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KNUST

EFFECTS OF SMALL SCALE GOLD MINING ON WATER RESOURCES: A CASE STUDY OF BOGOSO/PRESTEA MINING AREA.

A THESIS SUBMITTED TO THE DEPARTMENT OF THEORETICAL AND APPLIED BIOLOGY, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE (ENVIRONMENTAL SCIENCE)

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DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no materials which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

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iii

ABSTRACT

Small scale gold mining in Ghana is largely an informal industry employing thousands of people. The industry is largely undeveloped, unmonitored and unrestrained, and coupled with their intense reliance on water resources for the processing of gold have resulted in uncontrolled release of substances which impact negatively on the quality of these water resources. This study assessed the effects of small scale gold mining on the quality of water resources within the Bogoso / Prestea mining area in the Western Region of Ghana. Surface and ground water samples were collected monthly from the months of October, 2010 to March, 2011 at ten different sampling sites within the study area. Levels of selected metals, namely, Fe, As, Hg and Mn were determined by Atomic Absorption Spectrometer. Concentrations of phosphates, sulphates and chlorides, as well as some physicochemical parameters were determined using standard methods. The results obtained showed variations in the investigated parameters in surface and ground water samples. Surface water samples recorded high concentrations in most of the investigated parameters than the groundwater samples. However, Mn concentrations were high in the groundwater samples and were above the WHO permissible limit for drinking water. Iron and manganese levels in the surface and ground water samples exceeded the World Health Organization drinking water quality guidelines. In general, the results of the study indicated that, small scale gold mining operations negatively impacted on water resources, most especially on surface waters.



TABLE OF CONTENTS

		Pages
Title Page		i
Declaration		ii
Acknowledgement		iii
Abstract		iv
Table of contents		v-vii
List of Tables	3	viii
List of Figures		ix
List of Plates		Х
CHAPTER ONE	KNUST	
1.0 INTROD	DUCTION	1
1.1 Statement	t of the problem	3
1.2 Main Obj	ective	4
1.3	Specific Objectives	4
CHAPTER TWO	ETER () (III)	
2.0	LITERATURE REVIEW	5
2.1	Water Resources	5
2.2	Small Scale Gold Mining in Ghana	7
2.3	Methods of mining	9
2.4	Methods of processing	11
2.5	Environmental, Health and Safety Impacts	13
	2.5.1 Environmental Impacts	13
	2.5.1.1 Degradation of Land and Vegetation	13
	2.5.1.2 Deforestation	13
	2.5.1.3 Water Pollution	14
	2.5.1.4 Acid Rock Drainage	14
	2.5.1.5 Mercury Pollution	15
	2.5.1.6 Airborne Particulate Matter	16
	2.5.2 Safety and Health Impacts	17

CHAPTER THREE

3.0	MA	FERIALS AND METHODS	19
3	3.1 Stud	y Area	19
	3.1.1	Location	19
	3.1.2	Topography and Drainage	21
	3.1.3	Climate	21
	3.1.4	Vegetation	21
	3.1.5	Geology and Soil	22
	3.1.6	Demographics	24
	3.1.7	Economic Activities	24
3	3.2 Sam	pling Sites	24
3	3.3 Sam	ples collection	25
3	3.4 Labo	pratory Analysis	27
	3.4.1	Determination of Alkalinity	27
	3.4.2	Determination of sulphate and phosphate	27
	3.4.3	Total Metals	27
3	8.5 Qual	lity assurance	28
3	3.6 Stati	stical Analysis	28
CHAPTER FO	UR	Contraction of the second seco	
4.0	RES	SULTS	29
4	1.1 Phys	sicochemical parameters of water samples from the streams	
	and	boreholes	29
4	.2 Sulp	hates, phosphates and chlorides concentrations in	31
the s	treams and b	oreholes	
4	.3 Meta	al Concentrations in surface and ground water samples	32
CHAPTER FI	VE		
5.0	DIS	CUSSION	35
5	5.1 Physico-c	hemical parameters	35
5.	1.1 The pH o	f the water samples	35
5.	1.2 Temperat	ure	36
5.	1.3 Electrical	Conductivity	36
5.	1.4 Alkalinit	Ý	37

	5.1.5 Dissolved Oxygen	38
	5.1.6 Total Dissolved Solids	39
5.2	Anions concentrations	40
	5.2.1 Sulphate	40
	5.2.2 Phosphate	40
	5.2.3 Chloride	41
5.3	Metal concentrations	41
	5.3.1 Mercury	41
	5.3.2 Iron	42
	5.3.3 Manganese	43
	5.3.4 Arsenic	43
	KNUST	

CHAPTER SIX

CHAPTER SIX		
6.0	CONCLUSION AND RECOMMENDATIONS	46
6.1	Conclusion	46
6.2	Recommendations	47
REFERENCES APPENDICES		48 55
	W J SAME NO BADHER	

LIST OF TABLES

Table 1 Sampling sites and their designated codes	25
Table 2 Physico-chemical parameters of water samples	31
Table 3 Levels of anions determined in the water samples	32
Table 4 Metals concentrations determined in the water samples	33



LIST OF FIGURES

Figure 1 Schematic flow sheet for ore processing in Small scale Gold Mines	12
Figure 2 Map of Bogoso/Prestea Mining Area showing the sampling points	20



LIST OF PLATES

Plate 1 Sampling site at Asesere stream	26
Plate 2 Sampling site at Prestea Town borehole	26



GLOSSARY

- ECA: Economic Commission for Africa
- FAO: Food and Agriculture Organization
- GEM: Global Environment Monitoring System/Water Programme.
- GSBPL: Golden Star Bogoso Prestea Limited
- ILO: International Labour Organization
- PNDCL: Provisional National Defence Council Law
- **UN: United Nations**
- UNEP: United Nations Environmental Programme
- UNESCO: United Nations Educational, Scientific and Cultural Organization
- UNIDO: United Nations Industrial Development Organization



CHAPTER ONE

1.0 INTRODUCTION

Water is vital to the existence of all living organisms, but this valued resource is increasingly being threatened as human populations grow and demand more water of high quality for domestic purposes and economic activities. Water abstraction for domestic use, agricultural production, mining (both large and small scale), industrial production, power generation, and forestry practices can lead to deterioration in water quality and quantity that impact not only the aquatic ecosystem but also the availability of safe water for human consumption. It is now generally accepted that aquatic environments cannot be perceived simply as holding tanks that supply water for human activities. Rather, these environments are complex matrices that require careful use to ensure sustainable ecosystem functioning well into the future (UNEP GEM, 2006).

Water provides an environment for healthy populations. It serves the aesthetic and spiritual needs of societies and also forms the basis of agriculture and industries. In modern times, sustainable socio-economic progress is rarely possible without sufficient development of water resources to support food production, industry, the environment and other human needs. Water is one of the most important resources with great implications for development. Employment generation within peasant communities becomes a major issue of concern especially when land is degraded and water bodies contaminated through the activities of small scale gold mining (UN, 2003).

Small scale gold mining is a familial word in most developing countries where it is practiced and is the economic backbone in most developing nations today. Presently, it is speedily spreading throughout the tropics, primarily in Latin America, Asia and Africa where miners use simple methods to extract and process gold on small scale basis (Lacerda, 1997; Villas Boas *et al.*, 2001). Small Scale gold mining is currently estimated to be responsible for 12% of the world's gold production or approximately 330 tons per year (Telmer and Veiga, 2008). These activities are on the increase in Ghana and causing lots of environmental and health problems. Operations are usually located close to and are supported by water bodies. The miners dig up river channels, banks and their floodplains as well as surface trenching, using pick axes and shovels to recover the precious stones. The use of earth moving equipment such as bulldozers and backhoe excavators are sometimes employed. In some cases underground tunnels are constructed which eventually result in land subsidence. Blasting is often employed as last resort where hard rocks are encountered.

The most noticeable effect of these operations is siltation of rivers and streams which release enormous amounts of heavy metals into river systems. Siltation of rivers reduces river conveyance and deteriorates water quality. The transport of sediments into surface waters decreases the amount of sunlight limiting the production of algae and macrophytes.

Fish habitat can be degraded as spawning gravel becomes filled with fine particles, restricting oxygen availability for buried eggs. Turbid waters may also damage fish directly by irritating or scouring their gills, or by reducing the success of visual predators. The scouring action of turbid waters may also harm some benthic macro invertebrates (Owens *et al.*, 2005).

Small scale gold miners also clear wide areas of natural forests for firewood and infrastructural development. Deforestation openly contributes to speedy loss of soil moisture and topsoil resulting in disruption of climatic balances and the spread of desertification. This can lead to scarcity and stress of water within the area (Shoko and Love, 2005).

Enormous amount of waste are generated especially sand, gravel and rock dumps in small scale gold mines. These wastes are normally dumped haphazardly without proper planning due to high predisposition for the minerals. Ore and waste stockpiles on the surface commonly contain significant amounts of sulphides and with time lead to acid rock drainage. The impact of acid rock drainage on the ecosystem may be severe and may result in the total elimination of animal life from the receiving waters (Ravengai *et al.*, 2005).

Another major problem with small scale gold mining is the use of mercury amalgamation process and panning to extract gold from ores. Amalgamation is the ideal gold recovery method engaged by almost all small scale gold miners because it is a simple technique used in gold extraction. However, it is well known that the process is devastating to health, not only to users but also to those indirectly involved, including the unborn, through peripheral contamination and introduction into the food chain (Lombe, 2003).

Moreover, panning and amalgamation are commonly done along water bodies resulting in water pollution. Roasting gold bearing amalgam releases an estimated amount of 5 tonnes of mercury each year in Ghana from small scale gold mining operations (Hilson, 2001). According to Bannerman *et al.* (2003), there was mercury contamination in Ankobra river basin as a result of small scale gold mining operations. Also, in a study supported by UNIDO, Babut *et al.* (2003) studied Hg contamination in water, sediment, soil and food crops in the Apepre river basin at Dumasi in Bogoso, a well-known small scale gold mining village in Ghana.

1.1 STATEMENT OF THE PROBLEM

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

Surface waters (rivers and streams) are the main source of water for the communities within the Bogoso / Prestea mining area. Waters in the area have become colorized as a result of the intense small scale gold mining activities. Due to this, the communities are unable to use the water resources for domestic and industrial purposes. It is against this background that the project seeks to study the effects of the activities of these small scale gold miners on the quality of water resources in selected areas within the Bogoso / Prestea mining area.

1.2 MAIN OBJECTIVE

The main objective of this work was to study the effects of small scale gold mining on the water quality of some water resources within the Bogoso / Prestea mining area.

1.3 SPECIFIC OBJECTIVES

The specific objectives were to determine the:

• concentrations of Mercury, Arsenic, Manganese and Iron,

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- Levels of phosphate (PO_4^{3-}) , sulphate (SO_4^{2-}) and chloride (Cl^{-}) ,
- pH, temperature, conductivity, total dissolved solids (TDS), dissolved oxygen (DO) and alkalinity, in water samples collected from boreholes and streams within selected areas in the study area.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 WATER RESOURCES

Fresh water has become a scarce commodity due to over utilization and pollution. Increasing population and its necessities have led to the deterioration of surface and subsurface water (Shymamala *et al.*, 2008). A precondition of sustainable growth must ensure water bodies are not contaminated (Olajire, 2001).

Providing safe and secure water to people around the world, and promoting sustainable use of water resources are elemental objectives of the Millennium Development Goals. The global community has established the important links between ecosystem and human health and well-being, particularly as human populations expand creating greater pressures on natural environments (UNEP GEM, 2006).

The availability of water and its physical, chemical, and biological composition affect the aquatic life and its healthy ecosystems as lack of potable water leads to depletion of aquatic organisms which may lead to loss of ecosystem services. Moreover, an abundant supply of potable water is a basic requirement for human existence. These include, but not limited to:

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

Increasing human activities such as small scale gold mining threaten the water resources on which living things depend. Water has been called "mining's most common casualty" (McClure and Schneider, 2001). Mining affects fresh water through effluent from processing

of ore and seepage from tailings and waste rock impoundments. Small scale gold mining activities by its nature make use of a lot of water thereby seriously polluting water resources (Cunningham, 2005).

Small scale gold mining all over the world is noted for its effects on water bodies through pollution of both ground and surface waters (Owen, 2005). These have deprived communities of access to water, which is a basic need for human survival. A publication by Project Underground (2000) indicated that lack of access to clean potable water in small scale gold mining communities has a relationship with the reduced health status of the communities, as the communities are weighed down with many water related diseases.

According to the Environmental Protection Council (EPC) (1991), water resource in Ghana was estimated to 40 million acre-feet from rainfall, rivers, streams, spring and creeks, natural lakes impoundments and ground water from various aquifers. According to the EPC (1991), water should be accessible in potable form for the entire population with least effort, and that its accessibility on a sustained basis should be assured. In reference to this, Ghana established the Water Resources Commission by an Act of Parliament (ACT 522 of 1996) with the mandate to regulate and manage the country's water resources and to co-ordinate government policies in relation to them.

Acquah (1995) recounted that, very early in the history of small scale gold mining in Ghana, water resource depletion increased marginal cost of providing potable water which increased burden on women's time and hastened climate change. Large and small scale mining industries looked at water (surface water) as 'free good' which was exploited with lack of effective regulatory framework which had deforested headwaters because there was no motivation to conserve water. According to him, degraded quality of water resources had health implications and reduced labour productivity. In the developing countries, most

diseases which affect humanity can be traced to lack of safe and wholesome water supply (Shymamala *et al.*, 2008). Again, they believed that the harm caused by small scale gold mining transcends just the mere lack of access to potable water since there are other benefits that can never be quantified.

2.2 SMALL SCALE GOLD MINING IN GHANA

Small scale gold mining is a term used to describe gold mining activities that uses simple methods (e.g. picks, chisels, sluices and pans) to extract and process gold on a small scale (Shoko *et al.*, 2005). It is also characterized by a labour force that is not formally trained in mining, prospecting, extracting, and processing of minerals. Its operations are usually informal and sometimes illegal. Working conditions are typically hazardous and unhealthy, and living conditions appalling. It is a critical livelihood activity, employing more than 13 million workers and sustaining 80 to 100 million people worldwide (ILO, 1999). These people are usually members of poor rural households in developing countries. They depend on mining as a primary source of income or a critical supplement to meagre farming revenues.

Commercial small scale gold mining is believed to have started in Ghana by the British in the early 19th century. Other records indicate that it was practiced as early as the 4th century and the indigenous people of Ghana got more involved when the Europeans arrived in 1471 (Tsikata, 1997; Akabzaa & Dramani, 2001).

Small scale gold mining in Ghana, as in most developing countries, was for decades treated as an informal industrial sector which employs thousands of people but uses largely rudimentary, unmonitored and unrestrained practices (Hilson, 2001). Until the1980s, small scale gold mining activities in Ghana remained largely unregulated and received little, if any, support from governmental bodies. With the implementation of the legal framework for registration of small scale gold and diamond mining, the sector has seen tremendous transformation (Hilson, 2001).

The Small scale mining law, PNDCL 218 (Anon, 1989a) led to the institution of the Small Scale Mining Project within the Ghana Minerals Commission. The Small Scale Mining Project (now Small Scale Mining Department) has the responsibility of providing technical assistance to prospective and registered small scale miners in Ghana.

The Mercury Law, PNDCL 217 (Anon, 1989b) legalized the purchasing of mercury for gold recovery purposes from authorized dealers and the Precious Minerals Marketing Corporation (PMMC) Law, PNDCL 219 (Anon, 1989c), created an authority to buy and sell gold and diamonds. Since the regularization exercise, two types of small scale gold miners have emerged—legal and illegal.

Legal small scale gold miners comprise of those who have acquired mining licenses from the Minerals Commission of Ghana to cover their concessions. An area of 25 acres is the maximum allowable area that is allocated to each person or group of persons as a concession (Appiah, 1998).

Small scale gold mining, therefore, has a major impact on the employment situation in the developing world, especially in rural areas where there are few job alternatives (Shoko *et al.*, 2005). Moreover, the enactment of relevant legislation and effective legalization of small scale mining has had a positive impact on the economies of certain developing countries like Ghana. By formalizing operations, illegal smuggling channels are being eliminated, thereby enabling the complete capture of internally mined product. The successful containment of the minerals mined on a small scale contributes enormously to sector revenues, and also contributes positively to foreign-exchange earnings (Hilson, 2001).

Illegal operators, on the other hand, work without licenses, have no concessions of their own and operate uncontrollably within the concessions of large scale mining companies or in areas prohibited for mining such as forest reserves and environmentally sensitive areas (Appiah, 1998). Such miners are highly disorganized and operate in a "hit and run" manner, often initiating confrontations with both state law enforcement agencies and the security personnel of large scale mining companies. Illegal small scale gold mining is popularly known in local phraseology as galamsey, a corruption of the phrase 'gather them (the gold) and sell'.

Naturally the good geological setting of Ghana allows small scale mining of gold to blossom. Several small scale mining areas are scattered throughout the country, specifically within the Tarkwaian and Birimian rock systems of Ghana (Kesse, 1985).

Significant portions of these rocks have been re-deposited as placer formations in a number of streams and channels as a result of series of erosion. Placer Gold Deposits, which are also referred to as alluvial gold, are found in the majority of rivers draining Birimian rocks. Large deposits of placer gold also occur along the terraces, floodplains, channels and river beds of the Offin, Pra, Ankobra, Birim and Tano rivers, where large Birimian and Tarkwaian gold deposits have experienced several episodes of erosion and subsequent deposition. Small scale gold mining is, for the most part, confined to these areas, since most operators lack the requisite mechanized equipment to mine hard rock deposits of the Birimian and Tarkwaian Belts (Hilson, 2001).

2.3 Methods of mining

Mining methods employed by small scale gold miners vary according to the type of deposit being exploited and its location (Ntibrey, 2001). Due to the poor financial status of small scale gold miners, majority rely solely on traditional/manual methods of mining, which use simple equipment like shovels, pick-axes, pans, chisels and hammers.

One method is the shallow alluvial mining techniques, which are popularly called "dig and wash", or the 'Krowa method' (wooden bowl carved out of tree stem to serve as a pan) are used to mine shallow alluvial deposits usually found in valleys or low lying areas. Such deposits have depths not exceeding three metres. The area is initially cleared and the soil excavated until the gold-rich layer is reached. The mineralized material is removed and transported to nearby streams for sluicing to recover the gold. Gold from sluices is concentrated by using a smaller 'krowa' or the gold pan. Women are very effective in using the 'krowa' for the recovery of gold (Appiah, 1998). Illegal small scale gold miners practice this method because of easy access.

Deep alluvial mining techniques or land dredges are also another type used to mine deep alluvial deposits found along the banks of major rivers such as the Ankobra, Tano, and Offin and certain older river courses. These methods involve excavating a pit and digging until the gold bearing gravel horizon, which is typically located at depths of 7 to 12 metres, is reached. The gold bearing rocks are then removed and sluiced to recover the gold.

In recent years, some of the richer owners have introduced large machinery to this method, bulldozing and back-hoeing pits to access layers of gold bearing gravels more quickly or those formerly inaccessible by manual methods alone (Ntribrey, 2001)

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

2.4 Methods of processing

Firstly, ore is crushed into pebbles by physical or mechanical means. The pebbles undergo primary, secondary and tertiary grinding in preparation for washing. The ground ore are transferred to the riverside or pond in cloth bags to be refined (Amegbey and Eshun, 2003).

The gold containing material is washed on sluices where the heavier gold particles are caught and concentrated on carpets or jute sacks, due to gravity. The concentrate from the sluice box is re-assembled in rubber dishes or wooden pans (Krowa). Through panning, the undesirable sediments are separated from the gold particles until the latter clearly appear in the final concentrate.

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

Finally, the amalgam is roasted in a coal pot for 15–40 min, depending on size. Burning can also take place with a blowtorch.

During gold production mercury losses occur at various stages:

(1) Amalgamation, where mercury may be washed out during the gravity washing; and

(2) Burning, where mercury, with its high volatility, is released into the atmosphere. After burning, a sponge-like gold substance stays behind in the tin. When the gold has cooled, it is weighed and at the end of the day sold.



Figure 1: Schematic flow sheet for ore processing in small scale gold mines.

2.5 ENVIRONMENTAL, HEALTH AND SAFETY IMPACTS OF SMALL SCALE GOLD MINING

2.5.1 Environmental Impact

2.5.1.1 Degradation of Land

Large areas of land and vegetation are cleared to make way for small scale gold mining operations. This has crucial adverse impact on the people since land is the main sources of livelihood of the people living in these areas. There is therefore deterioration in the viability of the land for agricultural purposes and loss of habitat for micro and macro organisms. (Akabza and Dramani, 2001).

Small scale gold mining activity also causes significant damage to landscapes. More specifically, as a migratory industry, miners typically abandon pits and trenches without properly reclaiming the lands. It is therefore quite common to find potholes virtually devoid of vegetative cover after periods of intensive prospecting (Hilson, 2001).

2.5.1.2 Deforestation

The hasty emergent of overnight settlements in newly discovered gold areas lead to rapid "urbanization" in the form of messy settlements which do not only end in rampant deforestation, but also social evils associated with urbanization which include alcohol and drug abuse, prostitution, land use conflicts with local communities, as well as water pollution, child labour and diseases (Lacerda, 1997).

Deforestation is determined by the need for the building of shelters, underground support props, panning dishes and use of firewood. The excessive dependence on wood as a source of energy results in the reduction of biodiversity and increasing rates of desertification. For instance in Zimbabwe it is estimated that about 4 million tonnes of wood is used every year as fuel, which translates to felling trees covering approximately 100 000 hectares (Chiwawa, 1993).

2.5.1.3 Water Pollution

Water pollution (surface and ground) may be considered as a naturally induced change in water quality or conditions induced directly by man's numerous activities which render it unbefitting for food, human health, industry, agriculture or leisure per suit (Cifuentes and Rodriguez, 2005). Toxic chemicals in water pose the greatest threat to the safety of drinking water and their effects are enormous of which can cause damage to human health, crops and aquatic organism.

Pollution or destruction of rivers and streams deprives communities of their protein needs, incomes, recreation and other benefits. Polluted stream is an indication of its loss-based livelihoods, destruction of the recreational potential of rivers and the loss of all the valuable benefits that communities derive from rivers.

Most of the activities of small scale miners also divert watercourses away from the mining sites. This disturbs and disrupts the natural watercourse which leads to surface water pollution. Crispin (2003) reports that four key areas of impact that small scale gold mining may have on water systems are the release of metals, acid rock drainage (ARD), siltation and water use.

2.5.1.4 Acid Rock Drainage

Acid Rock drainage (ARD) is a potentially severe pollution hazard that can contaminate surrounding soil, groundwater, and surface water. The formation of acid rock drainage is a function of the geology, hydrology, and mining technology employed at mine sites. Although acid rock drainage is part of the natural weathering process. This is exacerbated by large scale disturbances that accumulate due to continuous small scale gold mining activities. The primary sources for acid generation are sulphide minerals, such as pyrite (iron sulphide), which decompose in air and water (Skousen *et al.*, 1990).

Many of these sulphide minerals originate from waste rocks removed from the mine or from tailings. If water infiltrates pyrite-laden rocks in the presence of air, it becomes acidified, often at a pH level of two or three. A naturally occurring type of bacteria called Thiobacillus ferroxidans may kick in, accelerating the oxidation and acidification processes, leaching even more trace metals from the wastes (Rozkowski and Rozkowski, 1994). Increased acidity in the water can destroy aquatic organisms and the food web changes significantly.

2.5.1.5 Mercury pollution

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

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Elemental mercury (Hg) is quite volatile and only slightly soluble in water. It is dispersed very effectively through the atmosphere with long residence times of about 2 years, and it is normally transported from likely sources of emission (Lodenius & Malm, 1998; Boening, 2000). Thus, Hg in the various oxidation states is released into the environment from a variety of anthropogenic activities and natural sources. Wet and dry deposition is the only primary mechanisms for transporting this element from the atmosphere to the terrestrial and aquatic systems (Meech *et al.*, 1998). Small scale gold mining is one such anthropogenic activity that has resulted in the use of an enormous amount of metallic mercury. The mercury used by the miners is usually discharged in an abusive manner into ecosystems (Pfeiffer & Larceda, 1988).

Elemental Hg is now known to spread very effectively from diverse sources to both terrestrial and aquatic systems (Hilson *et al.*, 2003). Sediments function as sinks and potential sources of Hg and once contaminated, pose a risk to aquatic life for many years. Depending on the

environmental conditions present Hg compounds in aquatic systems could be transformed and liberated from sediments to water phase, ingested by aquatic biota, be lost to the atmosphere and dispersed or be conveyed with sediment particulate matter to new previously uncontaminated locations (Ullrich *et al.*, 2001). Furthermore, research indicates that the ecological and toxicological effects of Hg strongly depend on the various chemical species present.

Inorganic Hg may be converted by microbial activity in an organic-rich environment to organic forms of Hg, e.g. methyl-Hg (MeHg), which are many times more toxic to organisms (Beijer & Jernelov, 1979). MeHg is a potent neurotoxin, damages the central nervous system and especially toxic to foetus. It is very soluble in lipids and therefore, crosses biological membranes with ease. Because of its protein binding properties, it readily bio-accumulates and bio-magnifies in aquatic food chains. As a result, it poses a threat to humans and other fish-eating animals (Lodenius & Malm, 1998). The main pathway of human exposure to this toxic metal is through the consumption of Hg contaminated foods. The presence of such heavy metal above a certain threshold can be injurious to human health and the environment, predominantly aquatic life (Aburge and Akabza, 1998).

2.5.1.6 Airborne Particulate Matter

Sulphide dioxide (SO₂), nitrogen dioxide (NO₂) and carbon monoxide are of major concern in mining areas. The activities that generate this particulate matter include grinding equipment, vehicular movement, ore and waste rock heaps and site clearance. Dust arising from small scale gold mining operations has a high silica content which has been responsible for silico-tuberculosis in the area (Baird, 1995).

2.5.2 Safety and Health Impacts

Small scale gold mine operators dig only to a limited depth, supported by wooden logs. Hand dug tunnels and shafts created by these miners are shallower and smaller than those of commercial mining companies, and have no logistical support (Ashton *et al.*, 2001). This makes them prone to various problems and dangers such as pit collapse and landslides. While it is impossible to say how many deaths and accidents occur in small scale mines due to under-reporting and the clandestine nature of the work, the risks of fatal and disabling accidents are high, particularly in underground mines (Hilson, 2001). In China, Pakistan and many other countries more than 6,000 fatalities are estimated to occur in small scale gold mines each year (ILO, 1999).

Similarly, in Ghana an estimated 30 small scale gold miners lost their lives as a result of a landslide at Dopoase in the Wassa Amenfi East District of the Western Region (Daily Graphic, 2009). Also over 124 people were trapped underground in a galamsey site at Dunkwa –on –Offin in the Central Region (Daily Graphic, 2010). In another development, 12 small scale gold miners were trapped in a collapsed pit at Attaso in the Ashanti Region (Daily Graphic, 2010).

The frequent anarchy prevailing in the gold rush conditions of many small scale gold mine sites means that health and safety considerations are often ignored (ILO, 1999).

The mining operations in the area promote environmental modifications that support malaria vector growth. The activities create open pits, divert watercourses and subsequently result in pools of stagnant water (Akabza and Dramani, 2001).

Other mining and environmental related diseases are on the increase in the area. These include diarrhoea and sexually transmitted diseases (STDs). The increasing incidence of

STDs is credited to the high invasion of people in to the area of emigrant employees and of Ghanaians looking for jobs and trade outlets (Baird, 1995).



CHAPTER THERE

3.0 MATERIALS AND METHODS

3.1 STUDY AREA

3.1.1 Location

The study area is Bogoso/Prestea in the newly created Prestea–Huni Valley district, which was carved out from the Wassa West District of the Western Region of Ghana. Bogoso is the administrative capital of the district. Bogoso/Prestea is located between Latitude 5°N and 5°40'N and Longitudes 1° 45' W and 2° 10' W. It shares boundaries on the North West with Wassa Amenfi East District, on the South West with Mpohor Wassa East District, on the West with Axim Municipal Assembly, on the South with Tarkwa Nsuaem Municipal Assembly and the North by Wassa Amenfi West District Assembly. The area lies within the South Western Equatorial Zone (Oduro, 2011).





Figure 2: Map of Bogoso/Prestea mining area showing the sampling points.

3.1.2 Topography and Drainage

The landscape of the area is dominated by a range of hills that run in a northeast-southwest direction. These hills are aligned with the main gold bearing ores, and therefore accommodate majority of ore extraction activities. The area is drained by the Mansi River and its tributaries. These include: Asesere (which is used for domestic purposes by the Bondaye village), Worawora, Bogo, Subri (which drains the Bondaye area, and flows into Ankasa), Kokodabo, and Pram. The Mansi River ultimately flows into the Ankobra River, which is the major drainage in the Bogoso/Prestea mining area (GSBPL EMP, 2008).

3.1.3 Climate

KNUST

The climatic condition of the project area is hot and humid, and it is characterized by seasonal weather patterns, which involve double wet season from April to June and October to November, and a main dry season from December to February.

The mean annual temperature is 26 °C with daily maximum temperature reaching 28 °C to 30 °C. The annual mean humidity is 86%, and ranges from 70 to 90%. It is highest in August-September and lowest in January-February. Mean annual rainfall is 1803.7 mm, ranging from 984 to 2,414 mm. The prevailing winds in the area are in the south-west and north-east directions. Daily measurements from 2001 show that the wind direction is influenced by diurnal changes. It is southwards in the mornings and then northwards in the afternoon (GSBPL EMP, 2008).

3.1.4 Vegetation

The natural vegetation of the area is wet moist evergreen rainforest. The research area is devoid of mature forest due to large scale agriculture, lumbering, large and small scale gold mining, and other land use. The existing forests are either in reserved areas or areas unsuitable for agriculture. The nature of the original ecology has resulted in thin riparian strips of vegetation along muddy streams which have had their courses diverted or dammed in several places to enhance small scale gold mining activities (GSBPL EMP, 2008).

3.1.5 Geology and Soil

The project area lie on the edge of the West African Craton and are underlain by the Precambrian metasediments of the Birimian rock (pelites, greywacke and occasional volcanics), dominating the west and central area of the Concession, and Tarkwaian rock (conglomerates, quartzites and phyllites) and Fahomegan systems.

Both the Birimian and Tarkwaian rocks have a general north-northeast strike direction with a steep of $60-90^{\circ}$ north westerly dip. The Fault Belt comprises an anastamosing network of reverse faults with a dominant set of three or more north easterly ($40^{\circ} - 60^{\circ}$) striking faults. The geology, in order of increasing age comprises:

- 10 m to 40 m of weathered regolith;
- Tarkwaian sequence consisting of conglomerates, quartzite and phyllite;
- Proterozoic Birimian sequence consisting of pelites, greywacke and occasional basic volcanic.
- Primary gold mineralisation is typically associated with arsenopyrite and pyrite. Minor sulphides that may also be present include chalcopyrite, pyrrhotite, galena, and sphalerite. Gold distribution can be summarized as follows; 54% particulate gold of which 44% of this is free and 10% would be locked in sulphide grains, this can be liberated through ultra fine grinding; 39% of the gold is in solid solution with 24% associated with arsenopyrite and 15% associated with pyrite, this gold can only be released through oxidation of the sulphides; the remaining 7% of the gold is locked in silicate minerals and cannot be recovered economically.

The oxidized ore contains very fine-grained free gold that has been largely liberated during the weathering of the sulphides. This has greatly enhanced recovery of gold from oxide ores. Generally, weathering extends down to about 40 m. This could, however, become shallower or deeper locally depending on geological structures and topography (GSBPL EMP, 2008).

The typical weathered profile consists of 10 m to 15 m of secondary clay alteration underlain by 25 m to 30 m of saprolites with abundant iron oxides. Material between surface and the base of the saprolites is referred to as oxide. Between the oxide and primary (unweathered) zones is a transition zone (with an average thickness of about 12 m) where oxidation has only partly broken down the sulphide minerals, resulting in a combination of oxidized, partially oxidized and un-oxidized lithologies. The transition zone usually occurs in the vicinity of the water table (GSBPL EMP, 2008).

Soils within the project area are broadly described as ferrasols with Dystic Gleysols based on FAO/UNESCO soil classification system. These are common along streams within the area and the Ankobra River. The ferrasols are weathered soils with strong acidity and very low base saturation. The soils have a weak blocky structure, and breaks down into fine crumby aggregates when they come under stress. Their fine structure generally enhances root penetration and good moisture retention, however, the high rainfall regime of the area promotes leaching, such that soil nutrients e.g. nitrates and phosphates are easily leached out. When these are cleared, the rate of decomposition of the organic reserves in the soil becomes faster than the rate of replenishment. These factors interplay to lower the fertility of the soils. (GSBPL EMP, 2008).

3.1.6 Demographics

According to the year 2010 population and housing census, the total provisional population of the Prestea / Huni-Valley District was 143911 of which males and females constituted 73126 and 70785, respectively.

The indigenous ethnic group is the Wassa people but the ethnic mix is highly varied due to mining activities (large and small scale). The growing influx of people in search of jobs in the mines and the drift of unemployed youth from other regions in the country to the area for small scale gold mining are major contributory factors to the growing population (Oduro, 2011).

3.1.7 Economic Activities

The main sources of employment in the area are farming (subsistence and commercial), small scale retail shops, commercial and small scale gold mining. The proliferation of small scale gold mining activities in the study area due the suspension of the Prestea underground mine operations in early 2002 has resulted in about 1,750 job losses in Prestea and its environs (GSBPL EMP, 2008).

3.2 Sampling Sites

Water samples were collected from both streams and boreholes. Ten sampling points were located within the study area: four groundwater (boreholes) sampling sites and three surface water sampling sites (each with a control station). The choice of the sampling sites was due to the bulk of human activities happening around the area and their effect on the water resources. The control stations were taken from the head streams where small scale gold mining has not impacted. The sampling sites are summarized in Table 1.

Sampling Site Code	Site Location
AS3	Surface water at Asesere
ASC	Surface water at Asesere (Control)
BO1	Surface water at Bogo
BOC	Surface water at Bogo (control)
WW1	Surface water at Worawora
WWC	Surface water at Worawora (control)
KK1	Borehole at Kokoase
BT1	Borehole at Bogoso Township
PT1	Borehole at Prestea Township
PS1	Borehole at Prestea Stadium

Table 1 Sampling sites and their designated codes

3.3 Samples Collection

KNUST

Water samples (surface and groundwater) were taken monthly in duplicates from the sampling sites from October, 2010 to March, 2011. The samples were collected in 1000 mL sterile plastic bottles and transported to the laboratory in a cool box for analysis. Temperature, pH, dissolved oxygen and conductivity were determined in-situ at the time of sample collection using TPS WP 81 HANNA Multifunctional meter.




Plate 1 Sampling site at Asesere stream



Plate 2 Sampling site at Prestea Township borehole.

3.4 Laboratory Analysis

3.4.1 Determination of Alkalinity

Alkalinity was determined from the water samples when about 100 mL of the sample was measured in to a 250 mL beaker. The initial pH of the sample was recorded; three drops of Bromocresol green indicator were added. The sample was then titrated with $0.02 \text{ NH}_2\text{SO}_4$ until the pH 4.5 endpoint (colour changes from blue to yellow) was reached. Total volume of acid needed to reach the endpoint was recorded, and the total alkalinity calculated.

3.4.2 Determination of sulphate and phosphate

Filtered water samples were poured into 10 mL sample cells (bottles) for each of the parameters. In determining sulphate and phosphate, Sulfa Ver. 4 and Phos Ver. 3 reagent powder were added to the samples and shaken for about thirty seconds. Readings of the samples were done by using the HACH DR 4000 spectrophotometer at a wavelength of 450 nm.

3.4.3 Total Metals

The concentrations of Arsenic, Manganese, Iron and Mercury 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. The concentrations of the total metals were determined at 1937 nm, 279.3 nm, 284.3 nm and 295 nm wavelengths, respectively.

For the determination of the total metals, about 100 mL of the water samples was measured for each metal under investigation into 50 mL volumetric flasks. The flasks were rinsed three times with the samples before pouring the actual samples into them. One mL of concentrated HNO₃ was added to the samples and allowed a digestion period of one hour. Filtration was done using 0.45 μm membrane filter paper. Samples were then analysed using the Varian 220 Spectra AA model of Atomic Absorption Spectrometer (AAS).

3.5 Quality assurance

The accuracy and precision of the analytical techniques were assessed by the analyses of reference materials and reagent blank before the samples were analysed using deionised water and reagent blank. Field instruments were calibrated according to the Standard Method for the analysis of water and wastewater.

3.6 Statistical Analysis

Statistical analysis of the results was done using Microsoft Excel and one-way randomised analysis of variance (ANOVA) in STATA. All statistical tests were estimated at 95% confidence level.



CHAPTER 4

4.0 RESULTS

4.1 Physicochemical parameters of water samples from the streams and boreholes

The mean values of the various physicochemical parameters determined in the study are presented in Table 2.

The mean pH values of the surface water samples from the sampling sites ranged between 6.62 and 7.08, with the highest value being recorded at Asesere control sample (ASC) while the lowest was recorded at Bogo control sample (BOC). For the ground water samples, the mean pH values were generally low, ranging between 6.26 and 6.65. The highest and lowest values were measured at Prestea Stadium borehole (PS1) and Kokoase borehole (KK1), respectively.

The mean temperature values of the surface water samples varied between 25.50 °C and 30.75 °C. These values were recorded in Asesere stream (AS3) and Asesere control sample (ASC), respectively. The groundwater samples also varied between 27.01 °C and 29.50 °C. The highest value of 29.50 °C was recorded at Prestea Township borehole (PT1) while the lowest was recorded at Prestea Stadium borehole (PS1).

The mean conductivity values of the surface water samples ranged from 28.5 to 213.40 μ s/cm. Bogo stream (BO1) measured the highest mean conductivity value of 213.40 μ s/cm and the lowest of 28.5 μ s/cm was measured at Asesere control sample (ASC). However, the mean conductivity values of the groundwater samples were high and varied between 68.83 and 853.30 μ s/cm. The highest mean value of 853.30 μ s/cm was recorded in the Bogoso Township borehole (BT1) whilst the lowest value of 68.83 μ s/cm was recorded in the Kokoase borehole (KK1).

Mean values of alkalinity determined in the surface water samples ranged from 15.91 to 87.88 mg/L. Bogo stream (BO1) recorded the highest mean value of 87.88 mg/L and Asesere control sample (ASC) recorded the lowest value of 15.91 mg/L. The groundwater samples recorded mean alkalinity values ranging between 21.0 and 93.0 mg/L. The highest value of 93.00 mg/L was measured in Bogoso Township borehole (BT1) whilst Kokoase borehole (KK1) measured the lowest value of 21.0 mg/L.

Mean dissolved oxygen (DO) values of the surface and ground water samples were generally high and ranged from 1.94 to 8.65 mg/L and 2.30 to 6.06 mg/L, respectively. For the surface water samples, Worawora control sample (WWC) recorded the highest mean value of 8.65 mg/L whilst Bogo control sample (BOC) recorded the minimum value of 1.94 mg/L. Prestea Township borehole (PT1) measured the maximum mean value of 6.06 mg/L for the groundwater samples and the minimum value of 2.30 mg/L was measured in Bogoso Township borehole (BT1).

Total dissolved solids (TDS) in the surface water samples recorded mean values ranging from 14.30 to 106.72 mg/L whiles the groundwater samples recorded values that ranged from 35.0 to 425.80 mg/L. For the surface water samples, highest TDS value of 106.72 mg/L was recorded in Bogo stream (BO1), whilst the lowest mean value of 14.30 mg/L was recorded in Asesere control sample (ASC). For the groundwater samples, the highest mean value of 425.80 mg/L was measured in Bogoso Township borehole (BT1) and the lowest value of 35.0 mg/L was recorded in the Kokoase borehole (KK1).

Streams	pН	Temp (°C)	EC (µS/cm)	Alk. (mg/L)	DO (mg/L)	TDS (mg/L)
AS3	6.66 ± 0.41	30.38 ± 1.71	90.65±52.43	30.34±12.41	$4.86{\pm}0.99$	$63.6{\pm}\ 27.15$
ASC	7.08 ± 0.64	25.5 ± 0.95	$28.5\ \pm 0.84$	15.91 ± 2.68	$5.81{\pm}1.56$	$14.3\ \pm 1.21$
BO1	6.76 ± 0.13	27.87 ± 1.24	213.4 ± 41.85	87.88 ± 9.05	$1.94{\pm}0.65$	$106.{\pm}~20.83$
BOC	6.62 ± 0.54	25.86 ± 0.38	77.6 ± 77.72	18.75 ± 5.88	6.11 ± 1.59	$32.6{\pm}\ 28.56$
WW1	6.85 ± 0.23	26.35 ± 0.93	82.57±15.47	43.38 ± 7.85	$4.62{\pm}~1.32$	$27.8{\pm}~16.33$
WWC	6.73 ± 0.18	$26.5\ \pm 1.62$	51.3 ± 35.39	16.9 ± 15.52	$8.65{\pm}7.96$	28.5 ± 16.32
Boreholes						
KK1	6.26 ± 0.17	27.7 ± 0.43	68.83 ± 3.25	21 ± 3.1	4.12 ± 0.9	35 ± 1.26
BT1	6.38 ± 0.30	27.75 ± 0.36	$853. \pm 31.73$	$93\ \pm 8.26$	2.3 ± 0.74	$425.{\pm}~17.57$
PT1	6.5 ± 0.30	29.5 ± 1.97	$178.{\pm}22.79$	$70.4{\pm}~34.70$	$6.06{\pm}~1.02$	$89.8{\pm}~11.05$
PS1	6.65 ± 0.29	27.01 ± 2.21	227.3 ± 9.85	$90.7{\pm}31.22$	4.6 ± 1.13	$104.{\pm}~27.03$
WHO		12				
LIMIT	6.5-8.5	22-29	300	500	-	1000

Table 2: Physicochemical parameters of the water samples.

4.2 Sulphates, Phosphates and Chlorides Concentrations in the Streams and Boreholes.

Mean values of sulphates (SO_4^{2-}) , phosphates (PO_4^{3-}) and chlorides (CI^-) in surface and ground water samples from the ten sampling sites are presented in Table 3.

Mean values of sulphate, phosphate and chloride in surface water samples ranged from 2.0 - 48.0, 1.8 - 7.0 and 7.9 - 80.6 mg/L, respectively. The anion concentrations in the groundwater samples ranged from 0.1 - 9.0 mg/L for sulphates, 0.8 - 3.1 mg/L for phosphates and 9.8 - 135.5 mg/L for chlorides.

For the surface water samples, the mean highest sulphate concentration of 48.0 mg/L was measured in Asesere stream (AS3) whilst the lowest value of 2.0 mg/L was recorded in Bogo control sample (BOC). The Prestea Township borehole (PT1) recorded the highest value of 9.0 mg/L whiles the Kokoase borehole (KK1) recorded the lowest mean value of 0.1 mg/L for the groundwater sample.

Mean phosphate concentration determined in the surface water samples showed a range of 1.8 to 7.0 mg/L. The maximum mean value of 7.0 mg/L was measured in Asesere stream (AS3) whiles the minimum, 1.8 mg/L, was recorded in Asesere control sample (ASC). The

groundwater samples also recorded mean values ranging from 0.8 to 3.1 mg/L. The highest mean value of 3.1 mg/L was measured in the Prestea Stadium borehole (PT1) and the lowest value of 0.8 mg/L was recorded in the Prestea Township borehole (PS1).

Mean concentrations of chloride (Cl⁻) determined in the surface water samples ranged from 7.9 to 80.6 mg/L. The highest value of 80.6 mg/L was recorded in the Bogo stream (BO1). The lowest value of 7.9 mg/L was measured in the Bogo control sample (BOC). For the groundwater samples, the mean Cl⁻ concentration ranged between 9.8 and 135.5 mg/L. The Bogoso Township borehole (BT1) recorded the highest value of 135.5 mg/L and the lowest value of 9.8 mg/L was measured in the Prestea Town borehole (PT1).

Streams	SO_4^{2-} (mg/L)	PO_4^{3-} (mg/L)	Cl (mg/L)
AS3	48 ± 11.26	7 ± 4.16	14.95 ± 2.38
ASC	3.0 ± 2.03	1.8 ± 1.5	8.1 ± 1.4
BO1	8 ± 6.27	1.85 ± 1.1	80.6 ± 3.22
BOC	2.0 ± 2.16	1.9 ± 1.61	7.9 ± 1.14
WW1	15.5 ± 9	3.25 ± 1.64	13.5 ± 2.09
WWC	4.0 ± 1.92	1.9 ± 1.65	8.4 ± 0.83
Boreholes		077	
KK1	0.1 ± 0.001	1.6 ± 0.75	13.3 ± 1.99
BT1	1 ± 1.24	1.4 ± 0.47	135.5 ± 11.98
PT1	9 ± 2.43	0.8 ± 0.8	9.8 ± 5.1
PS1	4 ± 1.44	3.1 ± 1.59	13.8 ± 2.67
WHO Limit	250	< 0.3	250

Table 3: Levels of anions determined in the water samples.

4.3 Metal Concentrations in Surface and Ground Water Samples

The concentrations of Hg, Fe, Mn and As were determined in the surface and ground water samples taken from the ten sampling sites and their mean concentrations are presented in Table 4.

Streams	Hg (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)
AS3	0.007 ± 0.002	5.85 ± 6.48	1.06 ± 0.52	0.02 ± 0.003
ASC	0.01 ± 0.003	0.04 ± 0.015	$0.04\ \pm 0.02$	$0.001 \ \pm 0.0002$
BO1	0.009 ± 0.004	1.67 ± 0.69	0.22 ± 0.08	0.01 ± 0.009
BOC	0.001 ± 0.001	$1.37 \hspace{0.1in} \pm 0.45$	$0.01 \hspace{0.1 cm} \pm \hspace{0.1 cm} 0.01 \hspace{0.1 cm}$	$0.016 \ \pm 0.001$
WW1	0.017 ± 0.011	13.64 ± 5.04	0.17 ± 0.08	0.02 ± 0.001
WWC	$0.001 \ \pm 0.001$	$0.013{\pm}~0.009$	0.005 ± 0.001	0.006 ± 0.001
Boreholes				
KK1	b/d	1.26 ± 0.28	0.003 ± 0.02	0.002 ± 0.001
BT1	b/d	1.65 ± 0.69	1.23 ± 0.06	$0.001 \ \pm 0.0007$
PT1	b/d	1.4 ± 0.33	0.64 ± 0.12	0.001 ± 0.0007
PS1	b/d	1.35 ± 0.26	0.15 ± 0.014	0.002 ± 0.0015
WHO LIMIT	0.001	0.3	— — — — — — — — — — — — — — — — — — — 	0.01
b/d means below the MDL of 0.0001 mg/L.				

Table 4:.Metals Concentrations in the water samples

Mean values of mercury (Hg) concentration determined in the surface water samples varied between 0.001 and 0.017 mg/L. The highest Hg concentration was recorded in Worawora stream (WW1) whereas Bogo (BOC), Worawora (WWC) and Asesere (ASC) control samples registered the lowest values. For the ground water samples, Hg was below the minimum detection limit (MDL) of 0.0001 mg/L.

The mean iron concentrations in the surface water samples were generally high and ranged from 0.013 to 13.64 mg/L. Highest mean Fe concentration was measured at site WW1 and the minimum at site WWC. Respective values for the ground water samples ranged from 1.26 to 1.65 mg/L. The highest was recorded at site BT1, whereas the lowest was recorded at KK1.

Mean Mn concentrations in the surface water samples varied from 0.005 to 1.06 mg/L. The highest mean value was registered in the Asesere stream (AS3) whilst the lowest was registered in the Worawora control sample (WWC). The groundwater samples recorded mean

values ranging from 0.03 to 1.23 mg/L. Bogoso Township borehole recorded the highest value and the lowest value was recorded in the Kokoase borehole (KK1).

Mean Arsenic concentrations in the surface water samples ranged from 0.001 to 0.02 mg/L. The highest values were recorded at Asesere stream (AS3) and Worawora stream (WW1) whiles the lowest value was recorded at Asesere control sample (ASC). For the groundwater samples, the mean values ranged from 0.001 to 0.002 mg/L. The maximum values were measured at Kokoase borehole (KK1) and Prestea Stadium borehole (PS1) while the minimum values were measured at Bogoso Township borehole (BT1) and Prestea Township borehole (PT1).



CHAPTER FIVE

5.0 DISCUSSION

5.1 Physico-chemical parameters

5.1.1 The pH of the water samples

The pH is considered a significant ecological factor and provides important information in many types of geochemical equilibrium. It is an important parameter in water bodies since most aquatic organisms are adapted to an average pH and do not withstand abrupt changes (Shymamala *et al.*, 2008). The pH values measured in the study were generally good in both stream and borehole samples. The pH values of the surface water samples including the control samples were within the acceptable range of 6.5-8.5 according to the WHO (2004) guidelines for drinking water. However, Asesere control sample recorded the highest pH value of 7.08. This site was located close to a previously mined pit by GSBPL, which used calcium carbonate (lime) in its operations, and could affect the pH value. Calcium carbonate can combine with hydrogen ions to induce precipitation of metal oxides (Prowse, 1987). In addition, rocks that have high carbonate levels have a high content of weatherable silicates, long residence times, and are well buffered and generally give rise to circumneutral (pH 7) or slightly alkaline waters (UNEP GEM, 2006).

The ground water samples were within WHO optimum limits of 6.5 to 8.5 except for the Kokoase and Bogoso Township boreholes which recorded mean pH values of 6.26 and 6.38, respectively. The slightly acidic nature of the water samples from the two boreholes might be due to drainage of metal-rich rocks in the soil and mine drainage (Essumang *et al.*, 2011). Small scale gold mining operations may expose mineralized rocks to rain water and produce acidic water which can infiltrate into the soil. Mine drainage can therefore introduce acidic water into groundwater supplies (Kuma, 2004). Acidity increases the capacity of leaching toxic trace metals into the water making it potentially harmful for human consumption. Thus,

the moderate to strong acidity of the ground waters suggests that the waters are polluted with trace metals which are present in the rock matrix through which the water percolates (Kortatsi, 1994).

Oxidation of soil organic matter generated in the soil zone could also contribute to the low pH (Hounslow, 1995; Langmuir, 1997). Water that percolates through soil in poorly buffered areas, usually those with hard igneous rocks, tends to be dominated by dissolved organic acids and can produce low pH values in watercourses (UNEPGEM, 2006).

5.1.2 Temperature

Temperature was found to be generally high in both surface and ground water samples with AS3 and PT1 samples recording the highest values of 30.38 and 29.5 °C, respectively. These values were above the WHO guidelines of 22 to 29 °C. The higher values of temperature observed in the study area could be attributed to the dry season during the period of investigation. Water temperature could be affected by the weather, storm water and groundwater influx (Fritz, 2001).

There were no significant differences (p>0.05) in temperature for the groundwater samples. However, statistically significant differences existed (p<0.05) among the surface water samples (Appendix II).

5.1.3 Electrical Conductivity

Electrical conductivity (EC) gives a measure of the ability of water to conduct an electric current; the greater the content of ions in the water, the more current the water can carry (Dharmappa *et al.*, 2000). All the EC values recorded in the study for the surface water samples were below the WHO allowable limit of 300 μ S/cm for drinking water. However, the control samples had lesser values than the test samples. This means that contaminations due to dissolve ions were low in the control samples.

The groundwater samples were also below the WHO permissible limit of 300 μ S/cm except for the Bogoso Township borehole which recorded a mean EC value 853.30 μ S/cm that exceeded the WHO permissible limit. High electrical conductivity of the water could be directly related to the concentration of dissolved salts or minerals in the water (Dharmappa *et al.*, 2000). Mining activities disturb mineralized rocks and could release absorbed ions into the water to increase the ionic content, and subsequently the conductivity of the water (Prowse, 1987). Therefore, the water sample was susceptible to high mineral salt concentration which comes from the dissolution of minerals in the soil (Ntengwe, 2006; Morrison *et al.*, 2001).

The differences that existed among the EC values for the streams were statistically significant (p<0.05). This meant that the EC value depended on the point of sampling, and hence the number of dissolved ions in the water sample. Statistically significant differences also existed for the groundwater samples (Appendix III).

5.1.4 Alkalinity

Alkalinity is the measurement of the water's ability to neutralize acids. The standard desirable limit of alkalinity in potable water is 500 mg/L according to the WHO (2004). Alkalinity values for all the water samples were all below the WHO permissible limits. However, for the surface water, all the test samples measured higher values than their respective control samples, suggesting an influence from the mining activities.

The groundwater samples generally recorded higher alkalinity values as compared with the surface water samples. High alkalinity usually indicates the presence of natural salts such as bicarbonates or phosphates, or hydroxide ions, in the water (Dharmappa *et al.*, 2000).

Statistically significant differences existed among the surface water samples (p<0.05). Differences among the groundwater samples were also statistically significant (Appendix IV).

5.1.5 Dissolved Oxygen (DO)

Dissolved oxygen values were generally lower for the test samples than the control samples. The lowest value of 1.94 mg/L was measured in the Bogo stream. The low dissolved oxygen could be attributed to warmer temperatures. Warmer temperatures decrease oxygen solubility in water while at the same time increases metabolic rates that affect sediment oxygen demand, nitrification, photosynthesis, and respiration (Simpson, 1991). Some pollutants such as acid rock drainage resulting from the small scale gold mining operations produce direct chemical demand on oxygen in the water for certain oxidation - reduction reactions (Grill, 2007). For the control samples the highest value of 8.65 mg/L was recorded in the Worawora control sample. High levels of DO in the control samples could be attributed to natural processes such as diffusion and photosynthesis (UNEP GEM, 2006). 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). Thus, streams in the study area can still support aquatic life.

For the groundwater samples, dissolved oxygen values were generally low and Bogoso Township borehole recorded the lowest value of 2.3 mg/L. This could be as a result of acid rock drainage resulting from the activities of small scale gold mining (Grill, 2007). However, the Prestea Town borehole measured a high value of 6.06 mg/L. The main factor contributing to changes in dissolved oxygen levels could be attributed to the build-up of organic waste which can seep into the soil to contaminate groundwater resources.

There were significant differences (p<0.05) in dissolved oxygen values for both the surface and ground water samples (Appendix V).

5.1.6 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) are a measure of the inorganic salts, organic matter, and other dissolved materials in water (U.S. EPA, 1986). TDS are generally present in water or are the results of human activities such as small scale gold mining or some industrial treatment of water (Weber-Scannell and Duffy, 2007). Dissolved salts and minerals are necessary components of good quality water as they help maintain the health and vitality of the organisms that rely on this ecosystem service (Stark *et al.*, 2000).

The mean values of total dissolved solids (TDS) obtained for all the surface and ground water samples (including the control samples) were within the acceptable limits of 1000 mg/L recommended by WHO for drinking water. However, the test samples generally had higher values than the control samples. Mining disturbances may increase the concentrations of suspended particles (such as nitrates, chlorides, carbonates, Ca and Mg) and metals (such as As and Cu), that form a large portion of the total dissolved solids in water resources. Also, constituent concentrations can be increased through dissolution or retransport of naturally occurring compounds which increases the level of TDS in water resources (Schemel *et al.*, 1998). The amount of dissolved solids (TDS) reflects the natural variations in various water bodies and major environmental factors (Chapman, 1996). An unusually high value was recorded for the Bogoso Township sampling site compared with the rest of the values. Lupankwa *et al.*, (2004a) attribute high TDS values to the nature of the mineralization and mining operations.

The differences that existed among the TDS values for the streams were statistically significant (p<0.05). Statistically significant differences also existed for the values for the groundwater samples (Appendix VI).

5.2 Anions Concentrations

5.2.1 Sulphate

The mean levels of $SO_4^{2^-}$ in the surface and ground water samples were low, and were all below the WHO permissible limit of 250 mg/L. However, comparing the test samples to the control samples, it was realized that, the test samples had higher concentrations. This could be attributed to the exposure of sulphide bearing rocks through mining to water and the atmosphere (Ravengai *et al.*, 2005). During the extraction process, those sulphides which are not part of the ore material are dumped in waste rock dumps with other rocks. Sulphides contain valuable materials as pyrites which are processed, and the residue dumped in 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 large amount of sulphate into surface water and groundwater (Bigham and Nordstrom, 2000).

There were significant differences in Sulphate levels in both surface and ground water samples (P < 0.05) (Appendix VII).

5.2.2 Phosphate

Phosphorus is a nutrient required by all organisms for the basic processes of life (Dharmappa *et al.*, 2000). It is a natural element found in rocks, soils and organic materials. Phosphorus in natural waters is usually found in the form of phosphates (PO_4^{3-}) (UNEP GEM, 2006).

The concentrations of phosphate in both surface and ground water samples were high and exceeded the WHO guideline of <0.3 mg/L for drinking water. The high concentrations could be accredited to the natural weathering of minerals in the drainage basin, from biological decomposition, and as runoff (UNEP GEM, 2006). In the case of a runoff when soil moves, it takes the soil-bound phosphate with it into streams and even migrates with groundwater

flows (Olajire *et al.*, 2001). Since groundwater often discharges into surface water, phosphate concentrations in groundwater affects the water quality of surface water (Cunningham, 2005). There were significant differences in phosphate levels (p< 0.05) between the test and control surface water samples, and also among borehole samples (Appendix VIII).

5.2.3 Chloride

The amounts of chloride found in both the surface and borehole water samples were far below the WHO recommend limit of 250 mg/L for drinking water, and thus do not pose any immediate health risk to consumers. However, the test samples recorded higher concentrations than the control samples for the surface water samples. The higher concentrations in the test samples could be as a result of the rocks being exposed to chemical weathering through mining. Chlorides concentrations could also be as a result of natural processes such as the passage of water through natural salt formations in the earth (Renn, 1970).

An unusually high chloride concentration of 135.50 mg/L was recorded for the Bogoso Township borehole compared with the rest of the sampling sites. This particular site also recorded extreme values for most of the other parameters, e.g. pH and TDS. The low pH could have contributed to the dissolution of salts, hence the high chloride concentration at this site.

Statistically, differences existed among the chloride concentrations for both surface and groundwater (p < 0.05) (Appendix IX).

5.3 Metal Concentrations

5.3.1 Mercury

Mercury concentrations in the test samples for the surface water were high and above the WHO permissible level of 0.001 mg/L. The control samples were within the allowable limit

of 0.001 mg/L. The groundwater samples recorded concentrations which were below the minimum detection limits of 0.0001 mg/L.

Mercury is used to recover gold from ore minerals by the process of amalgamation (Love, 2002); hence, the high values in the surface water samples could be attributed to the processing of gold which is widespread in the study area. It is more stable in sediments and in air (Boese-O'Reilly *et al.*, 2003). Therefore, its presence in water samples is indicative that there is probably more mercury in other forms in the study area (Boening, 2000). The occurrence of mercury in the surface water samples accentuated findings and reports that mercury is a major pollutant associated with gold panning in Bogoso / Prestea mining area and elsewhere (Hinton *et al.*, 2003).

There were significant differences (p < 0.05) in Hg concentrations measured at the different sites (Appendix X).

5.3.2 Iron

Generally, iron concentrations were high and exceeded the WHO (2004) guideline value of 0.3 mg/L for drinking water for all the sites. The test samples recorded higher concentrations than the control samples. Iron (Fe) occurs naturally from rocks and is found in many surface and groundwater sources at levels ranging 0.3 to 50 mg/L (WHO, 2004).

Bogoso / Prestea, where the study was conducted are underlain by arsenopyrite and pyrite rocks. When these rocks are disturbed through mining and processing, they become exposed to air and water (GSBPL EMP, 2008). Processing activities can release high concentrations of Fe to surface and ground waters through infiltration to ground water that exchanges with surface water and seepage to soil or bedrock which discharges to surface water (Langmuir, 1997). The reaction of pyrite with oxygen and water produces ferrous sulphate which contaminates surface and ground water, thereby increasing Fe concentrations in water resources (Kortatsi, 2004).

Higher concentration of iron in drinking water imparts metallic taste to the water and stains sinks and laundered textiles (Griffith, 2004).

There were no significant differences (p> 0.05) for total iron (Fe) concentration in the groundwater samples but the surface water samples showed significant differences (p < 0.05) (Appendix XI).

5.3.3 Manganese

The manganese concentrations measured in the surface water samples were high and above the allowable limit of 0.1 mg/L. The test samples recorded higher concentrations than the control samples. The groundwater samples were also generally high and above the allowable limit of 0.1 mg/L. The higher values of manganese within the study area could be from the operations of small scale gold miners. This occurs when mineralized rocks are disturbed through mining natural sources. Many types of rocks naturally contain manganese (Kuma, 2004). Water dissolves this element while percolating through the ground, carrying it along in solution (Griffith, 2004). This accounts for high manganese levels in water resources within the area. Acid rock drainage is also a contributing factor to elevated levels of manganese in water resources (Blodau, 2006). Manganese is a vital micronutrient for both plants and animals but when taken in very large doses can cause some diseases and liver damage (Wolfe, 1960). It also imparts an undesirable taste to drinking water. Manganese is believed to have a neurotoxin effect (Kuma, 2004).

There were significant differences (p < 0.05) in manganese concentrations for both surface and ground water samples (Appendix XII).

5.3.4 Arsenic

Arsenic concentrations were generally low in all the ground and surface water samples, except for the Worawora, Asesere, Bogo and Bogo control sites which were slightly above the WHO guidelines of 0.01 mg/L for drinking water. Arsenic can be liberated from arsenopyrite rocks through mining. Since arsenic in soils and rocks is highly mobile once it is liberated, it results in higher concentrations in water resources.

There were no significant differences for total arsenic concentrations in groundwater (p>0.05). However, there were significant differences (p < 0.05) for As values for the surface water samples (Appendix XIII).



CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The study has revealed the following:

- Most of the physicochemical parameters studied were within the guidelines set by the WHO (2004) for drinking water, except for a few boreholes where some of these indicators fell outside these limits. The groundwater samples, generally performed better in almost all the indicators measured than the surface water samples.
- 2. Generally, EC values were higher in the groundwater samples than the surface water samples. This could be credited to high mineral salt concentration which comes from the dissolution of minerals in the soil.
- 3. The concentrations of anions in the surface and ground water samples were found to be within acceptable limits according to the WHO guidelines for drinking water, except for phosphate which was slightly higher than the allowable limit. The anions concentrations generally pose neither physiological nor aesthetic problem to the surface and ground water for drinking and other domestic purposes within the study area.
- 4. The levels of mercury, iron and manganese at most of the sampling sites were high, exceeding the WHO recommended limit for drinking water. The occurrence of these metals could be due to the exposure of mineralized rocks to air and acidic water through mining. Mercury pollution was as a result of amalgamation and panning by the small scale gold miners. This poses toxicity risks to the aquatic environment and to the health of the miners. Exposure to high levels of this neurotoxin in drinking water poses major health risk to inhabitants around and downstream of Asesere, Worawora and Bogo streams.

- 5. There is a high possibility of Acid Rock Drainage (ARD) occurring in areas where there were high levels of Fe, Mn, and SO4²⁻ and low pH. Areas with high Fe and low Mn and SO4²⁻ may also indicate ARD since SO4²⁻ can be transformed by redox reactions and precipitate as sulphides.
- 6. Finally, the results of the study indicated that, small scale gold mining operations negatively impact on water resources in the study area, most especially, on surface waters. This was evident in the test samples which had deteriorated water quality with respect to the monitored parameters compared with the control samples. Therefore water source from these streams are not suitable for domestic use.



6.2 RECOMENDATION

The problems of small scale gold mining operations in the country particularly Bogoso / Prestea mining area cannot be over emphasised. The following recommendations are made based on the outcome of this study:

- Small scale gold mining activities should be permitted and an environmental impact assessment reports submitted to the regulatory bodies before a license to mine or explore be granted.
- 2. There should be collaboration between policy makers and regulatory bodies to ensure proper planning and monitoring of activities of the small scale gold mining operations.
- 3. Small scale gold miners should be educated by the regulatory agencies about the impacts of their activities on the environment and the safety / health hazards associated with their operations.
- 4. Other livelihood support systems such as communal / cooperative farming should be introduced by the Metropolitan, Municipal and District Assemblies to create alternative employments in order to reduce small scale gold mining which is inimical to the environment.
- Reclamation bond / deposit should be paid by the small scale gold mining operators to the regulatory agency to reclaim the mined sites should there be any residual environmental impacts.
- Similar studies should be carried out to look at the effect of seasonal variation on the levels of heavy metals in both surface and ground water resources within the study area.

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APPENDIX I

pH STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES IN THE STUDY AREA.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	6.66 ± 0.41	6.33	6.98	0.206
AS C	7.08 ± 0.64	6.57	7.59	
AS 3	6.66 ± 0.41	6.33	6.98	0.582
BO 1	6.76 ± 0.13	6.67	6.87	
AS 3	6.66 ± 0.41	6.33	6.98	0.888
BO C	6.62 ± 0.54	6.19	7.05	
AS 3	6.66 ± 0.41	6.33	6.98	0.346
WW 1	6.85 ± 0.23	6.67	7.03	
AS 3	6.66 ± 0.41	6.33	6.98	0.710
WW C	6.73 ± 0.15	6.61	6.85	JJI

Appendix I. a: A table of descriptive test of pH of AS 3 and other sampling sites.

Appendix I. b: A table of descriptive test of pH of AS C and other sampling sites.

X ± SD	Minimum	Maximum	P VALUE
7.08 ± 0.64	6.57	7.59	0.258
6.76 ± 0.13	6.67	6.87	1 THE
7.08 ± 0.64	6.57	7.59	0.208
6.62 ± 0.54	6.19	7.05	
7.08 ± 0.64	6.57	7.59	0.427
6.85 ± 0.23	6.67	7.03	
7.08 ± 0.64	6.57	7.59	0.226
6.73 ± 0.15	6.61	6.85	5/3
	X \pm SD7.08 \pm 0.646.76 \pm 0.137.08 \pm 0.646.62 \pm 0.547.08 \pm 0.646.85 \pm 0.237.08 \pm 0.646.73 \pm 0.15	X ± SDMinimum 7.08 ± 0.64 6.57 6.76 ± 0.13 6.67 7.08 ± 0.64 6.57 6.62 ± 0.54 6.19 7.08 ± 0.64 6.57 6.85 ± 0.23 6.67 7.08 ± 0.64 6.57 6.73 ± 0.15 6.61	X ± SDMinimumMaximum7.08 ± 0.646.577.596.76 ± 0.136.676.877.08 ± 0.646.577.596.62 ± 0.546.197.057.08 ± 0.646.577.596.85 ± 0.236.677.037.08 ± 0.646.577.596.73 ± 0.156.616.85

Appendix I. c: A table of descriptive test of pH of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	6.76 ± 0.13	6.67	6.87	0.551
BO C	6.62 ± 0.54	6.19	7.05	
BO 1	6.76 ± 0.13	6.67	6.87	0.424
WW 1	6.85 ± 0.23	6.67	7.03	
BO 1	6.76 ± 0.13	6.67	6.87	0.748
WW C	6.73 ± 0.15	6.61	6.85	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	6.62 ± 0.54	6.19	7.05	0.360
WW 1	6.85 ± 0.23	6.67	7.03	
BO C	6.62 ± 0.54	6.19	7.05	0.646
WW C	6.73 ± 0.15	6.61	6.85	

Appendix I. d: A table of descriptive test of pH of BO C and other sampling sites.

Appendix I. e: A table of descriptive test of pH of WW 1 and WW C sampling site.

WW 1 6.85 ± 0.23 6.67 7.03 0.3	LUE
	38
WW C 6.73 ± 0.15 6.61 6.85	

pH STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES IN THE STUDY AREA.

Appendix I. f: A table of descriptive te	of pH of KK	1 and other sampling sites.
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SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	6.26 ± 0.17	6.12	6.39	0.414
BT 1	6.38 ± 0.30	6.13	6.62	75
KK 1	6.26 ± 0.17	6.12	6.39	0.119
PT 1	6.5 ± 0.30	6.26	6.74	
KK 1	6.26 ± 0.17	6.12	6.39	0.018
PS 1	6.65 ± 0.29	6.42	6.88	
			551	No.

Appendix I. g: A table of descriptive test of pH of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	6.38 ± 0.30	6.13	6.62	0.504
PS 1	6.5 ± 0.30	6.26	6.74	
BT 1	6.38 ± 0.30	6.13	6.62	0.144
PS 1	6.65 ± 0.29	6.42	6.88	

Appendix I. h: A table of descriptive test of pH of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	6.5 ± 0.30	6.26	6.74	0.399
PS 1	6.65 ± 0.29	6.42	6.88	

APPENDIX II

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	30.38 ±1.71	29.01	31.74	0.000
AS C	25.5 ± 0.95	24.74	26.26	
AS 3	30.38 ±1.71	29.01	31.74	0.018
BO 1	27.87 ± 1.24	26.88	28.85	
AS 3	30.38 ± 1.71	29.01	31.74	0.000
BO C	25.86 ± 0.38	25.56	26.16	
AS 3	30.38 ± 1.71	26.88	28.85	0.001
WW 1	26.35 ± 0.93	25.60	27.09	Г
AS 3	30.38 ± 1.71	26.88	28.85	0.003
WW C	26.5 ± 1.62	25.20	27.79	

TEMPERATURE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix II.a**: A table of descriptive test of temperature of AS 3 and other sampling sites.

Appendix II.b: A table of descriptive test of temperature of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	25.5 ± 0.95	24.74	26.26	0.004
BO 1	27.87 ± 1.24	26.88	28.85	
AS C	25.5 ± 0.95	24.74	26.26	0.409
BO C	25.86 ± 0.38	25.56	26.16	
AS C	25.5 ± 0.95	24.74	26.26	0.148
WW 1	26.35 ± 0. <mark>93</mark>	25.6	27.09	
AS C	25.5 ± 0.95	24.74	26.26	0.221
WW C	26.5 ± 1.62	25.20	27.79	

Appendix II.c: A table of descriptive test of temperature of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	27.87 ± 1.24	26.88	28.85	0.004
BO C	25.86 ± 0.38	25.56	26.16	
BO 1	27.87 ± 1.24	26.88	28.85	0.037
WW 1	26.35 ± 0.93	25.6	27.09	
BO 1	27.87 ± 1.24	26.88	28.85	0.131
WW C	26.5 ± 1.62	25.20	27.79	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	27.87 ± 1.24	26.88	28.85	0.260
WW 1	26.35 ± 0.93	25.60	27.09	
BO C	25.86 ± 0.38	25.56	26.16	0.368
WW C	26.5 ± 1.62	25.20	27.79	

Appendix II.d: A table of descriptive test of temperature of BO C and other sampling sites.

Appendix II.e: A table of descriptive test of temperature of WW1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	26.35 ± 0.93	25.60	27.09	0.848
WW C	26.5 ± 1.62	25.20	27.79	
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TEMPERATURE STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES IN THE STUDY AREA.

Appendix II.f: A table of descriptive test of temperature of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	27.7 ± 0.43	27.36	28.04	0.832
BT 1	27.75 ± 0.36	27.46	28.04	
KK 1	27.7 ± 0.43	27.36	28.04	0.054
PT 1	29.5 ± 1.97	27.92	31.07	
KK 1	27.7 ± 0.43	27.36	28.04	0.470
PS 1	27.01 ± 2.21	25.24	28.78	
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Appendix II.g: A table of descriptive test of temperature of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	27.75 ± 0.36	27.46	28.04	0.058
PT 1	29.5 ± 1.97	27.92	31.07	
BT 1	27.75 ± 0.36	27.46	28.04	0.431
PS 1	27.01 ± 2.21	25.24	28.78	

Appendix II.h: A table of descriptive test of temperature of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	29.5 ± 1.97	27.92	31.07	0.066
PS 1	27.01 ± 2.21	25.24	28.78	

APPENDIX III

ELECTRICAL CONDUCTIVITY STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

Appendix III.a: A table of descriptive test of electrical conductivity of AS 3 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	90.65 ± 52.43	48.70	132.60	0.016
AS C	28.5 ± 0.84	27.83	29.17	
AS 3	90.65 ± 52.43	48.70	132.60	0.001
BO 1	213.4 ± 41.85	179.92	246.89	
AS 3	90.65 ± 52.43	48.70	132.60	0.740
BO C	77.6 ± 77.72	15.41	139.79	
AS 3	90.65 ± 52.43	48.70	132.60	0.723
WW 1	82.57 ± 15.47	70.19	94.94	
AS 3	90.65 ± 52.43	48.70	132.60	0.159
WW C	51.3 ± 35.39	22.98	79.62	

Appendix III.b: A table of descriptive test of electrical conductivity of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	28.5 ± 0.84	27.83	29.17	0.000
BO 1	213.4 ± 41.85	179.92	246.89)
AS C	28.5 ± 0.84	27.83	29.17	0.153
BO C	77.6 ± 77 <mark>.72</mark>	15.41	139.79	No.
AS C	28.5 ± 0.84	27.83	29.17	0.000
WW 1	82.57 ± 15.47	70.19	94.94	
AS C	28.5 ± 0.84	27.83	29.17	0.146
WW C	51.3 ± 35.39	22.98	79.62	

Appendix III.c: A table of descriptive test of electrical conductivity of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	213.4 ± 41.85	179.92	246.89	0.004
BO C	77.6 ± 77.72	15.41	139.79	
BO 1	213.4 ± 41.85	179.92	246.89	0.000
WW 1	82.57 ± 15.47	70.19	94.94	
BO 1	213.4 ± 41.85	179.92	246.89	0.000
WW C	51.3 ± 35.39	22.98	79.62	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	77.6 ± 77.72	15.41	139.79	0.881
WW 1	82.57 ± 15.47	70.19	94.94	
BO C	77.6 ± 77.72	15.41	139.79	0.468
WW C	51.3 ± 35.39	22.98	79.62	

Appendix III.d: A table of descriptive test of electrical conductivity of BO C and other sampling sites.

Appendix III.e: A table of descriptive test of electrical conductivity of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	82.57 ± 15.47	70.19	94.94	0.0755
WW C	51.3 ± 35.39	22.98	79.62	

ELECTRICAL CONDUCTIVITY STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES

Appendix III.f: A table of descriptive test of electrical conductivity of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	68.83 ± 3.25	66.23	71.43	0.000
BT 1	853.3 ± 31.73	827.91	878.69	
KK 1	68.83 ± 3.25	66.23	71.43	0.000
PT 1	178.65 ± 22.79	160.41	196.88	
KK 1	68.83 ± 3.25	66.23	71.43	0.000
PS 1	227.3 ± 9.85	219.42	235.18	/
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Appendix III.g: A table of descriptive test of electrical conductivity of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	853.3 ± 31.73	827.91	878.69	0.000
PT 1	178.65 ± 22.79	160.41	196.88	
BT 1	178.65 ± 22.79	160.41	196.88	0.000
PS 1	227.3 ± 9.85	219.42	235.18	

Appendix III.h: A table of descriptive test of electrical conductivity of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	178.65 ± 22.79	160.41	196.88	0.001
PS 1	227.3 ± 9.85	219.42	235.18	


APPENDIX IV

ALKALINITY STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix IV. a:** A table of descriptive test of alkalinity of AS 3 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	30.34 ± 12.41	20.41	40.26	0.019
AS C	15.91 ± 2.68	13.77	18.05	
AS 3	30.34 ± 12.41	20.41	40.26	0.000
BO 1	87.88 ± 9.05	80.64	95.11	
AS 3	30.34 ± 12.41	20.41	40.26	0.065
BO C	18.75 ± 5.88	14.05	23.45	
AS 3	30.34 ± 12.41	20.41	40.26	0.055
WW 1	43.38 ± 7.85	34.18	52.57	
AS 3	30.34 ± 12.41	20.41	40.26	0.129
WW C	16.9 ± 15.52	14.94	29.32	

Appendix IV. b: A table of descriptive test of alkalinity of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	15.91 ± 2.68	13.77	18.05	0.881
BO 1	87.88 ± 9.05	80.64	95.11	
AS C	15.91 ± 2.68	13.77	18.05	0.000
BO C	18.75 ± 5.88	14.05	23.45	
AS C	15.91 ± 2.68	13.77	18.05	0.307
WW 1	43.38 ± 7.85	34.18	52.57	
AS C	15.91 ± 2.68	13.77	18.05	0.000
WW C	16.9 ± 15.52	14.94	29.32	-

Appendix IV. c: A table of descriptive test of alkalinity of BO 1 and other sampling sites.

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SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	87.88 ± 9.05	80.64	95.11	0.881
BO C	18.75 ± 5.88	14.05	23.45	
BO 1	87.88 ± 9.05	80.64	95.11	0.000
WW 1	43.38 ± 7.85	34.18	52.57	
BO 1	87.88 ± 9.05	80.64	95.11	0.000
WW C	16.9 ± 15.52	14.94	29.32	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	18.75 ± 5.88	23.45	23.45	0.000
WW 1	43.38 ± 7.85	34.18	52.57	
BO C	18.75 ± 5.88	14.05	23.45	0.001
WW C	16.9 ± 15.52	14.94	29.32	

Appendix IV. d: A table of descriptive test of alkalinity of BO C and other sampling sites.

Appendix IV. e: A table of descriptive test of alkalinity of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	43.38 ± 7.85	34.18	52.57	0.790
WW C	16.9 ± 15.52	14.94	29.32	

ALKALINITY STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES **Appendix IV. f:** A table of descriptive test of alkalinity of KK 1 and other sampling sites.

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SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	21.00 ± 3.10	18.52	23.48	0.000
BT 1	93.00 ± 8.26	86.39	99.6	
KK 1	21.00 ± 3.10	18.52	23.48	0.00
PT 1	70.41 ± 34.70	42.64	98.18	
KK 1	21.00 ± 3.10	18.52	23.48	0.0030
PS 1	90.75 ± 31.22	65.77	115.73	

Appendix IV. g: A table of descriptive test of alkalinity of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	93.00 ± 8.26	86.39	99.60	0.152
PT 1	70.41 ± 34.70	42.64	98.18	
BT 1	93.00 ± 8.26	86.39	99.60	0.868
PS 1	90.75 ± 31.22	65.77	115.73	

Appendix IV. h: A table of descriptive test of alkalinity of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	70.41 ± 34.70	42.64	98.18	0.3109
PS 1	90.75 ± 31.22	65.77	115.73	

APPENDIX V

DISSOLVED OXYGEN (DO) STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	4.86 ± 0.99	4.06	5.65	0.237
AS C	5.81 ± 1.56	4.56	5.81	
AS 3	4.86 ± 0.99	4.06	5.65	0.000
BO 1	1.94 ± 0.65	1.39	2.49	
AS 3	4.86 ± 0.99	4.06	5.65	0.133
BO C	6.11 ± 1.59	4.84	7.38	
AS 3	4.86 ± 0.99	4.06	5.65	0.729
WW 1	4.62 ± 1.32	3.56	5.68	
AS 3	4.86 ± 0.99	4.06	5.65	0.274
WW C	8.65 ± 7.96	2.28	15.02	

Appendix V. a: A table of descriptive test of DO of AS 3 and other sampling sites.

Appendix V. b: A table of descriptive test of DO of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	5.81 ± 1.56	4.56	5.81	0.000
BO 1	1.94 ± 0.65	1.39	2.49	
AS C	5.81 ± 1.56	4.56	5.81	0.783
BO C	6.11 ± 1.59	4.84	7.38	
AS C	5.81 ± 1.56	4.56	5.81	0.184
WW 1	4.62 ± 1.32	3.56	5.68	
AS C	5.81 ± 1.56	4.56	5.81	0.411
WW C	8.65 ± 7.96	2.28	15.02	3
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Appendix V. c: A table of descriptive test of DO of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	1.94 ± 0.65	1.39	2.49	0.000
BO C	6.11 ± 1.59	4.84	7.38	
BO 1	1.94 ± 0.65	1.39	2.49	0.001
WW 1	4.62 ± 1.32	3.56	5.68	
BO 1	1.94 ± 0.65	1.39	2.49	0.067
WW C	8.65 ± 7.96	2.28	15.02	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	6.11 ± 1.59	4.84	7.38	0.108
WW 1	4.62 ± 1.32	3.56	5.68	
BO C	6.11 ± 1.59	4.84	7.38	0.461
WW C	8.65 ± 7.96	2.28	15.02	

Appendix V. d: A table of descriptive test of DO of BO C and other sampling sites.

Appendix V. e: A table of descriptive test of DO of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	4.62 ± 1.32	3.56	5.68	0.249
WW C	8.65 ± 7.96	2.28	15.02	
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DISSOLVED OXYGEN (DO) STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES

Appendix V. f: A table of descriptive test of DO of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	4.12 ± 0 <mark>.9</mark>	3.39	4.84	0.003
BT 1	2.3 ± 0.74	1.71	2.89	Ð
KK 1	4.12 ± 0.9	3.39	4.84	0.006
PT 1	6.06 ± 1.02	5.24	6.87	
KK 1	4.12 ± 0.9	3.39	4.84	0.390
PS 1	4.65 ± 1.13	3.75	5.55	

Appendix V. g: A table of descriptive test of DO of BT 1 and other sampling sites.

		- SA	NF N	
SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	2.3 ± 0.74	1.71	2.89	0.000
PT 1	6.06 ± 1.02	5.24	6.87	
BT 1	6.06 ± 1.02	5.24	6.87	0.002
PS 1	4.65 ± 1.13	3.75	5.55	

Appendix V. h: A table of descriptive test of DO of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	6.06 ± 1.02	5.24	6.87	0.047
PS 1	4.65 ± 1.13	3.75	5.55	



APPENDIX VI

TOTAL DISSOLVED SOLIDS (TDS) STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	63.65 ± 27.15	41.93	85.37	0.001
AS C	14.30 ± 1.21	13.33	15.27	
AS 3	63.65 ± 27.15	41.93	85.37	0.012
BO 1	106.72 ± 20.83	90.05	123.39	
AS 3	63.65 ± 27.15	41.93	85.37	0.083
B0 C	32.67 ± 28.56	9.82	55.52	
AS 3	63.65 ± 27.15	41.93	85.37	0.200
WW 1	27.89 ± 16.33	14.83	40.97	
AS 3	63.65 ± 27.15	41.93	85.37	0.022
WW C	28.50 ± 16.32	15.44	41.56	

Appendix VI. a: A table of descriptive test of TDS of AS 3 and other sampling sites.

Appendix VI. b: A table of descriptive test of TDS of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	14.30 ± 1.21	13.33	15.27	0.000
BO 1	106.72 ± 20.83	90.05	123.39	
AS C	14.30 ± 1.21	13.33	15.27	0.147
BO C	32.67 ± 28.56	9.82	55.52	
AS C	14.30 ± 1.21	13.33	15.27	0.069
WW 1	27.89 ± 16.33	14.83	40.97	
AS C	14.30 ± 1.21	13.33	15.27	0.059
WW C	28.50 ± 16.32	15.44	41.56	
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Appendix VI. c: A table of descriptive test of TDS of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	106.72 ± 20.83	90.05	123.39	0.004
BO C	32.67 ± 28.56	9.82	55.52	
BO 1	106.72 ± 20.83	90.05	123.39	0.000
WW 1	27.89 ± 16.33	14.83	40.97	
BO 1	106.72 ± 20.83	90.05	123.39	0.000
WW C	28.50 ± 16.32	15.44	41.56	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	32.67 ± 28.56	9.82	55.52	0.729
WW 1	27.89 ± 16.33	14.83	40.97	
BO C	32.67 ± 28.56	9.82	55.52	0.762
WW C	28.50 ± 16.32	15.44	41.56	

Appendix VI. d: A table of descriptive test of TDS of BO C and other sampling sites.

Appendix VI. e: A table of descriptive test of TDS of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	27.89 ± 16.33	14.83	40.97	0.9497
WW C	28.50 ± 16.32	15.44	41.56	

TOTAL DISSOLVED SOLIDS (TDS) STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES

Appendix VI. f: A table of descriptive test of TDS of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	35.00 ± 1.26	33.90	36.01	0.000
BT 1	425.83 ± 17.57	411.77	439.89	
KK 1	35.00 ± 1.26	33.9	36.01	0.000
PT 1	89.83 ± 11.05	80.98	98.67	
KK 1	35.00 ± 1.26 🗡	33.90	36.01	0.000
PS 1	104.50 ± 27.03	82.87	126.13	

Appendix VI. g: A table of descriptive test of TDS of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	425.83 ± 17.57	411.77	439.89	0.000
PT 1	89.83 ±11.05	80.98	98.67	
BT 1	425.83 ± 17.57	411.77	439.89	0.000
PS 1	104.50 ± 27.03	82.87	126.13	

Appendix VI. h: A table of descriptive test of TDS of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	89.83 ± 11.05	80.98	98.67	0.247
PS 1	104.50 ± 27.03	82.87	126.13	

APPENDIX VII

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	48.00 ± 11.26	38.98	57.01	0.000
AS C	3.00 ±2.03	1.38	4.62	
AS 3	48.00 ± 11.26	38.98	57.01	0.000
BO 1	8.00 ± 6.27	2.98	13.01	
AS 3	48.00 ± 11.26	38.98	57.01	0.000
BO C	2.00 ± 2.16	0.27	3.73	
AS 3	48.00 ± 11.26	38.98	57.01	0.000
WW 1	15.50 ± 9.00	8.29	22.70	
AS 3	48.00 ± 11.26	38.98	57.01	0.000
WW C	4.00 ± 1.92	2.46	5.53	
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SULPHATE (SO₄²⁻) STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix VII.a:** A table of descriptive test of sulphate of AS 3 and other sampling sites.

Appendix VII.b: A table of descriptive test of sulphate of AS C and other sampling sites.

-	withinfluin	Naxim um	P VALUE
3.00 ±2.03	1.38	4.62	0.093
8.00 ± 6.27	2.98	13.01	
3.0 0 ±2.03	1.38	4.62	0.428
2.00 ± 2.16	0.27	3.73	
3.00 ±2.03	1.38	4.62	0.008
15.50 ± 9.00	8.29	22.7	
3.00 ±2.03	1.38	4.62	0.401
4.00 ± 1.92	2.46	5 .53	1-1
	12	5	
	$\begin{array}{c} 3.00 \pm 2.03 \\ 8.00 \pm 6.27 \\ 3.0 0 \pm 2.03 \\ 2.00 \pm 2.16 \\ 3.00 \pm 2.03 \\ 15.50 \pm 9.00 \\ 3.00 \pm 2.03 \\ 4.00 \pm 1.92 \end{array}$	3.00 ± 2.03 1.38 8.00 ± 6.27 2.98 $3.0 0 \pm 2.03$ 1.38 2.00 ± 2.16 0.27 3.00 ± 2.03 1.38 15.50 ± 9.00 8.29 3.00 ± 2.03 1.38 4.00 ± 1.92 2.46	3.00 ± 2.03 1.38 4.62 8.00 ± 6.27 2.98 13.01 $3.0 0 \pm 2.03$ 1.38 4.62 2.00 ± 2.16 0.27 3.73 3.00 ± 2.03 1.38 4.62 15.50 ± 9.00 8.29 22.7 3.00 ± 2.03 1.38 4.62 4.00 ± 1.92 2.46 5.53

Appendix VII.c: A table of descriptive test of sulphate of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	8.00 ± 6.27	2.98	13.01	0.051
BO C	2.00 ± 2.16	0.27	3.73	
BO 1	8.00 ± 6.27	2.98	13.01	0.125
WW 1	15.50 ± 9.00	8.29	22.7	
BO 1	8 .00± 6.27	2.98	13.01	0.166
WW C	4.00 ± 1.92	2.46	5.53	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	2.00 ± 2.16	0.27	3.73	0.005
WW 1	15.50 ± 9.00	8.29	22.7	
BO C	2.00 ± 2.16	0.27	3.73	0.121
WW C	4.00 ± 1.92	2.46	5.53	

Appendix VII.d: A table of descriptive test of sulphate of BO C and other sampling sites.

Appendix VII.e: A table of descriptive test of sulphate of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	15.50 ± 9.00	8.29	22.7	0.012
WW C	4.00 ± 1.92	2.46	5.53	

SULPHATE (SO₄²⁻) STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES **Appendix VII.f:** A table of descriptive test of sulphate of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	0.10 ± 0.001	0.09	0.10	0.106
BT 1	1.00 ± 1.24	0.001	1.99	
KK 1	0.10 ± 0.001	0.09	0.10	0.000
PT 1	9.00 ± 2.43	7.06	10.94	
KK 1	0.10 ± 0.001	0.09	0.10	0.000
PS 1	4.00 ± 1.44	2.85	5.15	

Appendix VII.g: A table of descriptive test of sulphate of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	1.00 ± 1.24	0.001	1.99	0.000
PT 1	9.00 ± 2.43	7.06	10.94	
BT 1	1.00 ± 1.24	0.001	1.99	0.003
PS 1	4.00 ± 1.44	2.85	5.15	

3

Appendix VII.h: A table of descriptive test of sulphate of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	9.00 ± 2.43	7.06	10.94	0.002
PS 1	4.00 ± 1.44	2.85	5.15	

APPENDIX VIII

SITE	X ± SD	Minimum	Maximum	P VALUE
A S 3	7.00 ± 4.16	3.68	10.32	0.016
AS C	1.80 ± 1.5	0.59	3.00	
AS 3	7.00 ± 4.16	3.68	10.32	0.015
BO 1	1.85 ± 1.1	0.96	2.73	
AS 3	7.00 ± 4.16	3.68	10.32	0.019
BO C	1.90 ± 1.61	0.32	3.19	
AS 3	7.00 ± 4.16	3.68	10.32	0.067
WW 1	3.25 ± 1.64	1.94	4.56	
AS 3	7.00 ± 4.16	3.68	10.32	0.019
WW C	1.90 ± 1.65	0.58	3.22	
			1CUV	

PHOSPHATE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix VIII.a:** A table of descriptive test of phosphate of AS 3 and other sampling sites.

Appendix VIII.b: A table of descriptive test of phosphate of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	1.80 ± 1.50	0.59	3.00	0.948
BO 1	1.85 ± 1.10	0.96	2.73	
AS C	1.80 ± 1.50	0.59	3.00	0.914
B0 C	1.90 ± 1.61	0.32	3.19	
AS C	1.80 ± 1.50	0.59	3.00	0.141
WW 1	3.25 ± 1.640	1.94	4.56	
AS C	1.80 ± 1.50	0.59	3.00	0.915
WW C	1.90 ± 1.650	0.58	3.22	-1
	17	2		

Appendix VIII.c: A table of descriptive test of phosphate of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	1.85 ± 1.1	0.96	2.73	0.951
BO C	1.90 ± 1.61	0.32	3.19	
BO 1	1.85 ± 1.1	0.96	2.73	0.113
WW 1	3.25 ± 1.64	1.94	4.56	
BO 1	1.85 ± 1.1	0.96	2.73	0.952
WW C	1.90 ± 1.65	0.58	3.22	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	1.90 ± 1.61	0.32	3.19	0.181
WW 1	3.25 ± 1.64	1.94	4.56	
BO C	1.90 ± 1.61	0.32	3.19	1.000
WW C	1.90 ± 1.65	0.58	3.22	

Appendix VIII.d: A table of descriptive test of phosphate of BO C and other sampling sites.

Appendix VIII.e: A table of descriptive test of phosphate of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	3.25 ± 1.64	1.94	4.56	0.186
WW C	1.90 ± 1.65	0.58	3.22	
			CT	

PHOSPHATE (PO₄²⁻) STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES **Appendix VIII.f:** A table of descriptive test of sulphate of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	1.60 ± 0.75	0.10	2.20	0.592
BT 1	1.40 ± 0.47	1.02	1.78	1
KK 1	1.60 ± 0.75	0.10	2.20	0.104
PT 1	0.80 ± 0.8	0.10	1.40	
KK 1	1.60 ± 0.75	0.10	2.20	0.063
PS 1	3.10 ± 1.59	1.83	4.37	

Appendix VIII.g: A table of descriptive test of sulphate of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	1.40 ± 0.47	1.02	1.78	0.144
PT 1	0.80 ± 0.80	0.10	1.40	
BT 1	1.40 ± 0.47	1.02	1.78	0.031
PS 1	3.10 ± 1.59	1.83	4.37	

Appendix VIII.h: A table of descriptive test of sulphate of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	0.80 ± 0.80	0.10	1.40	0.010
PS 1	3.10 ± 1.59	1.83	4.37	

APPENDIX IX

CHLORIDE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix IX. a:** A table of descriptive test of chloride of AS 3 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	14.95 ± 2.38	13.04	16.86	0.000
AS C	8.10 ± 1.40	6.98	9.22	
AS 3	14.95 ± 2.38	13.04	16.86	0.000
BO 1	80.6 ± 3.22	77.63	83.18	
AS 3	14.95 ± 2.38	13.04	16.86	0.000
BO C	7.90 ± 1.14	6.98	8.81	
AS 3	14.95 ± 2.38	13.04	16.86	0.288
WW 1	13.50 ± 2.09	11.83	15.17	
AS 3	14.95 ± 2.38	13.04	16.86	0.000
WW C	8.40 ± 0.83	7.74	9.06	
0000 C	0.40 ± 0.03	7.74	5.00	

Appendix IX. b: A table of descriptive test of chloride of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	8.10 ± 1.40	6.98	9.22	0.000
BO 1	80.6 ± 3.22	77.63	83.18	
AS C	8.10 ± 1.4	6.98	9.22	0.792
BO C	7.90 ± 1.14	6.98	8.81	
AS C	8.10 ± 1.40	6.98	9.22	0.000
WW 1	13.5 ± 2.09	11.83	15.17	-
AS C	8.10 ± 1.40	6.98	9.22	0.661
WW C	8.40 ± 0.83	7.74	9.06	
		WJSANE	NO	

Appendix IX. c: A table of descriptive test of chloride of BO 1 other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	80.6 ± 3.22	77.63	83.18	0.000
BO C	7.90 ± 1.14	6.98	8.81	
BO 1	80.60 ± 3.22	77.63	83.18	0.000
WW 1	13.50 ± 2.09	11.83	15.17	
BO 1	80.60 ± 3.22	77.63	83.18	0.000
WW C	8.40 ± 0.83	7.740	9.06	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	7.90 ± 1.14	6.98	8.81	0.000
WW 1	13.50 ± 2.09	11.83	15.17	
BO C	7.90 ± 1.14	6.98	8.81	0.406
WW C	8.40 ± 0.83	7.74	9.06	

Appendix IX. d: A table of descriptive test of chloride of BO C sampling sites.

Appendix IX. e: A table of descriptive test of chloride of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	13.5 ± 2.09	11.83	15.17	0.000
WW C	8.4 ± 0.83	7.74	9.06	
			121	

CHLORIDE STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES Appendix IX. f: A table of descriptive test of chloride of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	13.30 ± 1.99	11.71	14.89	0.000
BT 1	135.50 ± <mark>11.98</mark>	125.91	145.05	
KK 1	13.30 ± 1. <mark>99</mark>	11.71	14.89	0.178
PT 1	9.80 ± 5.10	5.72	13.88	
KK 1	13.30 ± 1.99	11.71	14.89	0.738
PS 1	13.80 ± 2.67	11.66	15.94	

Appendix IX. g: A table of descriptive test of chloride of BT 1 and other sampling sites.

		- mark		
SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	135.50 ± 11.98	125.91	145.05	0.000
PT 1	9.80 ± 5.10	5.72	13.88	
BT 1	135.50 ± 11.98	125.91	145.05	0.000
PS 1	13.80 ± 2.67	11.66	15.94	

Appendix IX. h: A table of descriptive test of chloride of PT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	9.80 ± 5.10	5.72	13.88	0.128
PS 1	13.80 ± 2.67	11.66	15.94	

APPENDIX X

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	0.007 ± 0.002	0.005	0.008	0.069
AS C	0.01 ± 0.003	0.008	0.012	
AS 3	0.007 ± 0.002	0.005	0.008	0.300
BO 1	0.009 ± 0.004	0.005	0.007	
AS 3	0.007 ± 0.002	0.005	0.008	0.000
BO C	0.001 ± 0.001	0.0002	0.002	
AS 3	0.007 ± 0.002	0.005	0.008	0.053
WW 1	0.017 ± 0.011	0.008	0.026	
AS 3	0.007 ± 0.002	0.005	0.008	0.000
WW C	0.001 ± 0.001	0.0002	0.002	

TOTAL MERCURY STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix X. a:** A table of descriptive test of total mercury of AS 3 and other sampling sites.

Appendix X. b: A table of descriptive test of total mercury of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	0.01 ± 0.003	0.008	0.012	0.635
BO 1	0.009 ± 0.004	0.005	0.007	
AS C	0.01 ± 0.003	0.008	0.012	0.000
B0 C	0.009 ± 0.004	0.005	0.007	
AS C	0.01 ± 0.003	0.008	0.012	0.164
WW 1	0.017 ± 0.011	0.008	0.026	
AS C	0.01 ± 0.003	0.008	0.012	0.000
WW C	0.001 ± 0.001	0.0002	0.002	

Appendix X. c: A table of descriptive test of total mercury of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	0.009 ± 0.004	0.005	0.007	0.001
BO C	0.009 ± 0.004	0.005	0.007	
BO 1	0.009 ± 0.004	0.005	0.007	0.125
WW 1	0.017 ± 0.011	0.008	0.026	
BO 1	0.009 ± 0.004	0.005	0.007	0.001
WW C	0.001 ± 0.001	0.0002	0.002	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	0.009 ± 0.004	0.005	0.007	0.005
WW 1	0.017 ± 0.011	0.008	0.026	
BO C	0.009 ± 0.004	0.005	0.007	1.000
WW C	0.001 ± 0.001	0.0002	0.002	

Appendix X. d: A table of descriptive test of total mercury of BO C and other sampling sites.

Appendix X. e: A table of descriptive test of total mercury of WW 1 and WW C sampling sites.

	SITE	X ± SD	Minimum	Maximum	P VALUE
ſ	WW 1	0.017 ± 0.011	0.008	0.026	0.005
	WW C	0.001 ± 0.001	0.0002	0.002	
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APPENDIX XI

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	5.85 ± 6.48	1.07	11.04	0.053
AS C	0.04 ± 0.02	0.03	0.05	
AS 3	5.85 ± 6.48	1.07	11.04	0.147
BO 1	1.67 ± 0.69	1.12	2.23	
AS 3	5.85 ± 6.48	1.07	11.04	0.122
BO C	1.37 ± 0.45	1.01	1.73	
AS 3	5.85 ± 6.48	1.07	11.04	0.043
WW 1	13.64 ± 5.04	4.61	17.67	
AS 3	5.85 ± 6.48	1.07	11.04	0.052
WW C	0.013 ± 0.01	0.01	0.20	
			121	

TOTAL IRON STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix XI. a:** A table of descriptive test of total iron of AS 3 and other sampling sites.

Appendix XI. b: A table of descriptive test of total iron of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	0.04 ± 0.015	0.03	0.05	0.002
BO 1	1.67 ± 0.69	1.12	2.23	
AS C	0.04 ± 0.015	0.03	0.05	0.000
BO C	1.37 ± 0.45	1.01	1.73	
AS C	0.04 ± 0.015	0.03	0.05	0.000
WW 1	13.64 ± 5.04	4.61	17.67	
AS C	0.04 ± 0.015	0.03	0.05	0.004
WW C	0.013 ± 0.009	0.01	0.20	
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Appendix XI. c: A table of descriptive test of total iron of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	1.67 ± 0.69	1.12	2.23	0.393
BO C	1.37 ±0.45	1.01	1.73	
BO 1	1.67 ± 0.69	1.12	2.23	0.000
WW 1	13.64 ± 5.04	4.61	17.67	
BO 1	1.67 ± 0.69	1.12	2.23	0.000
WW C	0.013 ± 0.009	0.01	0.20	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	1.37 ± 0.45	1.01	1.73	0.000
WW 1	13.64 ± 5.04	4.61	17.67	
BO C	1.37 ± 0.45	1.01	1.73	0.000
WW C	0.013 ± 0.009	0.01	0.20	

Appendix XI. d: A table of descriptive test of total iron of BO C and other sampling site

Appendix XI. e: A table of descriptive test of total iron of WW 1 and WW C sampling site

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	13.64 ± 5.04	4.61	17.67	0.000
WW C	0.013 ± 0.009	0.01	0.20	

TOTAL IRON STATISTICAL ANALYSIS FOR GROUNDWATER SAMPLES Appendix XI.f: A table of descriptive test of total iron of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	1.26 ± 0.28	1.04	1.48	0.229
BT 1	1.65 ± 0.69	1.1	2.2	
KK 1	1.26 ± 0.28	1.04	1.48	0.447
PT 1	1.4 ± 0.33	1.13	1.66	
KK 1	1.26 ± 0.28	1.04	1.48	0.577
PS 1	1.35 ± 0.26	1.14	1.56	

Appendix XI.g: A table of descriptive test of total iron of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	1.65 ± 0.69	1.1	2.20	0.442
PT 1	1.4 ± 0.33	1.13	1.66	
BT 1	1.65 ± 0.69	1.1	2.20	0.343
PS 1	1.35 ± 0.26	1.14	1.56	

Appendix XI.h: A table of descriptive test of total iron of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	1.4 ± 0.33	1.13	1.66	0.777
PS 1	1.35 ± 0.26	1.14	1.56	

APPENDIX XII

TOTAL MANGANESE STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix XII. a:** A table of descriptive test of total manganese of AS 3 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	1.06 ± 0.52	0.65	1.47	0.001
AS C	0.04 ± 0.02	0.03	0.06	
AS 3	1.06 ± 0.52	0.65	1.47	0.003
BO 1	0.22 ± 0.08	0.16	0.28	
AS 3	1.06 ± 0.52	0.65	1.47	0.001
BO C	0.01 ± 0.01	0.005	0.02	
AS 3	1.06 ± 0.52	0.65	1.47	0.002
WW 1	0.17 ± 0.08	0.10	0.23	
AS 3	1.06 ± 0.52	0.65	C 1 .47	0.001
WW C	0.005 ± 0.001	0.004	0.01	

Appendix XII. b: A table of descriptive test of total manganese of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	0.04 ± 0.02	0.03	0.06	0.000
BO 1	0.22 ± 0.08	0.16	0.28	
AS C	0.04 ± 0.02	0.03	0.06	0.008
BO C	0.01 ± 0.01	0.005	0.02	
AS C	0.04 ± 0.02	0.03	0.06	0.003
WW 1	0.17 ± 0.08	0.10	0.23	
AS C	0.04 ± 0.02	0.03	0.06	0.002
WW C	0.005 ± 0.001	0.004	0.01	
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Appendix XII. c: A table of descriptive test of total manganese of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	0.22 ± 0.08	0.16	0.28	0.000
BO C	0.01 ± 0.01	0.005	0.02	
BO 1	0.22 ± 0.08	0.16	0.28	0.304
WW 1	0.17 ± 0.08	0.10	0.23	
BO 1	0.22 ± 0.08	0.16	0.28	0.000
WW C	0.005 ± 0.001	0.004	0.01	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	0.01 ± 0.01	0.005	0.02	0.001
WW 1	0.17 ± 0.08	0.1	0.23	
BO C	0.01 ± 0.01	0.005	0.02	0.251
WW C	0.005 ± 0.001	0.004	0.01	

Appendix XII. d: A table of descriptive test of total manganese of BO C and other sampling sites.

Appendix XII. e: A table of descriptive test of total manganese of WW1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	0.17 ± 0.08	0.10	0.23	0.001
WW C	0.005 ± 0.001	0.004	0.01	
		KINU	121	

Appendix XII. f: A table of descriptive test of total manganese of KK1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	0.003 ± 0.02	0.02	0.04	0.000
BT 1	1.23 ± 0.06	1.21	1.31	
KK 1	0.003 ± 0.02	0.02	0.04	0.000
PT 1	0.64 ± 0.12 🦯	0.38	0.9	
KK 1	0.003 ± 0.02	0.02	0.04	0.000
PS 1	0.15 ± 0.014	0.14	0.16	

Appendix XII. g: A table of descriptive test of total manganese of BT 1 and other sampling sites.

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SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	1.23 ± 0.06	1.21	1.31	0.000
PT 1	0.64 ± 0.12	0.38	0.90	
BT 1	1.23 ± 0.06	1.21	1.31	0.000
PS 1	0.15 ± 0.014	0.14	0.16	

Appendix XII. h: A table of descriptive test of total manganese of BT 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	0.64 ± 0.12	0.38	0.90	0.000
PS 1	0.15 ± 0.014	0.14	0.16	

APPENDIX XIII

TOTAL ARSENIC STATISTICAL ANALYSIS FOR SURFACE WATER SAMPLES **Appendix XIII. a:** A table of descriptive test of total arsenic of AS 3 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS 3	0.02 ± 0.003	0.019	0.025	0.000
AS C	0.001 ± 0.0002	0.0008	0.001	
AS 3	0.02 ± 0.003	0.019	0.025	0.027
BO 1	0.01 ± 0.009	0.008	0.02	
AS 3	0.02 ± 0.003	0.019	0.025	0.011
BO C	0.016 ± 0.001	0.015	0.017	
AS 3	0.02 ± 0.003	0.019	0.025	1.000
WW 1	0.02 ± 0.001	0.021	0.023	
AS 3	0.02 ± 0.003	0.019	0.025	0.000
WW C	0.006 ± 0.001	0.005	0.007	

Appendix XIII. b: A table of descriptive test of total arsenic of AS C and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
AS C	0.001 ± 0.0002	0.0008	0.001	0.034
BO 1	0.01 ± 0.009	0.008	0.02	
AS C	0.01 ± 0.009	0.008	0.02	0.000
BO C	0.016 ± 0.001	0.015	0.017	
AS C	0.001 ± 0.0002	0.0008	0.001	0.000
WW 1	0.02 ± 0.001	0.021	0.023	
AS C	0.001 ± 0.0002	0.0008	0.001	0.000
WW C	0.006 ± 0.001	0.005	0.007	
		WJ SANE N	0	

Appendix XIII. c: A table of descriptive test of total arsenic of BO 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
BO 1	0.01 ± 0.009	0.008	0.02	0.136
BO C	0.016 ± 0.001	0.015	0.017	
BO 1	0.01 ± 0.009	0.008	0.02	0.022
WW 1	0.02 ± 0.001	0.021	0.023	
BO 1	0.01 ± 0.009	0.008	0.02	0.305
WW C	0.006 ± 0.001	0.005	0.007	

SITE	X ± SD	Minimum	Maximum	P VALUE
BO C	0.016 ± 0.001	0.015	0.017	0.000
WW 1	0.02 ± 0.001	0.021	0.023	
BO C	0.016 ± 0.001	0.015	0.017	0.000
WW C	0.006 ± 0.001	0.005	0.007	

Appendix XIII. d: A table of descriptive test of total arsenic of BO C and other sampling sites.

Appendix XIII. e: A table of descriptive test of total arsenic of WW 1 and WW C sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
WW 1	0.02 ± 0.001	0.021	0.023	0.000
WW C	0.006 ± 0.001	0.005	0.007	
		NNU	121	

Appendix XIII. f: A table of descriptive test of total arsenic of KK 1 and other sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
KK 1	0.002 ± 0.001	0.001	0.003	0.073
BT 1	0.001 ± 0.0007	0.0004	0.0016	
KK 1	0.002 ± 0.001	0.001	0.003	0.073
PT 1	0.001 ± 0.0007	0.0004	0.0016	
KK 1	0.002 ± 0.001	0.001	0.003	1.000
PS 1	0.002 ± 0.0015	0.0008	0.0032	

Appendix XIII. g: A table of descriptive test of total arsenic of BT 1 and other sampling sites.

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SITE	X ± SD	Minimum	Maximum	P VALUE
BT 1	0.001 ± 0.0007	0.0004	0.0016	1.000
PT 1	0.001 ± 0.0007	0.0004	0.0016	
BT 1	0.001 ± 0.0007	0.0004	0.0016	0.170
PS 1	0.002 ± 0.0015	0.0008	0.0032	

Appendix XIII. h: A table of descriptive test of total arsenic of PT 1 and PS 1 sampling sites.

SITE	X ± SD	Minimum	Maximum	P VALUE
PT 1	0.001 ± 0.0007	0.0004	0.0016	0.169
PS 1	0.002 ± 0.0015	0.0008	0.0032	