface area of rock exposed, the greater the amount of acid. During the mining process, hundreds, sometimes thousands of tons of rock are dug up and crushed each day. The acid then leaches through the ground and releases heavy metals such as lead, zinc, copper, arsenic, selenium, mercury and cadmium (MEND, 2000).

Base metal, precious metal, uranium diamond and coal mines often contain sulphide minerals in the mined ore and the surrounding rock. When these sulphide minerals, particularly pyrite and pyrrholite, are exposed to oxygen and water, they oxidize and the drainage may become acidic when sufficient acid-neutralizing minerals such as caloite are present (MEND, 2000).

The acidic water may contain elevated concentrations of metals and salts. These can include typical major rock constituent (Ca, Mg, K, Na, Al, Fe, Mn) as well as trace heavy element such as Zn, Cu, Cd, Pb, Co, Ni. As, Sb and Se. Rainfall flush leachate from the waste sites (MEND, 2000).

Naturally occurring alkalinity, such as carbonate mineral and carbonate ions in solution may partially or completely neutralize acidity in site. The resulting leachate is non-acidic with very low iron concentrations. (Under anoxic conditions Fe will remain in solution in its reduced state) but can contain elevated concentrations of sulphate, calcium and magnesium (MEND, 2000).

Neutralization by reactions with acid consuming minerals (carbonate minerals in particular may result in low concentrations of dissolved metals due to the low solubility of metal carbonates, basic carbonate hydroxides and oxy hydroxides at pH 6 – 7). The primary factors which determine the rate of acid generation are:

- ≽ pH
- ➤ temperature
- > oxygen content of the gas phase, if saturation is less than 100%
- > oxygen concentration in the water phase
- degree of saturation with water
- \blacktriangleright chemical activity of Fe³⁺
- surface area of exposed metal sulfide
- > chemical activation energy required to initiate acid generation
- ▶ Biological activity (such as iron oxidizing bacteria) (MEND, 2000).

2.4 AMD Chemistry

There are four commonly accepted chemical reactions that represent the chemistry of pyrite weathering to form AMD. An **overall** summary reaction (equation 1) is as follows:

4 FeS₂ + 15 O₂ + 14 H₂O
$$\rightarrow$$
 4 Fe (OH) $_3 \downarrow$ + 8 H₂SO₄..... (equation 1)

Pyrite + Oxygen + Water
$$\rightarrow$$
 "Yellow boy" + Sulfuric Acid

The first reaction in the weathering of pyrite includes the oxidation of pyrite by oxygen. Sulfur is oxidized to sulfate and ferrous iron is released. In this step, $S_2^{2^2}$ is oxidized in the presence of H₂O to form hydrogen ions and sulfate, the dissolution products of sulfuric acid in solution. Soluble Fe²⁺ is also free to react further. Oxidation of the ferrous ion to ferric ion occurs more slowly at lower pH values. This reaction generates two moles of acidity for each mole of pyrite oxidized as shown in equation 2.

$$2 \text{ FeS}_2 + 7 \text{ O}_2 + 2 \text{ H}_2 \text{O} \rightarrow 2 \text{ Fe}^{2+} + 4 \text{ SO}_4^{2-} + 4 \text{ H}....2$$

Pyrite + Oxygen + Water → Ferrous Iron + Sulfate + Acidity

The second reaction involves the conversion of ferrous iron to ferric iron. The conversion of ferrous iron to ferric iron consumes one mole of acidity. Certain bacteria increase the rate of oxidation from ferrous to ferric iron. This reaction rate is pH dependent with the reaction proceeding slowly under acidic conditions (pH 2 - 3) with no bacteria present and several orders of magnitude faster at pH values near 5 (Rate determining step) in equation 3.

$$4 \text{ Fe}^{2+} + \text{O}_2 + 4 \text{ H}^+ \rightarrow 4 \text{ Fe}^{3+} + 2 \text{ H}_2\text{O}.....3$$

Ferrous Iron + Oxygen + Acidity → Ferric Iron + Water

The third reaction which may occur is the hydrolysis of iron. Hydrolysis is a reaction which splits the water molecule. Three moles of acidity are generated as a byproduct. Many metal ions are capable of undergoing hydrolysis. The formation of ferric hydroxide precipitate (solid) is pH dependant. Solids form if the pH is above about 3.5 but below pH 3.5 little or no solids will precipitate as showed in equation 4.

$$4 \operatorname{Fe}^{3+} + 12 \operatorname{H}_2 \operatorname{O} \rightarrow 4 \operatorname{Fe} (\operatorname{OH})_3 \downarrow + 12 \operatorname{H}^+ \dots \dots 4$$

Ferric Iron + Water \rightarrow Ferric Hydroxide (yellow boy) + Acidity

The fourth reaction is the oxidation of additional pyrite by ferric iron. The ferric iron is generated in reaction steps 1 and 2. This is the cyclic and self propagating part of the overall reaction and takes place very rapidly and continues until either ferric iron or pyrite is depleted. At pH levels between 3.5 and 4.5, iron oxidation is catalyzed by a variety of *Metallogenium*, a filamentous bacterium. Below a pH of 3.5 the same reaction is catalyzed by the iron bacterium *Thiobacillus ferroxidans*. Other bacteria capable of catalyzing the reaction are presented in Table 2.3. If the ferric ion is formed in contact with pyrite the following reaction can occur, dissolving the pyrite. Note that in this reaction iron is the oxidizing agent, not oxygen as indicated in equation 5.

$$\text{FeS}_2 + 14 \text{ Fe}^{3+} + 8 \text{ H}_2\text{O} \rightarrow 15 \text{ Fe}^{2+} + 2 \text{ SO}_4^{2-} + 16 \text{ H}^+.....5$$

Pyrite + Ferric Iron + Water \rightarrow Ferrous Iron + Sulfate + Acidity

This reaction generates more acid. The dissolution of pyrite by ferric iron (Fe $^{3+}$), in conjunction with the oxidation of the ferrous constitutes a cycle of dissolution of pyrite. Ferric iron precipitates as hydrated iron oxide as indicated in the equation 6 below.

$$\operatorname{Fe}^{3+} + 3\operatorname{H}_2\operatorname{O} \rightarrow \operatorname{Fe}(\operatorname{OH})_3(s) + 3\operatorname{H}^+ \dots 6$$

Ferric Iron + Water \rightarrow Ferrous Hydroxide (yellow boy) + Acidity

Fe (OH) $_3$ precipitates and is identifiable as the deposit of amorphous, yellow, orange, or red deposit on streams bottom ("yellow boy") (Brodie *et al.*, 1991).

Microorganism	pН	Temp. ° C	Aerobic	Nutrition
Thiobacillus thioparus	4.5-10	10-37	+	autotrophic
T. ferrooxidans	0.5-6.0	15-25	- + I	"
T. thiooxidans	0.5-6.0	10-37	+	"
T. neapolitanus	3.0-8.5	8-37		"
T. denitrificans	4.0-9 <mark>.5</mark>	10-37	+	"
T. novellus	5.0-9.2	25-35	+	"
T. intermedius	1.9-7.0	25-35	+	"
T. perometabolis	2.8-6.8	25-35	177	"
Sulfolobus acidocalderius	2.0-5.0	55-85	S+	"
Desulfovibrio desulfuricans	5.0-9.0	10-45		heterotrophic

 Table 2.2. Sulfide Ore Bacteria and Their Growth Conditions

Source: (Thompson, 1988)

2.5 Source of Acid and Contributing Factors

The potential for a mine to generate acid and release contaminants is dependent on many factors and is site specific. Ferguson and Erickson, 1988 identified primary, secondary, and tertiary factors that control acid drainage. These factors provide a convenient structure for organizing the discussion of acid formation in the mining environment. Primary factors involve production of the acid, such as the oxidation reactions. Secondary factors act to control the products of the oxidation reaction, such as reactions with other minerals that

consume acid. Secondary factors may either neutralize acid or react with other minerals. Tertiary factors refer to the physical aspects of the waste management unit (e.g., pit walls, waste rock piles, or tailings impoundments) that influence the oxidation reaction, migration of the acid, and consumption. Other downstream factors change the character of the drainage by chemical reaction or dilution (Ferguson and Erickson, 1988).

Primary factors of acid generation include sulfide minerals, water, oxygen, ferric iron, bacteria to catalyze the oxidation reaction, and generated heat. Some sulfide minerals are more easily oxidized (e.g., framboidal pyrite, marcasite and pyrrhotite) and hence, may have a greater impact on timing and magnitude during acid prediction analysis compared to other metal sulfides. Also important is the physical occurrence of the sulfide mineral. Well crystallized (euhedral) minerals will have smaller exposed surface areas than those that are disseminated (Ferguson and Erickson, 1988).

Both water and oxygen are necessary to generate acid drainage. Water serves as both a reactant and a medium for bacteria in the oxidation process. Water also transports the oxidation products. A ready supply of atmospheric oxygen is required to drive the oxidation reaction. Oxygen is particularly important to maintain the rapid bacterially catalyzed oxidation at pH values below 3.5. Oxidation of sulfides is significantly reduced when the concentration of oxygen in the pore spaces of mining waste units is less than 1 or 2 percent. Different bacteria are better suited to different pH levels and other edaphic factors (edaphic factors pertain to the chemical and physical characteristics of the soil and water environments). The type of bacteria and their population sizes change as their growth conditions are optimized (Ferguson and Erickson, 1988). Table 2.3 identifies some of the bacteria involved in catalyzing the oxidation reactions and their growth conditions. The oxidation reaction is exothermic, with the potential to generate a large amount of heat, and therefore thermal gradients within the unit. Heat from the reaction is dissipated by thermal conduction or convection.

Research by Lu and Zhang, 1994 on waste rock using stability analysis indicates that convective flow can occur because of the high porosity of the material. Convection cells formed in waste rock would draw in atmospheric air and continue to drive the oxidation reaction. Convection gas flow due to oxidation of sulfide minerals depends on the maximum temperature in the waste rock. The maximum temperature depends on ambient atmospheric temperature, strength of the heat source and the nature of the upper boundary. If the sulfide waste is concentrated in one area, as is the case with encapsulation, the heat source may be very strong (Lu and Zhang, 1994).

Secondary factors act to either neutralize the acid produced by oxidation of sulfides or may change the effluent character by adding metals ions mobilized by residual acid. Neutralization of acid by the alkalinity released when acid reacts with carbonate minerals is an important means of moderating acid production. The most common neutralizing minerals are calcite and dolomite. Products from the oxidation reaction (hydrogen ions, metal ions, etc.) may also react with other non-neutralizing constituents. Possible reactions include ion exchange on clay particles, gypsum precipitation, and dissolution of other minerals. Dissolution of other minerals contributes to the contaminant load in the acid drainage. Examples of metals occurring in the dissolved load include aluminum, manganese, copper, lead, zinc and others (Ferguson and Erickson, 1988).

Some of the tertiary factors affecting acid drainage are the physical characteristics of the material, how acid generating and acid neutralizing materials are placed, waste, and the hydrologic regime in the vicinity. The physical nature of the material, such as particle size, permeability, and physical weathering characteristics, is important to the acid generation potential. Particle size is a fundamental concern since it affects the surface area exposed to weathering and oxidation. Surface area is inversely proportional to particle size. Very coarse grain material, as is found in waste dumps, exposes less surface area but may allow air and water to penetrate deeper into the unit, exposing more material to oxidation and ultimately producing more acid. Air circulation in coarse material is aided by wind, changes in barometric pressure, and possibly convective gas flow caused by heat generated by the oxidation reaction. In contrast, fine-grain material may retard air and very fine material may limit water flow; however, finer grains expose more surface area to oxidation. The relationships between particle size, surface area, and oxidation play a prominent role in acid prediction methods. As materials weather with time, particle size is reduced, exposing more surface area and changing physical characteristics of the unit. Though difficult to weigh, each of these factors influences the potential for acid generation and are therefore important considerations for the long-term (Doepker et al., 1993).

The hydrology of the area surrounding mine workings and waste units is also important in the analysis of acid generation potential. When acid generating material occurs below the water table, the slow diffusion of oxygen in water retards acid production. This is reflected in the portion of pits or underground workings located below the water table. Where mine walls and underground workings extend above the water table, the flow of water and oxygen in joints may be a source of acid. A similar relationship is evident with tailings, which are typically fine grained and disposed of subaqueously; the slow diffusion of oxygen inhibits formation of acid. However, since tailings are placed in either raised or valley impoundments, they are likely to remain saturated for only a limited period of time during mine operation. Following mine closure, the free water surface in the impoundment may be drawn down substantially, favoring AMD conditions (Ferguson and Erickson, 1998).

2.6 DURATION

The lag time for acid drainage to appear (if at all) is controlled by the concentration and reactivity of the iron sulphides and the availability of carbonate minerals. Acid may be generated and released by high sulphur waste having small amounts of carbonate minerals a few days after exposure. Low sulphur (< 2%) wastes with some carbonate may not release acid for years and decades.

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Once acidic oxidation of iron sulphide minerals is initiated the rate tends to increase until a peak is reached. The general trends are for a long term decrease in acidity release. As the readily available mineral-grains are consumed, the reactive surface shrinks and oxidation product coatings limit reactivity. The rate of decease is determined by numerous factors but mainly the reactivity of the sulphide minerals, the size of particles and the availability of reactants (i.e. oxygen and other oxidants) (MEND, 2000).

2.7 SEASONAL EFFECT

Under all climatic regimes release of acidic is controlled, to varying degrees by seasonal precipitation patterns; the following is observed,

- During dry spells, base flow conditions develop. A small proportion of the reactive surfaces are leached which allows oxidation products to build up in unleached section.
- As infiltration increases (due to rainfall) a greater degree of leaching may occur due to rinsing of greater reactive surface areas. The contaminant load and usually the concentration increase.
- As wet conditions persist, the load leached decreases due to removal of acid products and flow are diluted resulting in lower acid concentrations and
- When dry conditions are reestablished, loads may be similar or lower than wet condition but concentrations may increase (MEND, 2000).

2.8 MINING IN GHANA

The resurgence in the mining industry in Ghana since 1989 cannot be considered an isolated phenomenon. It is driven by the global paradigm which emphasizes private sector-led development as the engine of economic recovery in developing countries. This is indeed the thrust of the structural adjustment programme (SAP) prescribed for such developing countries by the World Bank and allied institutions since the early 1980s. In these economic programmes, African countries with important mining sectors were obliged to shift their policy emphasis towards a primary objective of maximizing tax revenue from mining over the long term (which remains largely a mirage), rather than pursuing other economic or political objectives such as control of resources or enhancement of employment

(World Bank, 1992).

Many of the 16 countries identified by the Bank to be given priority for exploration and private mining investment were from sub-Saharan Africa, obviously because the region is an important supplier of a variety of minerals to the world. It accounts for about 8 % of world mine production. It holds more than 10 % market share in six minerals - bauxite, cobalt, manganese, rutile and uranium - and a 37 % share of world diamond production.

By the close of 1999, nearly all African countries, some of them without known mineral resources, had either modified their minerals codes or introduced them where they did not exist before. Ghana, long regarded as the African trailblazer, was an obvious laboratory for these reforms. After all, a comparative geological ranking of African countries placed Ghana third after South Africa and Zimbabwe (Nyanten, 1997).

The historical importance of mining in the economic development of Ghana is considerable and well documented, with the country's colonial name Gold Coast reflecting the importance of the mining sector. Gold dominates the mining sector and Ghana is Africa's second most important producer of gold after South Africa, the third largest producer of manganese and aluminum and a significant producer of bauxite and diamonds (Coakley, 1991). In addition, inventories of iron, limestone, kaolin, salt and other industrial mineral resources exist but are not exploited on a large scale.

Despite this boom, there is growing unease with regard to the real benefits accruing to the ordinary Ghanaian in the mining communities and to the country as a whole, in the light of the extremely generous fiscal and other incentives given to mining companies under the mining sector reforms. Ghana's structural adjustment programme generally generated considerable social costs and had considerable negative impact especially on the most vulnerable segments of the society (the rural poor, women and children) (World Bank, 1992).

It has been suggested that a thorough cost/benefit analysis of the resurgent mining sector would probably return a negative figure. This is because of such factors as the high level of fiscal incentives enjoyed by mining companies and the high level of foreign exchange earnings they are allowed to retain in offshore accounts. Other relevant factors include the negative environmental impact of mining and the growing redundancies associated with the privatization of state-owned mining companies. Thus, the growing incidence of conflict between mining communities and their chiefs on one hand and mining companies on the other hand echoes the growing disquiet about the effects of the mining sector-led structural adjustment programme on the population (World Bank, 1992).

2.9 IMPACT OF MINING ON THE AREA

Since mining projects are usually located in remote sites, mining companies have had to invest in considerable physical and social infrastructure such as roads, schools, libraries hospitals, electricity and water supplies. Communities within mine locations have generally been beneficiaries of some of these facilities. At the same time, these communities have been victims of air and water pollution as well as other forms of environmental degradation resulting from mining operations. Mining also often requires a considerable degree of land alienation. Thus, while mining projects generally have weak links with the rest of a host national economy, they can have a decisive impact on the communities in which or near which the mines are located (Graham, 1982).

2.10 ENVIRONMENTAL AND HEALTH IMPACT

In most parts of Bogoso, the environment is undergoing rapid degradation and its immense economic value is diminishing from year to year, due mainly to the heavy concentration of mining activities in the area. Agricultural lands are not only generally degraded, but the decrease in land for agricultural production has also led to a shortening of the fallow period from 10-15 years to 2-3 years. The traditional bush fallow system, which adequately recycled substantial amounts of nutrients and made the next cycle productive, can no longer be practiced due to inadequacy of land. Large-scale mining activities generally continue to reduce the vegetation of the area to levels that are destructive to biological diversity (Akabza and Darimani, 2001).

The principal elements of the environment, land, water and air have been severely impacted by mining operations. The continued viability of these elements to support the well-being and development of the rural populations in the Bogoso area is currently in doubt (Tsikata, 1997).

2.10.1 Degradation of Land and Vegetation

Considerable areas of land and vegetation in Bogoso have been cleared to accommodate surface mining activities. Currently, surface mining concessions have taken over 30% of the total land area of Bogoso. It is estimated that at the close of mining a company would use 30-35% of its total concession space for activities such as sitting of mines, heap leach facilities, tailings dump and open pits, mine camps, roads, and resettlement for displaced communities. This has significant adverse impact on the land and vegetation, the main sources of livelihood of the people. There is already a scramble for farmlands in Dumasi (Tsikata, (1997).

The deforestation that has resulted from surface mining has long-term effects even when the soil is replaced and trees are planted after mine decommissioning. The new species that might be introduced have the potential to influence the composition of the topsoil and subsequently determine soil fertility and fallow duration for certain crops. In addition to erosion when surface vegetation is destroyed, there is deterioration in the viability of the land for agricultural purposes and loss of habitat for birds and other animals. This has culminated in the destruction of the luxuriant vegetation, biodiversity, cultural sites and water bodies (Akabza and Darimani, 2001).

2.10.2 Water Pollution

Many mines have an active programme to lower the water table or divert major watercourses away from the mines. This exercise has disruptive consequences for the quality and availability of surface and ground water. The concentration of mining operations in Bogoso has been a major source of both surface and groundwater pollution.

Four main problems of water pollution have been noticed in Bogoso mining areas. These are chemical pollution of ground water and streams, siltation through increased sediment load, increased faecal matter and dewatering effects (Bird, 1994).

2.10.3 Chemical Pollution

Various chemicals such as cyanide and mercury are used during ore processing. These chemicals constitute the major pollutants of surface and ground water. Chemical pollution
could also occur through the misuse, mishandling and poor storage of explosives. Sulphur dioxide fumes from roasting ores could also generate extensive chemical pollution. In addition to chemical pollution, heavy metals from mining operations contribute to water pollution. The presence of such heavy metals above a certain threshold can be injurious to human health and the environment, particularly aquatic life (Abugre and Akabza, 1998).

The main concern of the communities has been potential cyanide pollution of surface and ground water resources by large-scale surface mining operations and mercury contamination from small-scale and illegal (galamsay) mining activities. The levels of pollution and the poor water yield from the new water sources, coupled with the complaints from the communities, are ample demonstration that the affected communities had marginal input in the decisions on where to site these water facilities. It also suggests that the concentration of mining activities in the area has worsened the living conditions of the people. The pollution also weakens the ability of the stream to support aquatic life and has denied the people access to clean water. The situation has become unbearable to the extent that many of the communities within the concession area of BPGL are reluctantly requesting relocation (Abugre and Akadza, 1998).

Ironically, national mining policies have not been helpful to the communities in this disaster. Also, the incident did not receive significant media coverage. This is an indication of the powerful, mining sector lobby and the extent to which the concentration of mining operations in the Bogoso area has deepened the plight of the people (Akabza, 2000).

2.10.4 Dewatering Effects

Mining has active dewatering effects. Apart from consuming a huge amount of water, extensive excavation of large tracts of land and the piling of large mounds of earth along watercourses remove the source of water recharge for groundwater sources and ultimately reverse the direction of flow of ground water, causing active dewatering. A number of boreholes, hand-dug wells and streams in the area have either become unproductive or now provide less water. It was observed during the survey that many of the boreholes and hand-dug wells in the area -- including those provided by some of the mining companies for resettled communities - have problems relating to yield. They were either not producing at all or produced very little water.

The same dewatering process reduces recharge to streams, especially during the dry season. Mining activities draw a huge amount of water from the underground water, resulting in lower water flow levels (water levels) in the boreholes provided in the communities during the dry season. The concentration of mining operations in Bogoso area has considerable, adverse impact on the accessibility and availability of both ground water and surface water resources (Akabza, 2000).

2.10.5 Air and Noise Pollution

Mining activities and mining support companies release particulate matter into the ambient air. The concerns of the affected communities on air quality have been the airborne particulate matter, emissions of black smoke, noise and vibration (Akabza, 2000).

2.10.6 Airborne Particulate Matter

Airborne particulates of major concern within the concession area include respirable dust, sulphur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO) and black smoke. The activities that generate this particulate matter include site clearance and road building, open-pit drilling and blasting, loading and haulage, vehicular movement, ore and waste rock handling as well as heap leach crushing by companies doing heap leach processing.

All fine dust at a high level of exposure has the potential to cause respiratory diseases and disorders and can worsen the condition of people with asthma and arthritis. Dust arising from gold mining operations has a high silica content which has been responsible for silicosis and silico-tuberculosis in the area (Akabza, 2000).

2.10.7 Noise and Vibration

The sources of noise and vibration in the area include mobile equipment, air blasts and vibration from blasting and other machinery. The effect of high-pitched and other noises is known to include damage to the auditory system, cracks in buildings, stress and discomfort. These noises can also frighten animals, interfere with their mating processes and also cause abortions, therefore adversely affecting the animal population (Akabza, 2000).

2.11 HEALTH IMPACT

Part of the major adverse environmental impact of mining is the generation of diseases due to pollutants and accidents at mines. The effects of some of these pollutants manifest themselves immediately (cyanide, for example) but others (such as mercury) take a long time to show. According to Akabza and Darimani, 2001, in Bogoso, the extraction and processing of gold has given rise to various environmentally related diseases and accidents, which include, but are not limited to:

- a) Vector-borne diseases such as malaria, schistomiasis and onchocerciasis.
- b) Respiratory tract diseases, especially pulmonary tuberculosis and silicosis.
- c) Skin diseases.
- d) Eye diseases, especially acute conjunctivitis
- e) Accidents resulting from galamsay activities, and

f) Mental cases

2.11.1 Malaria

Malaria is a major public health problem in Bogoso. Malaria is the primary cause of child mortality in the country and the Wassa West District is the worst affected area with an infant mortality rate (Akabza and Darimani, 2001). In 1994, for example, 75% of miners surveyed at the mines were carrying the malaria parasite. Between 400 and 500 shift losses were recorded in the peak of the rainy season.

Most of the communities contacted complained that the concentration of mining operations is responsible for the high incidence of malaria in the area. The mining activities in the area promote environmental modifications that favor malaria vector development. The activities create open pits, divert watercourses and subsequently result in bodies of stagnant water (Akabza and Darimani, 2001).

2.11.2 Skin Diseases

Cases of skin diseases were observed to be prevalent in communities that were contacted. The worst affected areas include communities along the Apepere River, Chujah River and their tributaries within the concession of BPGL. The community alleged that the rash was an allergic reaction affecting users of one of the hand-dug wells in Dumasi provided by BPGL, which they claim is highly polluted.

This is believed to be the result of cyanide and mercury pollution from gold processing. Mercury in particular is widely used by small-scale miners in the area for the processing of gold. Mercury can cause skin cancer. All the communities contacted blamed the high incidence of skin rashes on the activities of the mining companies, particularly BPGL. They alleged that occasional increases in levels of cyanide reaching downstream from mine-run-off and leakage from cyanide ponds (Akabza, 2000).

2.11.3 Other Diseases

Other mining and environment related diseases are reported to be on the increase in the area. These include diarrhea and sexually transmitted diseases (STDs). Two main factors are responsible for the increasing incidence of STDs. It has been attributed to the high influx of people into the area of expatriate employees and of Ghanaians looking for jobs and trade outlets (Akabza, 2000).

2.12 Static Tests

Static tests predict drainage quality by comparing the sample's maximum acid production potential (AP) with its maximum neutralization potential (NP). The AP is determined by

multiplying the percent of total sulfur or sulfide sulfur (depending on the test) in the sample by a conversion factor (AP = 31.25 * %S). NP is a measure of the carbonate material available to neutralize acid. The value for NP is determined either by adding acid to a sample and back titrating to determine the amount of acid consumed or by direct acid titration of the sample; the endpoint pH is usually 3.5 (Ferguson and Morin 1991; Lapakko 1993). Lapakko, (1992) reported that using an endpoint pH of 3.5 measures a sample's acid neutralizing potential below 6.0, but noted that a drainage pH in the range of 3.5 may not be environmentally acceptable. The net neutralization potential (NNP), or acid/base account (ABA) is determined by subtracting the AP from the NP (NNP = NP - AP). A ratio of NP to AP is also used. An NNP of 0 is equivalent to an NP/AP ratio of 1 (Ferguson and Morin, 1991). Units for static test results (AP, NP, and NNP) are typically expressed in mass (kg, metric ton, etc.) of calcium carbonate (CaCO₃) per 1000 metric tons of rock, parts per thousand.

If the difference between NP and AP is negative then the potential exists for the waste to form acid. If it is positive then there may be lower risk. Prediction of the acid potential when the NNP is between -20 and 20 is more difficult. If ratios are used, then in NP/AP greater than 3:1, indicates that there is lower risk for acid drainage to develop (Brodie *et al.*, 1991). For ratios between 3:1 and 1:1, referred to as the zone of uncertainty, additional kinetic testing is usually recommended. Those samples with a ratio of 1:1 or less are more likely to generate acid. Prediction of drainage quality for a sample based on these values requires assumptions that reaction rates are similar and that the acid consuming minerals will dissolve (Lapakko, 1992). When reviewing data on static tests, an important

consideration is the particle size of the sample material and how it is different from the waste or unit being characterized.

2.13 DETECTION LIMITS

The following detection limits are limits used in the environmental laboratory at the Golden Star Resource (Bogoso/Prestea) limited for the Varianc 220 Spectra AA and the HACH DR 4000 Spectrophotometer.

Parameter	Detection Limits mg/L			
As	0.001			
Mn	0.005			
Zn	0.001			
Cu	0.005			
Fe	0.01			
Mg	0.001			
Na	0.01			
Ni 💦 🖉	0.01			
Pb	0.01			
SO4 ²⁻	0.1			
Free CN	0.001			
Total Hardness	1mg CaCO ₃ /L			
Alkalinity 1mg CaCO ₃ /L				

Table 2.3 Detection limits use in the determination of research parameters

Parameter	Proposed	Draft world bank	World Health
	Ghanaian EPA	guidelines for	organization for
	guidelines for	discharges to water	drinking water
	discharges to water	August 1995	1993
	January 1997	-	
рН	6 - 9	6 - 9	6.5 - 8.5
Temp. ^o C (above ambient)	29 - 30	<5	-
Conductivity(µS/cm)	750	-	-
Colour (TCU)	200	-	15
Total Dissolved Solid	50	IICT	1000
(TDS)			
Total Suspended Solid	50	50	-
(TSS)			
Turbidity (NTU)	75	-	5
Sulfide	1.0	M	-
SO_4^{2-}	250	1 A	0.2
Alkalinity	AL V		-
BOD	50	50	-
COD	250	-	-
Total phosphorous	2.0	-	-
Nitrate	0.1	have a	50
Total coli forms	400	THE	0
(MPN/100mL)			
E.coli (MPN/100mg/L)	0		0
As (total)	1.0	1.0	0.01
As (dissolved)	0.2		-
Cr (total)	0.5	1.0	0.05
Cr (hexavalent)	0.1	0.05	-
Cd	0.1	0.1	0.003
Cu	1.0	0.3	2.0
Fe (total)	2.0	2.0	0.3
Fe (dissolved)	2.0	2.0	2.0
Ni	2R.	0.05	0.02
Pb	0.1	0.6	0.01
Zn	2.0	1.0	3.0
CN total	-	1.0	-
CN free	0.1	0.1	0.01
Mn	0.05	-	-

Table 2.4 Comparison of water quality guidelines (in mg/L except where indicated)

Source: (NSR Environmental Consultant Pty Ltd., 1997)

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 STUDY AREA

Golden Star Resources (Bogoso/Prestea) Mines is located 12 km from Bogoso and 9.5 km from Prestea, and in southwest Ghana approximately 200 kilometers west of the capital, Accra, and is accessible by sealed road. Bogoso/Prestea is located in the Wassa West District of the Western region of Ghana on the Latitude S 2° 35 W and Longitude N 5° 31W.

Golden Star Resources (Bogoso/Prestea) mines own the 145 km² Bogoso concession surface mining rights (to a depth of 200 meters) and the adjoining 129 km² Prestea property. The company owns 90% interest in the Prestea underground mine, including the underground mining rights for the Prestea surface concession, and a number of contiguous properties west and north of the Bogoso property known respectively as Akropong and Dunkwa. Collectively these properties are referred to as Bogoso/Prestea.

In total the Bogoso/Prestea's property covers a strike length of approximately 85 km on the Ashanti gold trend. The remaining 10% interest in Bogoso/Prestea property is a carried interest owned by the Government of Ghana, with dividends payable after capital costs have been recovered (GSR Technical Report, 2004).



Figure 3. 1. Map of the Bogoso Prestea Mine concession area showing the sampling points (•)

3.1.1 Geology of the Bogoso/Prestea Mine

The Golden Star Resources (Bogoso/Prestea) mines lies within the Eburnean Tectonic Province (1,800-2,166 Ma) in the West African Precambrian Shield. The palaeo-proterozoic rocks that comprise most of the West African craton and host the major gold mineralization in Ghana are subdivided into meta sedimentary and volcanic rocks of the Tarkwaian and Birimian sequences (GSR Technical Report, 2004).

The Birimian is composed largely of phyllites, schists, greywackes volcanoclastics, and metavolcanic rocks (including lavas, pyroclastics, and some finer-grained metasedimentary rocks). Uncomfortably overlying the Birimian are the continental clastics of the Tarkwaian sequence. These clastics were derived from the weathering of Birimian rocks and granitic intrusions found within the Birimian (GSR Technical Report, 2004).

The area is dominated by a major northeast-southwest trending structural fault zone referred to as the Ashanti Trend, which hosts the Prestea, Bogoso, Obuasi and Konongo gold deposits, among others. Parallel to the Ashanti Trend is the Akropong trend, which hosts the Ayanfuri deposit. The Akropong Trend is about 15 km west of the Ashanti Trend in the Bogoso region, and gradually converges with it, coalescing at Obuasi and forming the basis for the world class Obuasi deposit, owned and operated by AngloGold Ashanti Ltd.

Gold operations in the Tarkwaian sequence include the Teberebie, Abosso, Tarkwa and Iduapriem mines (GSR Technical Report, 2004).

3.1.2 Historical Mining Operations at Bogoso/Prestea

In total some 11 million ounces have been mined to date from the Bogoso and Prestea properties. Mining has been conducted at Prestea since 1873, primarily as an underground operation, with more than nine million ounces of gold recorded by the Ghana Chamber of Mines as having been produced during its more than 125-year history. From 1873 to 1965, the current Prestea concession comprised a number of different licenses operated by independent mining companies, which, in 1965, were amalgamated by the post-independence government. Production declined due to lack of sustained investment, and the mine operated at a loss. In 1985, the Government of Ghana secured a World Bank loan to rehabilitate the mines, but after three years of continued losses, the decision was taken to privatize the mines (GSR Technical Report, 2004).

In 1994, JCI Limited won the privatization bid for participation in the Prestea mining operation. JCI made improvements to the productivities and efficiencies of the underground operation and carried out exploration programs and feasibility studies on the near surface resources amenable to open pit mining. However, owing to the declining gold price and continued financial losses, JCI closed down the Prestea underground mine in September 1998 and commenced a process to sell their rights in the project. The closure of the underground mine was opposed by the Prestea workforce who consequently formed Prestea Gold Resources ("PGR"), which was granted a permit by the Government of Ghana to run the mine in December 1998.

In June 2001, the Government of Ghana granted two separate leases for the Prestea concession. One lease, over the surface rights down to a depth of 200m below general

ground elevation (an elevation of approximately 150m below sea level) was granted to BGL, and the second, for the underground mine below this level, was granted to PGR. In March 2002, BGL reached an agreement with PGR to form a joint venture, to be managed by BGL, for the assessment and future operations of the Prestea underground mine (GSR Technical Report, 2004).

3.2 SELECTION OF SAMPLING SITES

The sampling sites were chosen because of the activities taking place around the sampling point and their effect on the water and soil resources. A comparative test was to be done to find out the effect of acid mine drainage as it flows from the upstream to the downstream sampling site.

The selected surface water sampling sites were located at Ajormum creek (Embankment III) (RSW–01), Apepre creek (RSW-02), Apepre creek (at Dumasi township) (RSW- 03), Chujah creek (RSW-04) and Mansi River (at Juaben) (RSW-05) (Figure 3.1). The groundwater sampling sites were located at the Adikanfo Village (Residential) (RGW- 01) and Dumasi borehole (RGW- 02). The soil sample sites were located at a Tailing Storage Facility I (RSS - 01), Chujah East Dump (RSS - 02) and Chujah West Dump (RSS - 03) (Figure 3.1).

3.3 SAMPLING COLLECTION

Water samples (surface and groundwater) were taken in duplicates from the sampling sites between November, 2005 and April, 2006.

Water samples were collected in 500 ml sterile plastic bottles. Soil samples were collected using sterile plastic food bags. All samples were transported to the laboratory in a cool box over ice for analysis with the exception of pH, conductivity and temperature which were determined on site at the time of sample collection.



Plate 3.1 The Dumasi borehole sampling site (RGW-02).





Plate 3.2 Sampling site on the Mansi River (RSW-05).



Plate 3.3 Soil sampling at Tailing Storage Facility I (RSS-01)

3.4 LABORATORY ANALYSIS

Each surface and ground water were analyzed for the following: pH, temperature, conductivity, alkalinity, cyanide, sulphate, heavy metals (dissolved and total) - (Arsenic (As), Manganese (Mn), Iron (Fe), Zinc (Zn), Copper (Cu), Cadmium (Cd). And soil samples the percentage carbon and sulphur.

3.4.1 DETERMINATION OF pH, TEMPERATURE AND CONDUCTIVITY

pH, Temperature and Conductivity parameters were determined using the TPS WP – 81 meter. The meter was first calibrated for pH using solutions of pH 4 and pH 10 buffer. For conductivity, the electrodes were immersed in the solution of 0.1M KCl of conductivity 1413.0 μ scm⁻¹. The meter was allowed to stabilized and then set the display to read pH of 4 and 10 respectively and conductivity of 1413 μ scm⁻¹. The temperature was also set to 25 ^oC prior to its use with the TPS WP 81 meter. Readings was taken by dipping the probe into the water sample and the readings recorded at every sampling site (Standard Methods, 1992).

3.4.2 ALKALINITY DETERMINATION

Alkalinity was determined from the water sample when 100 ml of the sample was measured into a 250 ml beaker or Erlenmeyer flask. The initial pH of the sample was recorded; three drops of Bromocresol green indicator were added. The sample was then titrated with 0.02 N H_2SO_4 until the pH 4.5 endpoint (color changes from blue to yellow) was reached. Total volume of acid needed to reach the endpoint was recorded, and the total alkalinity calculated as follows:

Alkalinity (mg CaCO₃/L) =A x N x 50,000 / ml Sample

Where: A = the total volume in mL of the standard acid used.

N = the normality of the standard acid used

The 50,000 is a conversion factor to change the normality into units of mg $CaCO_3/L$ (Standard Methods, 1992).

3.4.3 DISSOLVED OXYGEN DETERMINATION

The dissolved oxygen levels (D.O mg oxygen/l) in water samples were determined using the Winkler's method (azide modification). 10 ml of water sample was measured into 25 ml Erlenmeyer flask. 0.1 ml of Manganese (II) Sulfate (48%) was added to the water sample and mixed. 0.2 ml of alkaline sodium azide/ potassium iodide was again added and mixed forming pinky-brown precipitate. Finally about 0.9 ml of 3 M Sulphuric acid was added to each water sample and mixed. The sample was allowed to stand for two minutes, before titration with sodium thiosulphate (0.31%) until it turns clear with drops starch indicator. Each 1 ml of sodium thiosulphate titration becomes equal to 0.1 mg of oxygen in the 10 ml sample (Standard Methods, 1992).

3.4.4 FREE CYANIDE DETERMINATION – PYRIDINE PYRAZALONE

The Spectrophotometer HACH DR 4000 was used in the determination of cyanide from the water samples. 10 ml of filtered sample was poured into a sample cell (bottle). One CyaniVer 3 Reagent Powder pillow was added and stopped. Sample cell was shaken for 30 seconds. An additional 30 seconds was waited while the sample remains undisturbed. Another one CyaniVer 4 Reagent Powder pillow was again added to the sample. The sample cell was again shaken for 10 seconds while stopped. The content of one CyaniVer 5 cyanide reagent powder pillow added to the sample cell bottle. The sample was then vigorously shaken to dissolve completely the CyaniVer 5 reagent powder.

A 30 minute reaction period was allowed before reading from the spectrophotometer. Reading of the sample was done by first reading blank, standard before the water sample at a wavelength of 612 nm.

3.4.5 SULPHATE DETERMINATION

The HACH DR 4000 spectrophotometer was used in the determination of sulphate in the water samples. 10 ml of sample was filtered using a 0.45 μ m membrane filter into a sample cell (bottle). The content of one SulfaVer 4 Reagent Powder pillow was added to the samples. The sample cell was stopped and shaken for 30 seconds. An additional 30 seconds was observed while the sample is undisturbed. Reading of the samples was done by reading the blank, standard before reading the samples at a wavelength of 450 nm.

3.4.6 TOTAL METALS

The concentrations of Arsenic, Manganese, Iron, Zinc, Copper and Cadmium were determined using Varian 220 Spectra AA model of Atomic Absorption Spectrometer (AAS). The AAS was calibrated using standard solutions of the different metals under investigation. Concentrations of the total and dissolved metals were determined at the following wavelengths: As = 193.7 nm, Mn = 279.3 nm, Fe = 284.3 nm, Zn = 213.9 nm, Cu = 324.8 nm and. Cd = 228 nm.

For the total metal about 100 ml was measured into the total metals small bottle. The bottle was rinsed three times with the sample before actual sample was put in the sample bottle. 1 ml of concentrated HNO_3 was added to the sample using the calibrated dispenser. The sample was shaken and allowed to stand for about an hour in order for digestion to take

place. Filtration was done using a 0.45 µm membrane filter. Sample was then analyzed using the Varian 220 Spectra AA model of Atomic Absorption Spectrometer (AAS).

3.4.7 DISSOLVED METALS

For dissolved metals about 100 ml of the filtered sample was measured into the dissolved metals bottle after washing with some distilled water. 1 ml of concentrated HCl was added and sample bottle shaken to allow further reaction to take place for about an hour. Samples were then analyzed using the Varian 220 Spectra AA model of Atomic Absorption Spectrometer (AAS).

3.5. ACID - BASE ACCOUNTING (ABA) OF SOIL SAMPLES

3.5.1 Drying

Soil samples were dried at a temperature of 105 degree Celsius for 4 - 6 hours to reduce the moisture content to the barest minimum. Once they became dry they are removed from the oven and allowed to cool down before it moves to the crushing point.

3.5.2 Crushing

This is the process of breaking rock and drill core sample into coarse fragments. A laboratory jaw crusher reduces the sample to less than 10mm and a rolls crusher to 2mm or less. Crushing was done to increase the surface area of the sample and also for easy pulverizing.

3.5.3 Splitting

Splitting was done using mechanical rotary splitters. The sample was well mixed before splitting and the sample was fed evenly across the splitter.

3.5.4 Pulverizing

The pulverizing takes place when the rings and pucks impact against the side of the bowl which is shaken in a processional fashion. About 500g capacity or dried soil sample was put into the bowl and the machine starts for about 2 - 3minutes. The end product became very fine, typically 90% less than 200 mesh (75microns), put into a paper envelope ready for analysis.

3.5.5 Determination of Carbonate - Carbon and Sulphate - Sulfur

The SC-144DR Carbon and Sulfur Analyzer is a software controlled instrument designed to determine the carbon and sulfur content in a wide variety of organic materials such as coal, coke, and oils, as well as some inorganic materials such as soil, cement, and limestone by combustion and non-dispersive infrared detection.

Analysis begins as a sample (0.350 g nominal) was weighed into a combustion boat. When Analyze is selected from the Samples menu, the sample was placed in a pure oxygen environment typically regulated at 1350°C. The combination of furnace temperature and oxygen flow causes the sample to combust. All sample materials contained in the combustion boat go through an oxidative - reduction process that causes carbon and sulfur bearing compounds to break down and free the carbon and sulfur. The carbon then oxidizes to form CO_2 and the sulfur forms SO_2 . (The design of the combustion system prevents the atmosphere from entering the combustion zone.)

Sample gases are first swept through the boat stop to the back of the inner combustion tube, then forward between the inner and outer combustion tubes, allowing the sample gases to remain in the high temperature zone for a longer period and permit efficient oxidation.

From the combustion system, the gases flow through two anhydrone tubes to remove moisture, through a flow controller that sets the flow of sample gases to 3.5 l/min, and then through the infrared detection cell.

The carbon IR cell measures the concentration of carbon dioxide gas. The sulfur IR cell measures the concentration of sulfur dioxide gas. The instrument converts these values to a percentage/ ppm value, using an equation preset in the software that takes into account the sample weight, calibration, and known moisture value.

3.6 STATISTICAL ANALYSIS

A one-way randomized analysis of variance (ANOVA) was used for testing data between variables. Raw data for both the dissolved and total heavy metals and other parameters determined in our analysis were transformed by adding a value of one to all scores in order to eliminate zero data points. The data were tested at 95% confidence level. The statistical software package used was the SPSS (Statistical Package for Social Scientist) (Anon, 1988).



CHAPTER FOUR

4.0 RESULTS

4.1 Mean pH, Temperature and Conductivity in underground and surface water samples

Mean pH of underground and surface water samples from the seven sampling sites showed that the groundwater values were generally low ranging between 5.54 and 5.85 compared to the surface water values which ranged between 5.75 and 6.68. The highest pH value of 5.85 was recorded at the Adikanfo Village (Residential) (RGW–01) and a lowest of 5.54 at Dumasi borehole (RGW–02). For surface water the highest value of 6.68 was recorded at the Chujah creek (RSW–04) and the lowest value of 5.57 at the Ajormum creek (Embankment III) (RSW–01) (Table 4.1).

Statistically, there were differences ($p \le 0.050$) in pH between the underground water samples and similarly between surface water samples (Appendix I). Differences between Ajormum creek (Embankment III) (RSW-01) and Apepre creek (RSW-02) and Apepre creek (at Dumasi township) and Ajormum creek (RSW-02) and Chujah creek (RSW-04) were obtained.

There was little variation in underground water temperatures as it varied between 26.30 and 26.40 but there was much variation in the surface waters (26.21 to 28.05) (Table 4.1). The highest temperature value of 26.40 was recorded at the Adikanfo village (RGW-01) and a lowest value of 26.30 °C at the Dumasi borehole (RGW-02). Mean surface water temperature recorded a highest value of 28.43 °C at the Mansi River (RSW-05) and lowest value of 26.22 °C recorded at the Ajormum creek (Embankment III) (RSW-01) (Table 4.1).

Differences in temperature were statistically not significant for underground water samples but there were statistically significant differences in surface water samples between Ajormum creek (Embankment III) (RSW-01) and Chujah creek (RSW-04) and Mansi river (RSW-05) and between Apepre creek (RSW-02) and Chujah creek (RSW-04) and Mansi river (RSW-05) and between Apepre creek (at Dumasi township) (RSW-03) and Mansi river (RSW-05) (Appendix II).



Table 4 .1. Mean and range of pH,	Temperature, Conductivity.	, Alkalinity, Dissolved	Oxygen, Free	Cyanide and Sulphate in	1
underground and surface water sam	ples at seven sampling sites	s within a mining conce	ession area.		

	Sampling	Mean pH	Mean Temp.ºC	Mean Cond.	Mean Alk.CaCO ₄	Mean D .O mgO ₂ /L	Mean CN mg/L	Mean SO ₄ ²⁻ mg/L
Sample Type	Sites	and Range	and Range	µs/cm and Range	and Range	and Range	and Range	and Range
Groundwater				IVINC	J J I			
		5.86	26.40	262.40	94.83	0.128	0.064	28.767
	RGW - 01	5.73 - 5.77	26.0 - 26.8	215.50 - 362.00	87.00 - 98.00	0.100 - 0.150	0.002 - 0.010	20.500 - 45.000
		5.54	26.30	185.33	84.50	0.664	0.088	10.017
	RGW - 02	5.35 - 5.77	25.7 - 26.7	169.50 - <mark>203</mark> .80	62.00 - 140.00	0.090 - 2.200	0.002 - 0.013	4.400 - 16.100
Surface water								
U		5.57	26.22	282.17	48.50	0.734	0.004	66.217
	RSW - 01	4.97 - 5.88	24.7 - 27.2	178.80 - 551.00	24.00 - 76.00	0.080 - 2.900	0.002 - 0.007	26.900 - 210.500
		6.21	26.52	178.43	52.5	0.866	0.005	27.083
	RSW - 02	5.81 - 6.58	25.9 - 27.0	162.30 - 194.20	26.00 - 88.00	0.090 - 3.500	0.001 - 0.014	11.700 - 52.800
		6.39	26.62	170.10	51.00	0.596	0.007	26.317
	RSW - 03	5.97 - 6.76	25.7 - 27.4	141.00 - 191.50	22.00 - 88.00	0.090 - 1.900	0.002 - 0.022	13.700 - 53.300
		6.69	28.05	923.83	85.33	0.820	0.015	66.217
	RSW - 04	6.05 - 7.23	26.1 - 30.0	725.0 - 1435.0	62.0 - 113.0	0.120 - 3.100	0.004 - 0.041	208.00 - 344.00
		6.40	28.43	95.03	47.83	0.788	0.004	6.96
	RSW - 05	6.17 - 6.55	26.1 - 30.0	39. <mark>60 - 123.5</mark> 0	32.00 - 62.00	0.110 - 2.800	0.002 - 0.007	0.100 - 27.600



Mean Conductivity (μ s/cm) of both underground and surface water samples generally varied between 95.03 μ s/cm and 282.17 μ s/cm. However, mean conductivity at the Chujah creek (RSW–04) was unusually high (923.83 μ s/cm) (Table 4.1).

The underground and surface waters samples showed statistically significant difference. Significant difference were recorded between Ajormum creek (Embankment II) (RSW-01) and Chujah creek (RSW-04) and Mansi creek (RSW-05) and between Apepre creek (at Dumasi) (RSW-03) and Chujah creek (RSW-04) and Mansi river (RSW-05) and between Chujah creek (RSW-04) and Mansi river (RSW-05) (Appendix III).

4.2 Mean Alkalinity and Dissolved Oxygen in underground and surface water samples

Mean levels of alkalinity (mg CaCO₃/l) in underground and surface water samples were relatively high for all seven sampling sites (Table 4.1). Values for underground water varied between 84.50 and 84.83 compared to surface waters which were between 47.83 mg CaCO₃/l and 85.33 mg CaCO₃/l (Table 4.1).

The were no statistically significant differences between underground water samples but there were differences in the surface water samples at Ajormum creek (Embankment III) (RSW-01) and Chujah creek (RSW-04) and between Apepre creek (RSW-02) and Chujah creek (RSW-04) and between Apepre creek (at Dumasi) (RSW-03) and Chujah creek (RSW-04) and between Chujah creek (RSW-04) and Mansi river (RSW-05) (Appendix IV).

Dissolved oxygen (mg O_2/l) were generally low in both underground and surface water samples (Table 4.1). The underground water samples were between 0.128 and 1.145 and surface water between 0.596 mg CaCO₃/l and 1.795 mg CaCO₃/l (Table 4.1).

Statistically the differences in dissolved oxygen were not significant for both under ground water and surface water samples (Appendix V).

4.3 Mean Free Cyanide and Sulphate underground and surface water samples

Mean concentration of free Cyanide (mg/l) for all the seven sampling sites were generally low for both the underground water and surface water samples with the exception of Chujah creek (RSW-04) sampling site which recorded a mean highest value of 0.041 mg/l (Table 4.1). The underground water samples varied between 0.064 mg/l and 0.088 mg/l and surface water samples between 0.004 mg/l and 0.015 mg/l (Table 4. 1).

Statistical differences in free cyanide were not significant for both groundwater and surface water (Appendix VI).

Mean sulphate (mg/l) for both the groundwater and surface water samples at the seven sampling sites were generally low, with the exception of surface water sample from Chujah creek (RSW-04) (Table 4.1). The surface water sample from Chujah creek (RSW-04) recorded a high concentration value of 267.75 mg/l (Table 4.1).

Statistically the differences in sulphate were significant ($p \le 0.050$) for underground and for surface water samples between Ajormum creek (Embankment III) (RSW-01) and Chujah creek (RSW-04) and between Apepre creek (RSW-02) and Chujah creek (RSW-04) and Mansi river (RSW-05) and between Apepre creek (at Dumasi) (RSW-03) and Chujah creek (RSW-04) and Mansi river (RSW-05) (Appendix VII).

4.4 Dissolved and Total Arsenic in underground and surface water samples

Mean dissolved and total arsenic concentration (mg/l) in the underground water samples were low and varied between 0.005 and 0.006 for dissolved and 0.005 and 0.007 for total arsenic in water samples. The concentration in surface water samples were however high and varied between 0.004 and 0.021 for dissolved and 0.007 and 0.037 for total arsenic concentration (Table 4.2 and Table 4.3).

Statistical differences were not significant ($p \le 0.050$) for both dissolved and total arsenic concentrations for underground water samples, but there were significant differences for both dissolved and total arsenic within surface water samples between Apepre creek (at the Dumasi township) (RSW-03) and Mansi river (RSW-05) (Appendix VIII) (Appendix IX).



Figure 4.1Dissolved and total Arsenic concentrations in water samples from seven sites
within the Bogoso Concession.

4.5 Dissolved and Total Iron in water sample in underground and surface water samples at seven sampling sites

Mean dissolved and total iron concentration (mg/l) in the underground water samples were high, 8.682 for dissolved and 11.597 for total iron. The concentration in surface water samples were however low, 0.307 for dissolved and 6.185 for total iron concentration (Table 4.2 and Table 4.3).

Statistically significant differences ($p \le 0.050$) for dissolved iron were recorded in both underground and surface water samples (Appendix X). There were significant differences between Ajormum creek (Embankment III) (RSW-01) and Apepre creek (RSW-02) and between Apepre creek (RSW-02) and Chujah creek (RSW-05) surface waters. There were also significant difference ($p \le 0.050$) for total iron in surface water samples between Ajormum creek (Embankment III) (RSW-01) and Mansi river (RSW-05) and between Apepre creek (at Dumasi township) (RSW-03) and Mansi river (RSW-05) (Appendix XI).



Figure 4.2 Dissolved and total Iron concentrations in water samples from seven sites within the Bogoso Concession.

Dissolved Metals	Sampling		Mean D-As and	Mean D-Fe	Mean D-Cu	Mean D-Zn	Mean D-Mn	Mean D-Cd
values in Sample	Sites	Unit	Range	and Range	and Range	and Range	and Range	and Range
Groundwater								
			0.006	0.018	0.213	0.015	0.260	0.006
	RGW – 01	mg/L	0.003 - 0.008	0.003 - 0.043	0.121 - 0.432	0.010 - 0.028	0.217 - 0.320	0.005 - 0.007
		-	0.005	8.682	0.031	0.028	0.188	0.006
	RGW - 02	mg/L	0.001 - 0.008	4 <mark>.946 - 1</mark> 2.640	0.005 - 0.077	0.018 - 0.042	0.144 - 0.270	0.005 - 0.007
Surface water								
5			0.004	0.984	0.052	0.071	0.802	< 0.005
	RSW – 01	mg/L	0.003 - 0.007	0.154 - 1.949	0.005 - 0.086	0.004 - 0.315	0.338 - 2.190	< 0.005
			0.009	0.307	0.035	0.014	0.269	< 0.005
	RSW - 02	mg/L	0.003 - 0.012	0.071 - 0.562	0.005 - 0.069	0.003 - 0.032	0.143 - 0.471	< 0.005
			0.014	0.494	0.006	0.006	0.123	< 0.005
	RSW - 03	mg/L	0.005 - 0.027	0.082 - 1.408	0.005 - 0.008	0.002 - 0.012	0.051 - 0.259	< 0.005
			0.021	0.838	0.065	0.016	2.206	< 0.005
	RSW - 04	mg/L	0.007 - 0.051	0.020 - 3.914	0.028 - 0.113	0.006 - 0.051	1.252 - 4.593	< 0.005
			0.005	0.747	0.020	0.020	0.099	< 0.005
	RSW - 05	mg/L	0.001 - 0.009	0.463 - 1.308	0.005 - 0.035	0.004 - 0.054	0.043 - 0.181	< 0.005

Table 4.2. Mean and range of dissolved arsenic, iron, Copper, Zinc, Manganese, Cadmium values of water samples in underground and surface water samples at seven sampling sites within a mining concession area.

Note: <0.005 implies Not detected

Total Metals	Sampling		Mean T- As	Mean T- Fe	Mean T- Cu	Mean T- Zn	Mean T- Mn	Mean T- Cd
values in Sample	Sites	Unit	and Range	and Range	and Range	and Range	and Range	and Ranges
Groundwater								
			0.007	0.047	0.212	0.024	0.280	0.006
	RGW - 01	mg/L	0.003 - 0.010	0.026 - 0.087	0.158 - 0.280	0.017 - 0.040	0.228 - 0.360	0.005 - 0.007
		-	0.005	11.597	0.031	0.044	0.224	0.007
	RGW - 02	mg/L	0.001 - 0.009	8.758 - 15.925	0.070 - 0.299	0.018 - 0.075	0.168 - 0.313	0.006 - 0.008
Surface water								
0			0.012	3.868	0.044	0.078	0.870	< 0.005
	RSW - 01	mg/L	0.007 - 0.021	0.804 - 5.094	0.005 - 0.119	0.004 - 0.333	0.525 - 2.195	< 0.005
			0.021	4.739	0.039	0.018	0.292	0.008
	RSW - 02	mg/L	0.008 - 0.037	1.618 - 13.938	0.008 - 0.077	0.002 - 0.037	0.165 - 0.485	0.007 - 0.009
			0.037	2.530	0.030	0.024	0.495	< 0.005
	RSW - 03	mg/L	0.007 - 0.081	1.749 - 3.342	0.005 - 0.045	0.015 - 0.034	0.097 - 2.265	< 0.005
			0.08	6.185	0.103	0.031	2.271	< 0.005
	RSW - 04	mg/L	0.013 - 0.251	0.212 - 17.703	0.024 - 0.331	0.009 - 0.055	1.346 - 4.655	< 0.005
			0.007	1.516	0.043	0.040	0.122	< 0.005
	RSW - 05	mg/L	0.003 - 0.012	0.491 - 2.325	0.005 - 0.072	0.006 - 0.066	0.050 - 0.203	< 0.005

Table 4.3. Mean and range of total arsenic, iron, Copper, Zinc, Manganese, Cadmium values of water samples in underground and surface water samples at seven sampling sites within a mining concession.

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Note: <0.005 implies Not detected

4.6 Dissolved and Total Copper in water sample in underground and surface water samples at seven sampling sites

Mean dissolved and total copper concentration (mg/l) in underground water samples were generally high and varied between 0.031 and 0.213 for dissolved and 0.124 and 0.212 for total copper. The concentration in surface water samples were however low and varied between 0.006 and 0.065 for dissolved and 0.030 and 0.103 for total copper concentration (Table 4.2 and Table 4.3).

There were no statistically significant differences ($p \le 0.050$) in total copper concentration in both underground and surface water samples but there were significant differences in dissolved copper (Appendix XIII) and (Appendix XII).



Figure 4.3 Dissolved and total Copper concentrations in water samples from seven sites within the Bogoso Concession.

4.11 Dissolved and Total Zinc in water sample in underground and surface water samples at seven sampling sites

Mean dissolved and total zinc concentration (mg/l) in underground water samples were high and varied between 0.015 and 0.028 for dissolved and 0.024 and 0.044 for total copper. The concentration in surface water samples were however low and varied between 0.006 and 0.071 for dissolved and 0.018 and 0.078 for total zinc concentration (Table 4.2 and Table 4.3).

There were no significant differences in total zinc ($p \le 0.050$) for both underground and surface water samples and for dissolved zinc in surface waters. However, there were significant differences ($p \le 0.050$) for dissolved zinc in underground water samples (Appendix XIV and Appendix XV).



Figure 4.4Dissolved and total Zinc concentrations in water samples from seven sites
within the Bogoso Concession.

4.12 Dissolved and Total Manganese in water sample in underground and surface water samples at seven sampling sites

Mean dissolved and total manganese concentration (mg/l) in underground water samples were low and varied between 0.188 and 0.260 for dissolved and 0.224 and 0.280 for total copper. The concentration in surface water samples were however high and varied between 0.0992 and 2.2063 for dissolved and 0.122 and 2.271 for total manganese concentration (Table 4.2 and Table 4.3).

There were no significant differences in dissolved manganese in surface water samples and total manganese in underground water. Statistically significant differences ($p \le 0.050$) were however recorded for dissolved manganese in underground and total manganese in surface water samples between Ajormum creek (Embankment III) (RSW-01) and Chujah creek (RSW-04) and between Chujah creek (RSW-04) and Mansi river (RSW-05) (Appendix XVII and Appendix XVII).



Figure 4.5 Dissolved and total Manganese concentrations in water samples from seven sites within the Bogoso Concession.

4.13 Dissolved and Total Cadmium in water sample in underground and surface water samples at seven sampling sites

Mean dissolved and total concentrations of cadmium in water samples were generally low (lower than the detection limit) with the exception of a few sampling sites recording significant values of cadmium. Mean levels of cadmium were 0.006 mg/l for dissolved cadmium and 0.0065 for total cadmium in underground water but the levels in surface waters were below detection (Table 4.2 and Table 4.3).

4.14 Percentage Carbon and Sulfur in Soil Samples

Carbon and sulfur in the soil samples at the three sites were between 0.057 to 2.172 % and 0.004 to 0.5582 % for carbon and sulfur respectively. Carbon was high (2.172 %) at the Tailing storage facility I (RSS–01) and low (0.057 %) at the Chujah west dump (RSS–03). Similarly, sulfur was high (4.221 %) at Tailing storage facility I (RSS–01) and a low (0.004 %) at Chujah west dump (RSS–03).

Statistically significant differences ($p \le 0.050$) were recorded for Carbon and Sulfur in soil samples between Tailing storage facility I (RSS-01) and Chujah east (RSS-02) and Chujah west dumps (RSS-03) (Appendix XVIII).



Figure 4. 6Percentage Carbon and Sulfur in three soil samples within the Bogoso
Concession.



CHAPTER FIVE

5.0 DISCUSSION, CONCLUSION AND RECOMMENDATION

5.1 **DISCUSSION**

This study shows that acid mine drainage (AMD) is occurring in the mining concession area investigated. This is because the main indicators of AMD; acidity, metal toxicity, metal precipitation and salinization were occurring at some of the sampling sites (Gray, 1997). Surface water samples from the Chujah creek (RSW-04) was extremely polluted with average electrical conductivity of (725.0–1435.0 μ S/cm), sulphate concentration of (208.00– 377.00 mg/l), iron concentrations of (0.02-3.914 mg/l and 0.212-17.703 mg/l) for dissolved and total iron respectively and manganese concentrations of (0.043-4.593mg/l and 0.0510-4.655mg/l) for dissolved and total manganese respectively. These levels were higher than the Ghana Environmental Protection Agency (GEPA) maximum acceptable limits of 750 μ S/cm for electrical conductivity, 250 mg/l for sulphate, 1.0 mg/l for iron and 0.05 mg/l for manganese.

Acidity in AMD is comprised of mineral acidity (iron, aluminum, manganese, and other metals depending on the specific geologic setting and metal sulfide) and hydrogen ion acidity (Brown, 1994). Sulphate is considered the best indicator of AMD as it is unaffected by neutralization (Gray, 1996) and has been used as the reference indicator in previous AMD impact studies (Garcı'a-Criado *et al.*, 1999). The drainage quality emanating from underground mines or backfills of surface mines is dependent on the acid-producing (sulfide) and alkaline (carbonate-poor materials) are expected to produce acidic drainage. In general, sulfide-rich and carbonate-poor materials are expected to produce acidic drainage.
produce alkaline conditions in water (Brown, 1994). Similarly, iron concentration was used to assess the effect of ochre formation, which was found to decrease with distance from the input of AMD in earlier studies (Gray, 1998) suggesting that this iron metalloid occurs naturally in the surface waters of the Golden Star Resources (Bogoso concession) mines.

High electrical conductivity in the river could be attributed to high mineral salt concentration which comes from the dissolution of minerals in the soil (Ntengwe, 2006; Morrison *et al.*, 2001). When a river is disturbed, for instance by mining within a river, adsorbed ions are released from the riverbed into the water (Prowse, 1987; Stouffer, 1996). Although gold mining activities within the creeks and river were in the form of crashed rocks and pits waters, the electrical conductivity levels remained below the minimum guideline level with the exception of the Chujah creek sampling site.

Maintenance of high electrical conductivity, sulphate, iron and manganese during the entire period of field investigation suggest that the H^+ generated and metals leachates from sulfide oxidation in the contamination source (i.e. the waste rock dumps upstream of the Chujah East) was readily available for discharging and the amount of ions being transported outwards depends on the volume of out-flowing waters (both surface and underground runoffs). Other downstream factors change the character of the drainage by chemical reaction or dilution (Ferguson and Erickson, 1998). It is worth noting that the critical factors responsible for disrupting the macro invertebrate community in AMD impacted rivers appears to be pH (Allen *et al.*, 1996), metal concentrations (Soucek *et al.*, 2000; Kim and Chon, 2001) or a combination of the two (Cherry *et al.*, 2001).

No increases were noted in acidity, temperature, alkalinity, dissolved oxygen, free cyanide, arsenic, copper, zinc or cadmium in the Mansi River as it flows past the study area.

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Underground water samples from Dumasi borehole (RGW-02) also recorded very high levels of iron and manganese concentrations that exceeded the maximum acceptable limits set by the GEPA. This could be attributed to the rock bearing underground of the borehole at Dumasi township which is characterized by the pyrite ore and the release of metals from the oxidation of metal-bearing sulphides in the mine dumps and pits. Additionally, waters pumped from the Chujah pits where dewatering processes occur contained elevated concentration of manganese. Manganese is difficult to remove from discharges because the pH must be raised to above 10.0 before manganese will precipitate. Manganese, therefore, is persistent and can be carried for long distances downstream of a source of mine drainage. Less information is available on the effects of elevated manganese concentrations on aquatic life than the effects of iron and aluminum. Perhaps this is because manganese in mine drainage is usually associated with other metals which may have a more deleterious effect or mask the effect of the manganese. Manganese discharge limits have traditionally been based on the objectionable discoloration effects of manganese at concentrations as low as 0.2 mg/L in water supplies rather than effects on aquatic life (Kleinmann and Watzlaf, 1988).

pH values were low for underground water (5.35 - 5.77) and surface water (4.97 - 7.23) samples compared to the GEPA discharges limit of 6-9. These values were neutral or very mildly acidic. This mildly acidity characteristic could be attributed to the influence of alkaline added to mined pit before they are pumped out into the environment. The solubility of Fe (OH)₃ is both temperature and pH dependent. So some of the Fe(OH)₃ that is in solution in the acidic conditions of the mine will precipitate out when the effluent (runoff) mixes with river water (Prowse, 1987). Once in the waterways, the sulfuric acid lowers the

pH of the streams or rivers virtually killing anything that cannot handle the stress of the stronger acidity levels. Sometimes, a stream's natural buffering system, due to carbonates, may hide the fact that the pH is being lowered. The acid in the water neutralizes the carbonate and bicarbonate ions resulting in the formation of carbonic acid (H_2CO_3), which weakens the natural buffering action of the water (Stouffer, 1996).

Temperature values (24.7- 30.0 °C) were also within the acceptable range 29-30 °C as indicated by the GEPA.

Mine drainage is a complex of elements that interact to cause a variety of effects on aquatic life that are difficult to separate into individual components. Toxicity is dependent on discharge volume, pH, total acidity and concentration of dissolved and total metals. pH is the most critical component, since the lower the pH, the more severe the potential effects of mine drainage on aquatic life. The overall effect of mine drainage is also dependent on the flow (dilution rate), pH and alkalinity or buffering capacity of the receiving stream. The higher the concentration of bicarbonate and carbonate ions in the receiving stream, the higher the buffering capacity and the greater the protection of aquatic life from adverse effects of acid mine drainage (Kimmel, 1983).

Alkalinity levels in underground waters samples were higher (62.00-140.00 mg CaCO₃/l) than in surface water samples (22.00-113.00 mg CaCO₃/l) this could be attributed to calcium carbonate (lime) added to pond water in the pit as neutralization processes. The drainage quality emanating from underground mines or backfills of surface mines is dependent on the acid-producing (sulfide) and alkaline (carbonate) minerals contained in the disturbed rock. In general, sulfide-rich and carbonate-poor materials are expected to produce

acidic drainage. In contrast, alkaline-rich materials, even with significant sulfide concentrations, often produce alkaline conditions in water (Skousen *et al.*, 1990).

Dissolved oxygen values were generally low for both underground and surface water samples with only Apepre creek (RSW-02) recorded high of 0.866 mg O_2/l . The main factor contributing to changes in dissolved oxygen levels is the build-up of organic waste. Dissolved oxygen levels below 3 mg/l are stressful to most aquatic organisms and levels below 2 or 1 mg/l will not support fish (Skousen *et al.*, 1990). The build up of organic material from human activities such as mining is one source of oxygen depletion. Microorganisms in the stream consume oxygen as they decompose sewage, urban and agricultural runoff, and discharge from food-processing plants, meat-packaging plants, and dairies (Skousen *et al.*, 1990).

The free cyanide concentrations for both the underground and surface water samples were below the GEPA threshold limit of 0.1 mg/l. Reduction of cyanide concentration in streams often depends on the dilution and natural decomposition which reduces cyanide concentration in water occurs during short and long distance flow of the river (Shehong *et al.*, 2005). Cyanide is often not the only pollutant from tailings dam breakages but along with the water containing the cyanide, often the spills involve the solid waste products which are usually mud's containing very high amounts of heavy metals such as lead, copper, cadmium and zinc (Macklin *et al.*, 2003).

Heavy metals can increase the toxicity of mine drainage and also act as metabolic poisons. Iron, aluminum and manganese are the most common heavy metals which can compound the adverse effects of mine drainage. Heavy metals are generally less toxic at circum neutral pH. Trace metals such as zinc, cadmium, and copper, which may also be present in mine drainage, are toxic at extremely low concentrations and may act synergistically to suppress algal growth and affect fish and benthos (Hoehn and Sizemore, 1977).

Ratios obtained from the three soil sampling sites had only the Old Tailing Facility I (RSS-01) recording a 3: 1 ratio whereas the other sampling sites recorded higher ratios values above the 3: 1 ratios. The ratio of neutralizing potential and acid production potential levels in the soil samples were equal or more than the uncertainty limit of 3: 1. If ratios are used, when the ratio of a sample's neutralization potential and acid production potential is greater than 3: 1, experience indicates that there is lower risk for acid drainage to develop (Brodie *et al.*, 1991) for Chujah East Dump (RSS-02) which had a ratio of 5: 1 and Chujah West Dump (RSS-03) a ratio of 22: 1. For ratios between 3: 1 and 1: 1, referred to as the zone of uncertainty, additional kinetic testing is usually recommended. Those samples with a ratio of 1: 1 or less are more likely to generate acid. Prediction of drainage quality for a sample based on these values requires assumptions that reaction rates are similar and that the acid consuming minerals will dissolve (Lapakko, 1992).

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5.2 CONCLUSION

This study has indicated that pyrite oxide contaminated as a result of mining activities is contributing significantly to the quality of underground and surface water emanating from the Chujah environs, and is not only affecting the pH of the water, but is also contributing heavy metals to the surface water environment. The local streams (creeks) were contaminated with heavy metals in the vicinity of the gold mining area, but the impact is localised and does not appear to affect the chemistry of the main river system (Mansi River). This could be explained by low run-off volumes from the mining sites compared to the rest of the Chujah pit and Chujah creeks sub catchments. Alternatively, the data could be explained by acid mine drainage having developed only partially in the study area. The levels of irons and manganese recorded suggest these metals occur naturally in the area-and is probably leaching out of the rock formations.

Levels, with some sampling sites exceeding the maximum tolerable concentrations for iron (Fe) and manganese (Mn) established by GEPA for the mine effluent from wastewater facilities. As regards to the surrounding creeks, streams and lands, moderately high concentrations of SO_4^{2-} and electrical conductivity were detected in many of the samples, showing a certain extent of dispersion of pollution from the mine area.

The study has shown that the distance between the creeks or stream and the generation point is a major factor that determines the influence of acid mine drainage on stream water quality. The Mansi river downstream (at Juaben) (RSW-05) site had not been affected by any acid mine drainage due to its distance from the creeks. However, Chujah creek (RSW-04) which is upstream was being affected because of its close proximity to the pits.

It is evident that acid mine drainage, if not correctly managed may contribute to the pollution of our water bodies. Ghana Chamber of Mine and Ghana Environmental Protection Agency must take action to regulate the operations of mining along watercourses. Operators need to be encouraged to treat waste water to reduce pollution of water bodies.



5.3 **RECOMMENDATION**

Mining operations along watercourses is still hazardous to the sustainable use of rural waters and soil resources. Improved operator guidance with management practices, treatment methods and acceptable discharge locations is thus considered necessary.

The following recommendations are made as a result of the outcome of the research:

- New conventional methods should be employed in the treatment of acidic water in the pits which are pumped into the environment and recommend. Passive Treatment of AMD such as; Aerobic wetland, Compost or Anaerobic Wetland, Open Limestone Channels, Diversion wells, Anoxic Limestone Drains (ALD), Vertical Flow Reactors (VFR) and Pyrolusite[®] Process.
- 2. Sitting up of monitoring ponds as a preventive methods should be considered by the various mining companies to help stop acid mine drainage from getting into the environment.
- 3. A similar study should be carried out in the other mining areas in Ghana.

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4. Reafforestation or revegetation of the mined sites should be considered to help reduce the exposure of the land to geochemical reaction.

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APPENDIX I

pH STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES

Appendix I. a: A TABLE OF A DESCRIPTIVE TEST OF pH RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	5.8550	0.1060	0.0433	5.7300	6.0300	16.808	0.002
RGW-02	5.5417	0.1543	0.0630	5.3500	5.7700		

pH STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

Appendix I. b: A TABLE OF A DESCRIPTIVE TEST OF pH RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	5.5700	0.3294	0.1345	4.9700	5.8800	13.770	0.004
RSW-02	6.2100	0.2646	0.1080	5.8100	6.5800		
RSW-01	5.5700	0.3294	0.1345	4.9700	5.8800	21.382	0.001
RSW-03	6.3900	0.2832	0.1156	5.9700	6.7600		
RSW-01	5.5700	0.3294	0.1345	4.9700	5.8800	28.222	0.000
RSW-04	6.6850	0.3948	0.1612	6.0500	7.2300		
RSW-01	5.5700	0.3294	0.1345	4.9700	5.8800	31.009	0.000
RSW-05	6.3967	0.1541	0.0629	6.1700	6.5500		

Appendix I. c: A TABLE OF A DESCRIPTIVE TEST OF pH RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	6.2100	0.2646	0.1080	5.8100	6.5800	1.294	0.282
RSW-03	6.3900	0.2832	0.1156	5.9700	6.7600		
RSW-02	6.2100	0.2646	0.1080	5.8100	6.5800	5.995	0.034
RSW-04	6.6850	0.3948	0.1612	6.0500	7.2300		
RSW-02	6.2100	0.2646	0.1080	5.8100	6.5800	2.230	0.166
RSW-05	6.3967	0.1541	0.0629	<mark>6</mark> .1700	6.5500		

Appendix I. d: A TABLE OF A DESCRIPTIVE TEST OF pH RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	6.3900	0.2832	0.1156	5.9700	6.7600	2.212	0.168
RSW-04	6.6850	0.3948	0.1612	6.0500	7.2300		
RSW-03	6.3900	0.2832	0.1156	5.9700	6.7600	0.003	0.961
RSW-05	6.3967	0.1541	0.0629	6.1700	6.5500		

Appendix I. e: A TABLE OF A DESCRIPTIVE TEST OF pH RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	6.6850	0.3948	0.1612	6.0500	7.2300	2.778	0.127
RSW-05	6.3967	0.1541	0.0629	6.1700	6.5500		

APPENDIX II

TEMPERATURE STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix II. a: A TABLE OF A DESCRIPTIVE TEST OF TEMPERATURE RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	26.4000	0.3162	0.1291	26.0000	26.8000	0.259	0.622
RGW-02	26.3000	0.3633	0.1483	25.7000	26.7000		

TEMPERATURE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

Appendix II. b: A TABLE OF A DESCRIPTIVE TEST OF TEMPERATURE RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	26.2167	0.9725	0.3970	24.7000	27.2000	0.500	0.496
RSW-02	26.5167	0.3656	0.1493	25.9000	27.0000		
RSW-01	26.2167	0.9725	0.3970	24.7000	27.2000	0.690	0.426
RSW-03	26.6167	0.6676	0.2725	25.7000	27.4000		
RSW-01	26.2167	0.9725	0.3970	24.7000	27.2000	6.641	0.028
RSW-04	28.0500	1.4460	0.5903	26.1000	30.0000		
RSW-01	26.2167	0.9725	0.3970	24.7000	27.2000	12.323	0.006
RSW-05	28.4333	1.2028	0.4910	26.9000	30.0000		

Appendix II. c: A TABLE OF A DESCRIPTIVE TEST OF TEMPERATURE RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	26.5167	0.3656	0.1493	25.9000	27.0000	0.104	0.754
RSW-03	26.6167	0.6676	0.2725	25.7000	27.4000		
RSW-02	26.5167	0.3656	0.1493	25.9000	27.0000	6.341	0.030
RSW-04	28.0500	1.4460	0.5903	26.1000	30.0000		
RSW-02	26.5167	0.3656	0.1493	25.9000	27.0000	13.947	0.004
RSW-05	28.4333	1.2028	0.4910	26.9000	3 <mark>0.000</mark> 0		

Appendix II. d: A TABLE OF A DESCRIPTIVE TEST OF TEMPERATURE RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	26.6167	0.6676	0.2725	25.7000	27.4000	4.859	0.052
RSW-04	28.0500	1.4460	0.5903	26.1000	30.0000		
RSW-03	26.6167	0.6676	0.2725	25.7000	27.4000	10.464	0.009
RSW-05	28.4333	1.2028	0.4910	26.9000	30.0000		

Appendix II. e: A TABLE OF A DESCRIPTIVE TEST OF TEMPERATURE RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	28.0500	1.4460	0.5903	26.1000	30.0000	0.249	0.628
RSW-05	28.4333	1.2028	0.4910	26.9000	30.0000		

APPENDIX III

CONDUCTIVITYSTATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES

Appendix III. a: A TABLE OF A DESCRIPTIVE TEST OF CONDUCTIVITY RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	262.4000	51.6888	21.1018	215.8000	362.0000	12.639	0.005
RGW-02	185.3333	12.1589	4.9638	169.5000	203.8000		

CONDUCTIVITYSTATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix III. b: A TABLE OF A DESCRIPTIVE TEST OF CONDUCTIVITY RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	282.1667	137.0455	55.9486	178.8000	551.0000	3.400	0.095
RSW-02	178.4333	14.3926	5 .8758	162.3000	194.2000		
RSW-01	282.1667	137.0455	55.9486	178.8000	551.0000	3.944	0.075
RSW-03	170.1000	17.9576	7.3312	141.0000	191.5000		
RSW-01	282.1667	137.0455	55.9486	178.8000	551.0000	29.270	0.000
RSW-04	923.8333	256.1612	104.5774	725.0000	1435.000		
RSW-01	282.1667	137.0455	55.9486	178.8000	551.0000	10.696	0.008
RSW-05	95.0333	29.3585	11.9855	39.6000	123.5000		

Appendix III. c: A TABLE OF A DESCRIPTIVE TEST OF CONDUCTIVITY RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	178.4333	14.3926	5.8758	162.3000	194.2000	0.787	0.396
RSW-03	170.1000	17.9576	7.3312	141.0000	191.5000		
RSW-02	178.4333	14.3926	5.8758	162.3000	194.2000	50.645	0.000
RSW-04	923.8333	256.1612	104.5774	725.0000	1435.000		
RSW-02	178.4333	14.39 <mark>26</mark>	5.8758	162.3000	194.2000	39.037	0.000
RSW-05	<mark>95.03</mark> 33	29.3 <mark>585</mark>	11.9855	39.6000	123.5000		

Appendix III. d: A TABLE OF A DESCRIPTIVE TEST OF CONDUCTIVITY RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	170.1000	17.9576	7.3312	141.0000	191.5000	51.693	0.000
RSW-04	923.8333	256.1612	104.5774	725.0000	1435.000		
RSW-03	170.1000	17.9576	7.3312	141.0000	191.5000	28.546	0.000
RSW-05	95.0333	29.3585	11.9855	39.6000	123.5000		

Appendix III. e: A TABLE OF A DESCRIPTIVE TEST OF CONDUCTIVITY RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	923.8333	256.1612	104.5774	725.0000	1435.000	61.995	0.000
RSW-05	95.0333	29.3585	11.9855	39.6000	123.5000		

APPENDIX IV

ALKALINITY STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix IV. a: A TABLE OF A DESCRIPTIVE TEST OF ALKALINITY RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	94.8333	4.0702	1.6617	87.000	98.000	0.806	0.390
RGW-02	84.5000	27.8909	11.3864	62.000	140.000		

ALKALINITY STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix IV. b: A TABLE OF A DESCRIPTIVE TEST OF ALKALINITY RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	48.5000	18.0416	7.3655	24.000	76.000	0.109	0.748
RSW-02	52.5000	23.5181	9.6012	26.000	88.000		
RSW-01	48.5000	18.0416	7.3655	24.000	76.000	0.040	0.846
RSW-03	51.0000	24.8113	10.1292	22.000	88.000		
RSW-01	48.5000	18.0416	7.3655	24.000	76.000	11.679	0.007
RSW-04	85.3333	19.2735	7.8684	62.000	113.000		
RSW-01	48.5000	18.0416	7.3655	24.000	76.000	0.006	0.940
RSW-05	47.8333	10.8336	4.4228	32.000	62.000		

Appendix IV. c: A TABLE OF A DESCRIPTIVE TEST OF ALKALINITY RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	52.5000	23.5181	9.6012	26.000	88.000	0.012	0.917
RSW-03	51.0000	24.8113	10.1292	22.000	88.000		
RSW-02	52.5000	23.5181	9.6012	26.000	88.000	6.996	0.025
RSW-04	85.3333	19.2735	7.8684	62.000	113.000		
RSW-02	52.5000	23.5181	9.6012	26.000	88.000	0.195	0.668
RSW-05	4 <mark>7.833</mark> 3	10.8336	4.4228	32.000	62 <mark>.00</mark> 0		

Appendix IV. d: A TABLE OF A DESCRIPTIVE TEST OF ALKALINITY RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	51.0000	24.8113	10.1292	22.000	88.000	7.165	0.023
RSW-04	85.3333	19.2735	7.8684	62.000	113.000		
RSW-03	51.0000	24.8113	10.1292	22.000	88.000	0.082	0.780
RSW-05	47.8333	10.8336	4.4228	32.000	62.000		

Appendix IV. e: A TABLE OF A DESCRIPTIVE TEST OF ALKALINITY RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	85.3333	19.2735	7.8684	62.000	113.000	17.260	0.002
RSW-05	47.8333	10.8336	4.4228	32.000	62.000		

APPENDIX V

DISSOLVED OXYGEN STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix V. a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED OXYGEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.1280	0.0217	0.0097	0.100	0.150	1.859	0.210
RGW-02	0.6640	0.8787	0.3930	0.090	2.200		

DISSOLVED OXYGEN STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix V. b: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED OXYGEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.7340	1.2128	0.5424	0.080	2.900	0.024	0.881
RSW-02	0.8660	1.4743	0.6593	0.090	3.500		
RSW-01	0.7340	1.2128	0.5424	0.080	2.900	0.047	0.833
RSW-03	0.5960	0.7394	0.3307	0.090	1.900		
RSW-01	0.7340	1.2128	0.5424	0.080	2.900	0.012	0.916
RSW-04	0.8200	1.2778	0.5714	0.120	3.100		
RSW-01	0.7340	1.2128	0.5424	0.080	2.900	0.005	0.944
RSW-05	0.7880	1.1366	0.5083	0.110	2.800		

Appendix V. C: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED OXYGEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.8660	1.4743	0.6593	0.090	3.500	0.134	0.724
RSW-03	0.5960	0.7394	0.3307	0.090	1.900		
RSW-02	0.8660	1.4743	0.6593	0.090	3.500	0.003	0.959
RSW-04	0.8200	1.2777	0.5714	0.120	3.100		
RSW-02	0.8660	1.4743	0.6593	0.090	3.500	0.009	0.928
RSW-05	0.7880	1.1366	0.5083	0.110	2.800	_	

Appendix V. d: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED OXYGEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.5960	0.7394	0.3307	0.090	1.900	0.115	0.743
RSW-04	0.8200	1.2777	0.5714	0.120	3.100		
RSW-03	0.5960	0.7394	0.3307	0.090	1.900	0.100	0.760
RSW-05	0.7880	1.1366	0.5083	0.110	2.800		

Appendix V. e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED OXYGEN RGW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.8200	1.2777	0.5714	0.120	3.100	0.002	0.968
RSW-05	0.7880	1.1366	0.5083	0.110	2.800		

APPENDIX VI

FREE CYANIDE STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix VI. a: A TABLE OF A DESCRIPTIVE TEST OF CYANIDE RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std.Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0640	0.0321	0.0144	0.002	0.010	1.231	0.296
RGW-02	0.0883	0.0392	0.0160	0.002	0.013		

FREE CYANIDE STATISTICAL ANALYSIS FOR SURFACE WATER

Appendix VI. b: A TABLE OF A DESCRIPTIVE TEST OF CYANIDE RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std.Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.0043	0.0022	0.0011	0.002	0.007	0.099	0.764
RSW-02	0.0053	0.0060	0.0030	0.001	0.014		
RSW-01	0.0043	0.0022	0.0011	0.002	0.007	0.391	0.552
RSW-03	0.0070	0.0085	0.0038	0.002	0.022		
RSW-01	0.0043	0.0022	0.0011	0.002	0.007	1.819	0.219
RSW-04	0.0146	0.0150	0.0067	0.004	0.041		
RSW-01	0.0043	0.0022	0.0011	0.002	0.007	0.026	0.877
RSW-05	0.0040	0.0022	0.0011	0.002	0.007		

Appendix VI. c: A TABLE OF A DESCRIPTIVE TEST OF CYANIDE RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std.Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.0053	0.0060	0.0030	0.001	0.014	0.121	0.738
RSW-03	0.0070	0.0085	0.0038	0.002	0.022		
RSW-02	0.0053	0.0060	0.0030	0.001	0.014	1.349	0.283
RSW-04	0.0146	0.0150	0.0067	0.004	0.041		
RSW-02	0.0053	0.0060	0.0030	0.001	0.014	0.155	0.707
RSW-05	0.0040	0.0022	0.0010	0.002	0.007		

Appendix VI. d: A TABLE OF A DESCRIPTIVE TEST OF CYANIDE RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std.Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0070	0.0085	0.0038	0.002	0.022	0.973	0.353
RSW-04	0.0146	0.0150	0.0067	0.004	0.041		
RSW-03	0.0070	0.0085	0.0038	0.002	0.022	0.467	0.516
RSW-05	0.0040	0.0022	0.0011	0.002	0.007		

Appendix VI. e: A TABLE OF A DESCRIPTIVE TEST OF CYANIDE RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std.Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0146	0.0150	0.0067	0.004	0.041	1.910	0.209
RSW-05	0.0040	0.0022	0.0011	0.002	0.007		
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APPENDIX VII

SULPHATE STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix VII. a: A TABLE OF A DESCRIPTIVE TEST OF SULPHATE RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	28.7667	8.9135	3.6390	20.500	45.000	21.060	0.001
RGW-02	10.01667	4.5508	1.85790	4.400	16.100		

SULPHATE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

Appendix VII. c: A TABLE OF A DESCRIPTIVE TEST OF SULPHATE RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

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SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	66.2167	71.2267	29.0782	26.900	210.500	1.721	0.219
RSW-02	27.0833	16.2615	6.6387	11.700	52.800		
RSW-01	66.2167	71.2267	29.0782	26.900	210.500	1.799	0.209
RSW-03	26.3167	15.3660	6.2731	13.700	53.300		
RSW-01	66.2167	71.2267	29.0782	26.900	210.500	32.055	0.000
RSW-04	267.7500	50.2909	20.5312	208 .000	344.000		
RSW-01	66.2167	71.2267	29.0782	26.900	210.500	3.326	0.101
RSW-05	6.9600	11.6616	5.2152	0.100	27.600		

Appendix VII. d: A TABLE OF A DESCRIPTIVE TEST OF SULPHATE RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	27.0833	16.2615	6.6388	11.700	52.800	0.007	0.935
RSW-03	26.3167	15.3660	6.2731	13.700	53.300		
RSW-02	27.0833	16.2615	6.6388	11.700	52.800	124.399	0.000
RSW-04	267.7500	50.2909	20.5312	208.000	344.000		
RSW-02	27.0833	16.2615	6.6388	11.700	52.800	5.326	0.046
RSW-05	6.9600	11.6616	5.2152	0.100	27.600		

Appendix VII. e: A TABLE OF A DESCRIPTIVE TEST OF SULPHATE RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	28.8400	15.7286	7.0340	14.000	53.300	102.747	0.000
RSW-04	267.7500	50.2909	20.5312	208.000	344.000		
RSW-03	28.8400	15.7286	7.0340	14.000	53.300	6.244	0.037
RSW-05	6.9600	11.6616	5.2152	0.100	27.600		

Appendix VII. f: A TABLE OF A DESCRIPTIVE TEST OF SULPHATE RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	267.7500	50.2909	20.5312	208.000	344.000	126.565	0.000
RSW-05	6.9600	11.6616	5.2152	0.100	27.600		

APPENDIX VIII

DISSOLVED ARSENIC STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix VIII. a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ARSENIC BETWEEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0055	0.0035	0.0025	0.003	0.008	0.054	0.838
RGW-02	0.0045	0.0049	0.0035	0.001	0.008		

DISSOLVED STATISTICAL ARSENIC ANALYSIS FOR SURFACE WATER SAMPLES Appendix VIII. c: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ARSENIC BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.0043	0.0019	0.0010	0.003	0.007	3.888	0.096
RSW-02	0.0085	0.0039	0.0019	0.003	0.012		
RSW-01	0.0043	0.0019	0.0010	0.003	0.007	5.286	0.051
RSW-03	0.0137	0.0079	0.0032	0.005	0.027		
RSW-01	0.0043	0.0019	0.0010	0.003	0.007	3.018	0.126
RSW-04	0.0208	0.0187	0.0084	0.007	0.051		
RSW-01	0.0043	0.0019	0.0010	0.003	0.007	0.179	0.685
RSW-05	0.0050	0.0031	0.0014	0.001	0.009		

Appendix VIII. d.: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ARSENIC BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.0085	0.0039	0.0019	0.003	0.012	1.438	0.265
RSW-03	0.0137	0.0079	0.0032	0.005	0.027		
RSW-02	0.0085	0.0039	0.0019	0.003	0.012	1.628	0.243
RSW-04	0.0208	0.0187	0.0084	0.007	0.051		
RSW-02	0.0085	0.0039	0.0019	0.003	0.012	2.296	0.173
RSW-05	0.0050	0.0031	0.0014	<mark>0</mark> .001	0.009	2	

Appendix VIII. e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ARSENIC BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0137	0.0079	0.0032	0.005	0.027	0.729	0.415
RSW-04	0.0208	0.0187	0.0084	0.007	0.051		
RSW-03	0.0137	0.0079	0.0032	0.005	0.027	5.278	0.047
RSW-05	0.0050	0.0031	0.0014	0.001	0.009		

Appendix VIII. f.: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ARSENIC BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0208	0.0187	0.0084	0.007	0.051	3.470	0.099
RSW-05	0.0050	0.0031	0.0014	0.001	0.009		

APPENDIX IX

TOTAL ARSENIC STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix IX. a: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ARSENIC BETWEEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0065	0.0050	0.0035	0.003	0.010	0.080	0.804
RGW-02	0.0050	0.0057	0.0040	0.001	0.009		

TOTAL ARSENIC STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix IX. c: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ARSENIC BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.0118	0.0061	0.0027	0.007	0.021	2.512	0.147
RSW-02	0.0213	0.0122	0.0050	0.008	0.037		
RSW-01	0.0118	0.0061	0.0027	0.007	0.021	3.395	0.098
RSW-03	0.0365	0.0292	0.0119	0.007	0.081		
RSW-01	0.0118	0.0061	0.0027	0.007	0.021	2.698	0.135
RSW-04	0.0802	0.0921	0.0376	0.013	0.251		
RSW-01	0.0012	0.0061	0.0027	0.007	0.021	3.585	0.091
RSW-05	0.0065	0.0030	0.0012	0.003	0.012		

Appendix IX. d: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ARSENIC BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.0213	0.0122	0.0050	0.008	0.037	1.379	0.268
RSW-03	0.0365	0.0292	0.0119	0.007	0.081		
RSW-02	0.0213	0.0122	0.0050	0.008	0.037	2.408	0.152
RSW-04	0.0802	0.0921	0.0376	0.013	0.251		
RSW-02	0.0213	0.0122	0.0050	0.008	0.037	8.389	0.016
RSW-05	0.0065	0.0030	0.0012	0.003	0.012		

Appendix IX. e: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ARSENIC BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0365	0.0292	0.0119	0.007	0.081	1.227	0.294
RSW-04	0.0802	0.0921	0.0376	0.013	0.251		
RSW-03	0.0365	0.0292	0.0119	0.007	0.081	6.266	0.031
RSW-05	0.0065	0.0030	0.0012	0.003	0.012		

Appendix IX. f: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ARSENIC BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0801	0.0921	0.0376	0.013	0.251	3.838	0.079
RSW-05	0.0065	0.0030	0.0012	0.003	0.012		

APPENDIX X

DISSOLVED IRON STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix X. a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED IRON BETWEEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0177	0.0220	0.0127	0.003	0.043	30.300	0.001
RGW-02	8.6815	2.6337	1.0752	4.946	12.640		

DISSOLVED IRON STATISTICAL ANALYSIS FOR SURFACE WATER Appendix X. b: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED IRON BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.9836	0.6514	0.2913	0.154	1.949	5.891	0.038
RSW-02	0.3065	0.2065	0.0843	0.071	0.562		
RSW-01	0.9836	0.65134	0.2913	0.154	1.949	2.045	0.186
RSW-03	0.4935	0.4870	0.1988	0.082	1.408		
RSW-01	0.9836	0.6514	0.2913	0.154	1.949	0.031	0.864
RSW-04	0.8382	1.7203	0.7693	0.020	3.914		
RSW-01	0.9836	0.6514	0.2913	0.154	1.949	0.601	0.458
RSW-05	0.7467	0.3447	0.1407	0.463	1.308		

Appendix X. C: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED IRON BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.3065	0.2065	0.0843	0.071	0.562	0.750	0.407
RSW-03	0.4935	0.4869	0.1988	0.082	1.408		
RSW-02	0.3065	0.2065	0.0843	0.071	0.562	0.576	0.467
RSW-04	0.8382	1.7203	0.7693	0.020	3.914		
RSW-02	0.3065	0.2065	0.0843	0.071	0.562	7.201	0.023
RSW-05	0.7467	0.3447	0.1407	<mark>0</mark> .463	1.3 <mark>08</mark>	1	

Appendix X. d: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED IRON BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.4935	0.4869	0.1988	0.082	1.408	0.224	0.647
RSW-04	0.8382	1.7203	0.7693	0.020	3.914		
RSW-03	0.4935	0.4869	0.1988	0.082	1.408	1.081	0.323
RSW-05	0.7467	0.34467	0.1407	0.463	1.308		

Appendix X. e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED IRON BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.8382	1.7203	0.7693	0.020	3.914	0.017	0.900
RSW-05	0.7467	0.3447	0.1407	0.463	1.308		

APPENDIX XI

TOTAL IRON STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XI. a: A TABLE OF A DESCRIPTIVE TEST OF TOTAL IRON BETWEEN RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0466	0.0247	0.0110	0.026	0.087	84.858	0.000
RGW-02	11.5973	2.7781	1.1342	8.758	15.925		

TOTAL IRON STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix XI. b: A TABLE OF A DESCRIPTIVE TEST OF TOTAL IRON BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	3.8682	1.5869	0.6478	0.804	5.094	0.195	0.668
RSW-02	4.7385	4.5556	1.8598	1.618	13.938		
RSW-01	3.8682	1.5869	0.6478	0.804	5.094	3.775	0.081
RSW-03	2.5303	0.5712	0.2332	1.749	3.342		
RSW-01	3.8682	1.5869	0.6478	0.804	5.094	0.837	0.382
RSW-04	6.1850	5.9981	2.4487	0.212	17.703		
RSW-01	3.8682	1.5869	0.6478	0.804	5.094	11.033	0.008
RSW-05	1.5155	0.7014	0.2864	0.491	2.325		

Appendix XI. C: A TABLE OF A DESCRIPTIVE TEST OF TOTAL IRON BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	4.7385	4.5556	1.8598	1.618	13.938	1.388	0.266
RSW-03	2.5303	0.5712	0.2332	1.749	3.342		
RSW-02	4.7385	4.5556	1.8598	1.618	13.938	0.221	0.648
RSW-04	6.1850	5.9981	2.4487	0.212	17.703		
RSW-02	4.7385	4.5556	1.8598	1.618	13.938	2.934	0.118
RSW-05	1.5155	0.7014	0.2864	0.491	2. <mark>325</mark>		

Appendix XI. d: A TABLE OF A DESCRIPTIVE TEST OF TOTAL IRON BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	2.5303	0.5712	0.2332	1.749	3.342	2.207	0.168
RSW-04	6.1850	5.9981	2.4487	0.212	17.703		
RSW-03	2.5303	0.5712	0.2332	1.749	3.342	7.551	0.021
RSW-05	1.5155	0.7014	0.2864	0.491	2.325		

Appendix XI. e: A TABLE OF A DESCRIPTIVE TEST OF TOTAL IRON BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	6.1850	5.9981	2.4487	0.212	17.7030	3.587	0.087
RSW-05	1.5155	0.7014	0.2864	0.491	2.325		

APPENDIX XII

DISSOLVED COPPER STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XII. a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED COPPER BETWEEN RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.2127	0.1123	0.0458	0.121	0.432	6.977	0.033
RGW-02	0.0310	0.0400	0.0231	0.005	0.077		

DISSOLVED COPPER STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix XII. b: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED COPPER BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.0518	0.0408	0.0204	0.005	0.086	0.327	0.592
RSW-02	0.0353	0.0321	0.0186	0.005	0.069		
RSW-01	0.0518	0.0408	0.0204	0.005	0.086	3.580	0.117
RSW-03	0.0060	0.0017	0.0010	0.005	0.008		
RSW-01	0.0518	0.0408	0.0204	0.005	0.086	0.171	0.696
RSW-04	0.0650	0.0436	0.0252	0.028	0.113		
RSW-01	0.0518	0.0408	0.0204	0.005	0.086	0.986	0.377
RSW-05	0.0200	0.0212	0.0150	0.005	0.035		

Appendix XII. C: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED COPPER BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.0353	0.0321	0.0186	0.005	0.069	2.493	0.189
RSW-03	0.0060	0.0017	0.0010	0.005	0.008		
RSW-02	0.0353	0.0321	0.0186	0.005	0.069	0.901	0.396
RSW-04	0.0650	0.0436	0.0252	0.028	0.113		
RSW-02	0.0353	0.0321	0.0186	0.005	0.069	0.337	0.603
RSW-05	0.0200	0.0212	0.0150	0.005	0.03 <mark>5</mark>	2	

Appendix XII. d: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED COPPER BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0060	0.0017	0.0010	0.005	0.008	5.496	0.079
RSW-04	0.0650	0.0436	0.0251	0.028	0.113		
RSW-03	0.0060	0.0017	0.0010	0.005	0.008	1.547	0.302
RSW-05	0.0200	0.0212	0.0150	0.005	0.035		

Appendix XII. e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED COPPER BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0650	0.0436	0.0251	0.028	0.113	1.718	0.281
RSW-05	0.0200	0.0212	0.0150	0.005	0.035		

APPENDIX XIII

TOTAL COPPER STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES

Appendix XIII .a: A TABLE OF A DESCRIPTIVE TEST OF TOTAL COPPER BETWEEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum M	aximum	F	Sig.
RGW-01	0.2116	0.0525	0.0235	0.158	0.280	3.105	0.116
RGW-02	0.1236	0.0986	0.0441	0.070	0.299		

TOTAL COPPER STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix XIII .b: A TABLE OF A DESCRIPTIVE TEST OF TOTAL COPPER BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum I	Maximum	F	Sig.
RSW-01	0.0442	0.0492	0.0220	0.005	0.119	0.048	0.832
RSW-02	0.0388	0.0251	0.0112	0.008	0.077		
RSW-01	0.0442	0.0492	0.0220	0.005	0.119	0.316	0.591
RSW-03	0.0295	0.0176	0.0088	0.005	0.045		
RSW-01	0.0442	0.0492	0.0220	0.005	0.119	0.928	0.364
RSW-04	0.1034	0.1283	0.0574	0.024	0.331		
RSW-01	0.0442	0.0492	0.0220	0.005	0.119	0.001	0.975
RSW-05	0.0433	0.0336	0.0168	0.005	0.072		
RSW-01 RSW-03 RSW-01 RSW-04 RSW-01 RSW-05	0.0442 0.0295 0.0442 0.1034 0.0442 0.0433	0.0492 0.0176 0.0492 0.1283 0.0492 0.0336	0.0220 0.0088 0.0220 0.0574 0.0220 0.0168	0.005 0.005 0.005 0.024 0.005 0.005	0.119 0.045 0.119 0.331 0.119 0.072	0.316 0.928 0.001	0.5 0.3 0.9

Appendix XIII .c: A TABLE OF A DESCRIPTIVE TEST OF TOTAL COPPER BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum Max	kimum F	Sig.
RSW-02	0.0388	0.0251	0.0112	0.008 0.	.077 0.391	0.552
RSW-03	0.0295	0.0176	0.0088	0.005 0.	.045	
RSW-02	0.0388	0.0251	0.0112	0.008 0.	.077 1.221	0.301
RSW-04	0.1034	0.1283	0.0574	0.024 0.	.331	
RSW-02	0.0388	0.0251	0.0112	0.008 0.	.077 0.052	0.826
RSW-05	0.0433	0.0336	0.0168	0.005 0.	.072	

Appendix XIII .d: A TABLE OF A DESCRIPTIVE TEST OF TOTAL COPPER BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum Ma	aximum	F	Sig.
RSW-03	0.0295	0.0176	0.0088	0.005 0).045	1.273	0.296
RSW-04	0.1034	0.1283	0.0574	0.024 0).331		
RSW-03	0.0295	0.0176	0.0088	0.005 0).045	0.525	0.496
RSW-05	0.0433	0.0336	0.0168	0.005 0).072		

Appendix XIII .e: A TABLE OF A DESCRIPTIVE TEST OF TOTAL COPPER BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.1034	0.1283	0.0574	0.024	0.331	0.813	0.397
RSW-05	0.0433	0.0336	0.0168	0.005	0.072		

APPENDIX XIV

DISSOLVED ZINC STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XIV .a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ZINC BETWEEN RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0150	0.0069	0.0028	0.010	0.028	7.967	0.018
RGW-02	0.0279	0.0089	0.0036	0.018	0.042		

DISSOLVED ZINC STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XIV .b: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ZINC BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum I	Maximum	F	Sig.
RSW-01	0.0713	0.1365	0.0611	0.004	0.315	0.682	0.436
RSW-02	0.0139	0.0134	0.0067	0.003	0.032		
RSW-01	0.0713	0.1365	0.0611	0.004	0.315	0.895	0.376
RSW-03	0.0058	0.0048	0.0024	0.002	0.012		
RSW-01	0.0713	0.1365	0.0611	0.004	0.315	0.973	0.350
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-01	0.0713	0.1365	0.0611	0.004	0.315	0.529	0.491
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

Appendix XIV .c: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ZINC BETWEEN RSW-02 AND OTHER SAMPLING S ITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum N	Maximum	F	Sig.
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	1.310	0.296
RSW-03	0.0058	0.0048	0.0024	0.002	0.012		
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	0.057	0.817
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	.241	0.641
RSW-05	0.0204	0.0230	0.0115	0.004	0.054	2/	

Appendix XIV .d: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ZINC BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.365	0.276
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.558	0.258
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

Appendix XIV .e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED ZINC BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0164	0.0174	0.0071	0.006	0.051	0.102	0.758
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

APPENDIX XV

TOTAL ZINC STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XV .a: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ZINC BETWEEN RGW-01 AND RGW-02 SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.0235	0.0085	0.0035	0.017	0.040	4.773	0.054
RGW-02	0.0442	0.0215	0.0088	0.018	0.075		

TOTAL ZINC STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix XV .b: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ZINC BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum Ma	iximum	F	Sig.
RSW-01	0.0777	0.1430	0.0639	0.004 0).333	1.048	0.333
RSW-02	0.0182	0.0149	0.0061	0.002 0).037		
RSW-01	0.0777	0.1430	0.0639	0.004 0).333	0.873	0.374
RSW-03	0.0237	0.0079	0.0032	0.015 0).034		
RSW-01	0.0777	0.1430	0.0639	0.004 C).333	0.636	0.446
RSW-04	0.0313	0.0166	0.0068	0.009 0).055		
RSW-01	0.0777	0.1430	0.0639	0.004 0).333	0.336	0.578
RSW-05	0.0400	0.0254	0.0114	0.006 0).066		

Appendix XV .c: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ZINC BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum Ma	aximum	F	Sig.
RSW-02	0.0182	0.0149	0.0061	0.002 (0.037	0.625	0.448
RSW-03	0.0237	0.0079	0.0032	0.015 (0.034		
RSW-02	0.0182	0.0149	0.0061	0.002 (0.037	2.048	0.183
RSW-04	0.0313	0.0166	0.0068	0.009 (0.055		
RSW-02	0.0182	0.0149	0.0061	0.002 (0.037	3.166	0.109
RSW-05	0.0400	0.0254	0.0114	0.006 (0.066	-	

Appendix XV .d: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ZINC BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum Max	kimum F	Sig.
RSW-03	0.0237	0.0079	0.0032	0.015 0	.034 1.027	0.335
RSW-04	0.0313	0.0166	0.0068	0.009 0	.055	
RSW-03	0.0237	0.0079	0.0032	0.015 0	.034 2.280	0.165
RSW-05	0.0400	0.0254	0.0114	0.006 0	.066	

Appendix XV .e: A TABLE OF A DESCRIPTIVE TEST OF TOTAL ZINC BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0313	0.0166	0.0068	0.009	0.055	0.475	0.508
RSW-05	0.0400	0.0254	0.0114	0.006	0.066		

APPENDIX XVI

DISSOLVED MANGANESE STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XVI .a: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED MANGANESE BETWEEN RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RGW-01	0.2595	0.0448	0.0183	0.217	0.320	4.946	0.050
RGW-02	0.1883	0.0643	0.0263	0.114	0.270		

DISSOLVED STATISTICAL MANAGESE ANALYSIS FOR SURFACE WATER SAMPLES Appendix XVI .b: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED MANGANESE BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum I	Maximum	F	Sig.
RSW-01	0.8023	0.6888	0.2812	0.338	2.190	3.483	0.092
RSW-02	0.2685	0.1281	0.0523	0.143	0.471		
RSW-01	0.8023	0.6888	0.2812	0.338	2.190	5.782	0.037
RSW-03	0.1225	0.0717	0.0293	0.051	0.259		
RSW-01	0.8023	0.6888	0.2812	0.338	2.190	6.142	0.033
RSW-04	2.2063	1.2047	0.4918	1.252	4.593		
RSW-01	0.8023	0.6888	0.2812	0.338	2.190	5.090	0.051
RSW-05	0.0992	0.0548	0.0245	0.043	0.181		

Appendix XVI .c: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED MANGANESE BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

	SITES	Mean	Std. Deviation	Std. Error	Minimum Maxi	mum F	Sig.
	RSW-02	0.0139	0.0134	0.0067	0.003 0.0	032 1.310	0.296
	RSW-03	0.0058	0.0048	0.0024	0.002 0.0)12	
	RSW-02	0.0139	0.0134	0.0067	0.003 0.0	0.057	0.817
	RSW-04	0.0164	0.0174	0.0071	0.006 0.0)51	
	RSW-02	0.0139	0.0134	0.0067	0.003 0.0	0.241	0.641
	RSW-05	0.0204	0.0230	0.0115	0.004 0.0)54	
1							

Appendix XVI .d: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED MANGANESE BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum N	laximum	F	Sig.
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.365	0.276
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.558	0.258
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

Appendix XVI .e: A TABLE OF A DESCRIPTIVE TEST OF DISSOLVED MANGANESE BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	0.0164	0.0174	0.0071	0.006	0.051	0.102	0.758
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

APPENDIX XVII

TOTAL MANAGESE STATISTICAL ANALYSIS FOR UNDERGROUND WATER SAMPLES Appendix XVII .a: A TABLE OF A DESCRIPTIVE TEST OF TOTAL MANGANESE BETWEEN RGW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum N	Maximum	F	Sig.
RGW-01	0.2802	0.0514	0.0210	0.228	0.360	2.820	0.124
RGW-02	0.2240	0.0638	0.0260	0.168	0.313		

TOTAL MANAGESE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES Appendix XVII .b: A TABLE OF A DESCRIPTIVE TEST OF TOTAL MANGANESE BETWEEN RSW-01 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

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SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-01	0.8703	0.6522	0.2663	0.525	2.195	4.531	0.059
RSW-02	0.2923	0.1304	0.0533	0.165	0.485		
RSW-01	0.8703	0.6522	0.2663	0.525	2.195	0.716	0.417
RSW-03	0.4953	0.8674	0.3541	0.097	2.265		
RSW-01	0.8703	0.6522	0.2663	0.525	2.195	6.297	0.031
RSW-04	2.2710	1.2017	0.4906	1.346	4.655		
RSW-01	0.8703	0.6522	0.2663	0.525	2.195	7.843	0.019
RSW-05	0.1222	0.0533	0.0218	0.050	0.203		

Appendix XVII .c: A TABLE OF A DESCRIPTIVE TEST OF TOTAL MANGANESE BETWEEN RSW-02 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	1.310	0.296
RSW-03	0.0058	0.0048	0.0024	0.002	0.012		
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	0.057	0.817
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-02	0.0139	0.0134	0.0067	0.003	0.032	0.241	0.641
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

Appendix XVII .d: A TABLE OF A DESCRIPTIVE TEST OF TOTAL MANGANESE BETWEEN RSW-03 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.365	0.276
RSW-04	0.0164	0.0174	0.0071	0.006	0.051		
RSW-03	0.0058	0.0048	0.0024	0.002	0.012	1.558	0.258
RSW-05	0.0204	0.0230	0.0115	0.004	0.054		

Appendix XVII .e: A TABLE OF A DESCRIPTIVE TEST OF TOTAL MANGANESE BETWEEN RSW-04 AND OTHER SAMPLING SITE IN THE CONCESSIONAL AREA

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSW-04	2.2710	1.2017	0.4906	1.346	4.655	19.147	0.001
RSW-05	0.1222	0.0533	0.0218	0.050	0.203		

APPENDIX XVIII

PERCENTAGE CARBON ANALYSIS FOR SOIL SAMPLES

Appendix XVIII .a: A TABLE OF A DESCRIPTIVE TEST FOR PERCENTAGE CARBON OF THE SOIL SAMPLE USED IN THE ANALYSIS. TAILING SAMPLE COMPARED WITH A NEW AND AN OLD WASTE DUMP.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSS-01	1.8247	0.4190	0.1710	0.994	2.172	78.517	0.000
RSS-02	0.2720	0.0931	0.0380	0.118	0.400		
RSS-01	1.8247	0.4190	0.1710	0.994	2.172	75.379	0.000
RSS-03	0.1922	0.1913	0.0781	0.057	0.477		

Appendix XVIII .b: A TABLE OF A DESCRIPTIVE TEST FOR PERCENTAGE CARBON OF THE SOIL SAMPLE USED IN THE ANALYSIS. NEW WASTE DUMP COMPARED WITH AN OLD WASTE DUMP SAMPLES.

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.	
RSS-02	0.2720	0.0931	0.0380	0.118	0.400	0.845	0.380	
RSS-03	0.1922	0.1913	0.0781	0.057	0.477			

PERCENTAGE SULFUR ANALYSIS FOR SOIL SAMPLES

Appendix XVIII .c: A TABLE OF A DESCRIPTIVE TEST FOR PERCENTAGE SULFUR OF THE SOIL SAMPLE USED IN THE ANALYSIS. TAILING SAMPLE COMPARED WITH A NEW AND OLD WASTE DUMP

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSS-01	1.5830	1.3673	0.5582	0.553	4.221	6.256	0.031
RSS-02	0.15700	0.2842	0.1160	0.020	0.735		
RSS-01	1.5830	1.3673	0.5582	0.553	4.221	7.803	0.019
RSS-03	0.0237	0.0155	0.0063	0.004	0.044		

Appendix XVIII .d: A TABLE OF A DESCRIPTIVE TEST FOR PERCENTAGE SULFUR OF THE SOIL SAMPLE USED IN THE ANALYSIS. NEW WASTE DUMP COMPARED AND OLD WASTE DUMP SAMPLE

SITES	Mean	Std. Deviation	Std. Error	Minimum	Maximum	F	Sig.
RSS-02	0.1570	0.2842	0.1160	0.020	0.735	1.317	0.278
RSS-03	0.0237	0.0155	0.0063	0.004	0.044		